Continuous IAQ monitoring with low-cost monitors: protocol development, performance and application in residential buildings.

Thesis submitted for the degree of

Doctor of Philosophy

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BSc Architecture

MArch Zero-Energy Mass Customised Housing

The Glasgow School of Art

Mackintosh School of Architecture

April 2019

Abstract

Over recent decades, dwellings have become more energy-efficient. While many studies have focused on looking at energy conservation and decarbonisation of the housing stock, very few had a look at the indoor air quality (IAQ). The current approach to IAQ and occupational health studies is limited by current knowledge on ventilation, indoor air pollutants and the instruments to measure them. The ventilation and indoor pollution measurements required are expensive and invasive; therefore, these studies tend to be small and isolated.

Perhaps one of the most significant barriers for IAQ studies is the instrumentation needed for current approaches. Their cost, size, process control and required specialised training makes them unfeasible. For these reasons, IAQ studies tend to be based on short-term or spot measurements. Recent developments in technologies and communications have led to the development of low-cost IAQ monitors, that have the potential to be used in IAQ studies. This study aims to develop, test the performance and application of a method to measure the IAQ using low-cost (<£200.00) monitors and remote data collection.

After assessing the capabilities of several low-cost IAQ monitors, the Foobot was selected for this study. The Foobot data were compared to traditional IAQ monitors to address accuracy and quality concerns. Foobot has the potential to be used in IAQ studies; however, it is limited by the range of parameters to measure. While it is capable of measuring the most common air pollutants, the Foobot may not be ideal to established IAQ assessment routines, such as the CIBSE KS17 or the EPA. The methodology presented in this work uses online surveys to collect qualitative data about the perception of the IAQ, thermal comfort and self-reported illnesses.

The methodology was tested in seven dwellings located in Mexico City, San Francisco and Dunfermline. Air temperature, relative humidity, particulate matter and total volatile organic compounds were collected at five-minute intervals in three rooms of each of the dwellings. The analysis of the data suggests that IAQ is mostly related to occupant's behaviour, outdoor pollution and ventilation rates. While the methodology presented in this work may have some limitations, it nevertheless provides an alternative and innovative method for IAQ monitoring. This should encourage IAQ data collection, enhancing our knowledge on IAQ and promote healthier indoor environments.

Glossary

Absolute humidity :	Measurement of water vapour in the air, regardless of the air temperature.	g/kg
Air flow (m):	Movement of an air volume from one space to another.	m^3/h
Air speed (v):	Also called air velocity, describes the air flow rate at a measurement point and can be derived from the average or standard deviation of velocity over an interval of time.	m/s
Air temperature (θ_a):	Also called dry bulb temperature (θ_{db}), is the temperature registered by a dry thermometer, shield from radiation and moisture, suspended in the air.	˚C
CO_2:	Carbon dioxide	ppm
$CO_{2\text{-equivalent}}$:	Carbon dioxide equivalent	ppm
Dew point temperature (θ_d):	Temperature at which, if the air were cooled slowly, it would reach saturation point; beyond this point any further cooling will provoke the airborne water condensate and form liquid water.	˚C
Dew Point temperature (θ_{dp}):	Temperature where water vapour starts to condensate out of the air, in other words the temperature at which the air becomes completely saturated.	˚C
Dry bulb temperature (θ_{db}):	Also called air temperature (θ_a), is the temperature registered by a dry thermometer, shield from radiation and moisture, suspended in the air.	˚C
Dry resultant temperature (θ_{res}):	It is identical to the θ_{op} in concept, which is used in International Standards (BSI and ANSI/ASHRAE).	˚C
Globe temperature (θ_g):	Globe temperature is the resultant of measuring the temperature with a globe thermometer. This thermometer consists of a hollow cooper sphere painted in matt black to absorb radiant heat, with a temperature sensor at its centre. When reaching a steady state the heat exchange by convection and radiation will be in equilibrium and the temperature recorded will be somewhere between the radiant temperature and air temperature.	˚C
Dryness:	Refers to a higher frequency of complaints with low humidity. At the design temperatures normally appropriate for sedentary occupancy, the room humidity should be above 40%RH. Humidity of 30%RH or lower may generate dust and airborne irritants.	
IAQ:	Indoor air quality	
IEQ:	Indoor environmental quality	
Inside/indoor air temperature (θ_{ai}):	Temperature of the air of an enclosed space.	˚C

Internal/inside surface temperature (θ_{si}):	Temperature at or near a surface of the surface immediately adjacent to an air space.	˚C
Operative temperature(θ_{op}):	Also called dry resultant temperature (θ_{res}), is a weighted mean temperature between air (θ_{air}) and radiant (θ_r) temperatures, the weight depending on the heat transfer of the coefficients by convention and radiation. Air speed relates this weighting; thus the θ_{op} can be calculated from: $$\theta_{op} = \frac{\theta_{air}\sqrt{(10v + \theta_r)}}{1 + \sqrt{(10v)}}$$ In a well-designed building, most of the surface temperatures (θ_{surf}) are close to air temperature and the θ_{air} and θ_{op} are often equal.	˚C
Outside/outdoor air temperature (θ_{ao}):	Temperature of the air surrounding the building. For the purposes of this work this was assumed to be the air temperature measured at the nearby meteorological station.	˚C
$PM_{2.5}$ and PM_{10}:	Particulate matter under 10μm and 2.5μm.	$\mu g/m^3$
Radiant temperature (θ_r):	Generally understood to be the mean radiant temperature (θ_{mr}), which is the temperature of a black sphere at the point in question that would exchange no net radiation with the surroundings.	˚C
Radiant temperature asymmetry:	Measure of difference in radiant temperatures on two opposite sides of a small plane element	˚C
Relative humidity (ϕ); text abbreviation RH:	Ratio of water vapour pressure to the saturation of water pressure (over water) at air temperature.	%RH
Surface temperature (θ_s):	Temperature at or near a surface of an element or building material.	˚C
tVOC:	Total Volatile Organic Compounds	$\mu g/m^3$
Wet bulb temperature (θ_{wb}):	Temperature registered by a thermometer wrapped in wet muslin. It indicates the adiabatic evaporation of water from the thermometer bulb and the cooling effect	˚C

Table of contents

List of tables

List of figures

Acknowledgements

This study is a personal interpretation of the journey through my Doctoral Studies conducted at “The Glasgow School of Art”. The point of views and ideas expressed are mine. However, the debt owed to several friends, professionals and researchers in various fields of study, in addition to those experts on sustainable architecture is vast. I would like to express my gratitude to everyone who worked directly or indirectly to make this possible. Several people helped to make numerous corrections and useful editing and proofreading of this work, especially Adam Hotson and Ian Faller.

This project was possible with the support and collaboration of INHAB Arquitectura sustentable, One Sky Homes, Edinburgh Napier University. This work would never have been possible without the support from CONACyT, who partially funded me during this journey, and Airboxlab, who kindly supported this study with discounted and free IAQ monitors.

I also would like to express sincere gratitude to Prof Tim R Sharpe, Dr Filbert Musau and Dr Gráinne McGill, my supervisors, for their emotive and persistent encouragement to push ahead and during all this time sharing their time and knowledge. I have as well a debt to all the Mackintosh School of Architecture staff who supported me, especially from the Mackintosh Environmental Research Unit, in particular to Janice Foster, Anna Poston and Lynette Robertson.

I would like to extend my gratitude to Prof Colin Porteuos and Dr Paul Gerard Tuohy for agreeing to examine my research and taking the time to read it.

Finally, I express my full gratitude to my family, in particular to Luis Ignacio and Virginia, my parents, whom even from a distance keept close and encourage me to do my best on this adventure. Their unconditional support crossed seas when I needed it most.

I, Alejandro Moreno-Rangel, declare that this work for the degree of Doctor of Philosophy and consisting of a thesis meets the regulations stated in the handbook for the mode of submission selected (PhD by Thesis) and approved by the Research Degrees Sub-Committee.

I declare that this submission is my own work, and has not been submitted for any other academic award.

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Chapter 1 Introduction

1.1 Background – climate change.

Climate change is one of the most significant changes caused by human activities (Treut *et al.*, 2007), and its influence is one of the most pressing challenges of our time (Mcnutt, 2013). Over the last few decades, we have started to wake up to what scientists have been warning us about: humans are polluting the Earth to a point beyond which natural systems cannot remain stable. Moreover, humanity is consuming non-renewable resources faster than at any previous point in history; in fact, deforestation and fossil fuel emissions have led to the destabilisation of Earth's carbon cycle, creating new risks and amplifying existing risks to natural and human systems (IPCC, 2014).

Global energy demand has continued to increase, to the point of nearly doubling in the past 30 years (IEA, 2015, 2017b). The International Energy Agency (IEA) has noted that coal has supplied almost half of this energy demand and that fossil fuel consumption is growing faster than all currently available renewable sources put together (IEA, 2015). The increasing demand for energy and the reduction on fossil-fuel reserves has led to increased prices (IEA, 2017a) – and these are expected to continue to rise (Worldwatch Institute, 2014). For instance, the IEA's 2008 report documented that the price of crude oil was on average $100 US dollars per barrel and estimated that by 2030 this price would rise to $200 US dollars. According to the IEA's executive director, Nobuo Tanaka, the most worrying factor was that *"global energy-related greenhouse gas emissions will increase by 45% by 2030"* (IEA, 2008, p. 3).

The destabilisation of the Earth's carbon cycle has affected how natural carbon sinks absorb CO_2 from the atmosphere, which the evidence demonstrates is related to an increase of 2°C of the planet's mean surface temperature (Schellnhuber *et al.*, 2006), which is unlikely to be avoided by the end of this century. Historical emissions of greenhouse gases have already caused an increase of 0.6-0.7°C, from 1951 to 2010 (IPCC, 2014, p. 48), with the International Panel of Climate Change's (IPCC) fifth report (IPCC, 2013, p. 4) noting:

"Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and the ocean have warmed, the amounts of snow and ice have diminished, sea levels have risen, and the concentrations of greenhouse gases have increased."

Accordingly to the IPCC (2014) report, the surface temperature is projected to rise (0.3-5.4°C) over all the projected scenarios by 2100 (Figure 1.1). Also, heat waves are very likely to occur more often and last longer, and extreme precipitation will become more intense and frequent, while oceans will continue to warm and acidify, and sea levels will continue to rise.

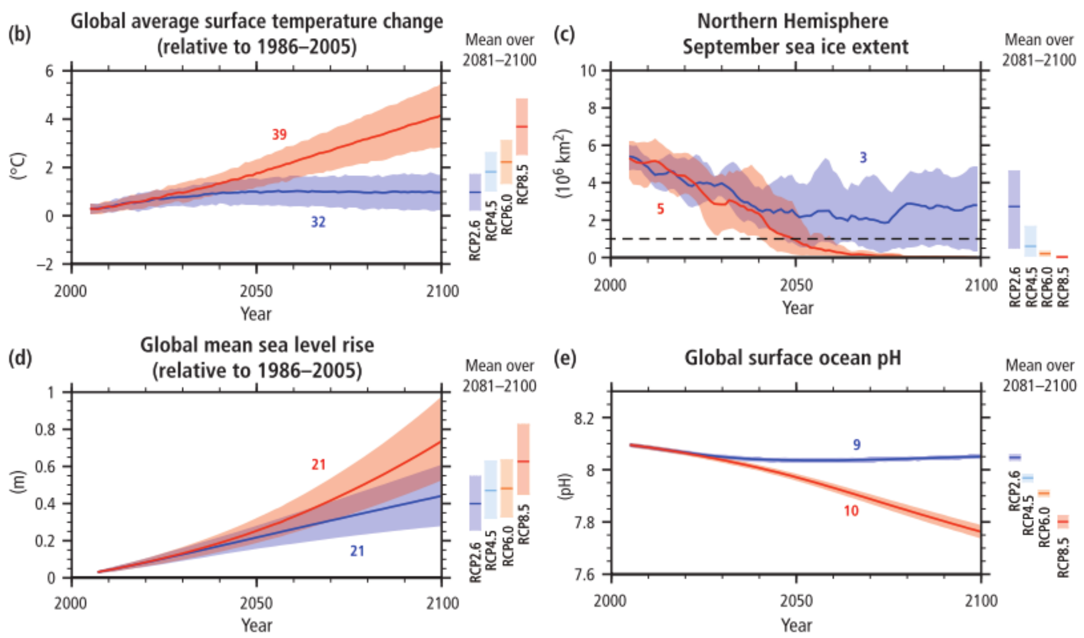


Figure 1.1 Time series of global climate changes, risks and impacts (2006-2100). These graphs show the highest and lowest projected impacts of climate changes from the four different models, as illustrated by the International Panel on Climate Change. Source: (IPCC, 2014)**.**

As highlighted by Hopfe & McLeod (2015, p.3), "*society faces rising energy prices, increased resource competition and a moral imperative to create a sustainable built environment*," therefore clean growth, the sensible use of resources and an increased emphasis on a reduction in energy consumption, sustainability and resilience should be at the top of the agenda.

1.2 Drivers to change the way we build

The way we build has evolved in recent years, particularly with regards to housing. Environmental concerns, high energy costs and an increasing demand for housing have stimulated the shift towards low-energy homes (Sadineni, Madala and Boehm, 2011) and the ambition to provide zero energy buildings (ZEB, Marszal et al. 2011). The ZEB concept is based on the energy balance calculation where the energy consumption of a building is balanced with on-site and/or off-site energy generation systems — interacting with the utility grid — aiming to fulfil 'zero'. The built environment is responsible for considerable of energy consumption; it is estimated that building energy consumption accounts for approximately 40% of the global annual figure (Liu, Zhao and Tang, 2010; Anderson, Wulfhorst and Lang, 2015). Buildings, on their own, should provide acceptable indoor environmental conditions for human activities (Anderson, Wulfhorst and Lang, 2015). Indoor comfort plays a vital role in a building's energy consumption, as heating and cooling may account for as much as 60-70% of it (Pérez-Lombard, Ortiz and Pout, 2008; Anderson, Wulfhorst and Lang, 2015).

A pressing matter, however, is that CO_2 emissions from the built environment are growing. The Kyoto Protocol (United Nations, 1998) and the Paris Agreement (United Nations, 2016) seek to mitigate climate change by reducing greenhouse emissions. In a way, they represent the first step toward sustainable buildings. CO_2 emissions due to energy consumption of buildings are estimated to have grown at an annual rate of 1.7% for residential buildings between 1971 and 2004 (IPCC, 2007). In the European Union, buildings are responsible for 40% of the total CO_2 emissions (Petersdorff, Boermans and Harnisch, 2006), while in the UK, it is estimated that carbon emissions related to the residential sector stand at around 15%, (BEIS, 2019). Similarly, in the US, 19% of carbon emissions are related to residential buildings (EPA, 2018). In contrast, carbon emissions from the built environment represent only 10% of the total in Mexico (one of the settings for this research), though the residential sector is accountable for 74% (SEMARNAT and INECC, 2015) of this. Moreover, the Mexican residential sector's CO_2 emissions are expected to increase close to nine-fold by 2050 (de Buen, 2009).

The demand for housing will continue to grow in the coming years, due to the extension of developed regions – and so, in turn, will related energy demands (Pérez-Lombard, Ortiz and Pout, 2008; Liu, Zhao and Tang, 2010). Usually, building energy efficiency is improved by implementing either passive or active energy-efficient methodologies. Active methods include a range of improvements that require energy to function, such as heating, mechanical ventilation with heat recovery (MVHR), energy efficient electric bulbs, white goods and other appliances, whereas passive technologies rely on, or make the best use of natural resources, including daylight, solar power for lighting and heating, thermal mass, or natural ventilation. As interest in low-energy homes is growing, approaches to new energy-efficient buildings have been developed.

Governments have, in recent years, set targets for low-energy buildings, to reduce carbon emissions. In Europe, the Energy Performance in Buildings Directive, established in 2010, requires all new buildings to be near ZEB by 2020 (CEC, 2010). In the UK, the government set the goal to achieve zero carbon homes by 2016 - new apartments and mid-terraced houses were targeted to achieve a minimum of 39kWh/m^2, while semi-detached, detached and end of terrace homes 46kWh/m^2 for heating and cooling. However, this initiative came to an end in 2015 (Ares, 2016), following the governments' announcement to terminate the Allowable Solutions Carbon Offsetting Scheme, stating an intention to '*keep energy efficiency standards under review'* (HM Treasury, 2015, p. 46). Primary barriers for its implementation were the increased capital cost, scheme viability, public awareness, and knowledge of occupants (Heffernan *et al.*, 2016). Some states in the US, such as California set similar goals in terms of nZEB dwellings by 2020 (CEC, 2007). Mexico, has been setting programmes seeking to ensure energy-efficient homes since 2007 (de Buen, 2009), and the "Nationally Appropriate Mitigation Actions for New Housing" studyied the impact of low-energy options, using the PassivHaus approach, to reduce CO_2 emissions by 2020 (Feist, 2012; Kaineg *et al.*, 2012; GIZ, 2014).

1.3 Low-energy building approach

Since the 1970s, new approaches to building have aimed to reduce energy demand and improve indoor conditions by reducing heat loss through passive and active techniques. Existing components and energy systems have been improved, and some pioneering buildings have achieved incredible heat demand reductions, however; the additional costs were so excessive that they could not be amortised by saving fuel costs. At this point in time, we are in a transition between traditional building practices and nZEB using different design approaches for low-energy demands. This transition has been made possible with buildings that not only offer a well-established template for being low/ultra-low-energy but are also economical and resource-efficient whilst providing high levels of occupant comfort and resilience to future climate changes (Hopfe and McLeod, 2015). To address the energy and environmental impacts of buildings, different institutions have formulated rating systems to promote low-energy-low-carbon design and construction; and also, to quantify and recognise such achievements through certification. Such systems include BREEAM (Building Research Establishment Environmental Assessment Methodology), LEED (Leadership in Energy & Environmental Design) and PassivHaus Standard.

Adopting a standard or regulation does not guarantee the desired results, as buildings still exhibit performance gaps (Miguez *et al.*, 2006), such as poor IAQ and energy. Some studies suggest that Belgian (Hens, Parijs and Deurinck, 2010), Dutch (Tigchelaar and Daniëls, 2011), French (Cayre *et al.*, 2011), German (Sunikka-Blank and Galvin, 2012) and British (Kelly, 2011) low-energy homes may consume more energy than expected, with occupant behaviour, such as window opening, lighting use, heating expectations and regulation (Masoso and Grobler, 2010), the main determinant (Stern, 2000; Santin, Itard and Visscher, 2009; Gram-hanssen and Gram-hanssen, 2010). For instance, the Standard Assessment Procedure (SAP) for new dwellings and reduced SAP (RdSAP) in the UK do not estimate the energy efficiency but relates the cost to the performance effectiveness of the building leading to additional CO_2 emissions (Kelly, Crawford-brown and Pollitt, 2012) therefore providing misleading estimations. While most discussions on low-energy buildings often include energy, site impacts, materials, water use and indoor environmental quality, IAQ merits more serious consideration (Persily, 2014). For instance, as the building envelope achieves higher levels of airtightness minimising thermal – and energy – losses, we do not understand its effects on the indoor environment completely.

In the BREEAM certification, IAQ is assessed according to criteria set out in *Health & Well-being Hea 02 – Indoor Air Quality* and covering two elements for residential and commercial buildings: minimising sources of indoor air pollution, and the potential for natural ventilation (for detailed information, see BRE Global 2014, pp.84–90). The indoor environmental quality criteria for LEED certification assess IAQ and ventilation based on ASHRAE 62.1, sections 4-7. It also uses a comprehensive monitoring programme to evaluate air flows, outdoor air intake and carbon dioxide levels, which suggests air testing through a chemical analysis of formaldehyde, 36 volatile organic compounds, carbon monoxide, ozone and particulate matter (2.5μm and 10μm, for detailed information, see ASHRAE 2007; U.S. Green Building Council 2015). The PassivHaus principle is based on providing thermal comfort, as defined in ISO 7730, by post-heating or post-cooling with controlled ventilation without recirculating used air, as described in DIN1946 (Bere, 2013): "*The [PassivHaus] aim is to provide an acceptable and even improved indoor environment in terms of IAQ and thermal comfort at minimum energy demand and cost*" (Feist *et al.*, 2005, p. 1187). However, PassivHaus lacks criteria that address or evaluate IAQ, thus, it was selected for the settings of this research

1.4 PassivHaus: current state

Between 1990 and 2005, only a few thousand PassivHaus buildings existed, but this number has increased (Feist *et al.*, 2005) reaching locations including Scotland, the US and Mexico. According to the PassivHaus Trust, the PassivHaus standard is one of the fastest growing building energy performance systems in the world, and it is estimated that there are over 65,000 PassivHaus buildings worldwide (iPHA, 2017). Over the last decade, interest in the PassivHaus standard has begun to spread and with it, research to support the approach and ethos. Some research projects have contributed to developing the standard as we know it today: the Cost-Efficient Passive Houses as European Standard (CEPHEUS, Krapmeier and Drossler, 2001; Schnieders, 2003), Passive Houses for different climate zones (PHI, 2011) and the Passive House Regions with Renewable Energies (PassREg, PHI, 2015b, 2016).

Since PassivHaus focuses primarily on energy reduction, most research tends to look at building physics, their relation to energy as well as cost-effectiveness, and very little attention has been given to studying side effects. A search by the author in Scopus, using *TITLE-ABS-KEY* (*'Passive House' OR 'PassivHaus'*) as a metric for the search, recorded 864 peer-reviewed publications since 1999. Initial analysis of these papers by the author confirmed two main aspects in the PassivHaus literature. Firstly, it is clear that interest in understanding PassivHaus buildings has increased in the last decade. Secondly, PassivHaus literature tends to focus on engineering (60.5%, 513 studies), energy (31.1%, 264 studies) and environmental science (19.6%, 166 studies, Figure 1.2). A possible explanation is that the standard is based on an ultra-low-energy specification rather than other factors. It is clear that other important factors such as indoor air quality (5.18%, 44 studies) and health impact (1.18%, 10 studies) have yet to be appropriately addressed.

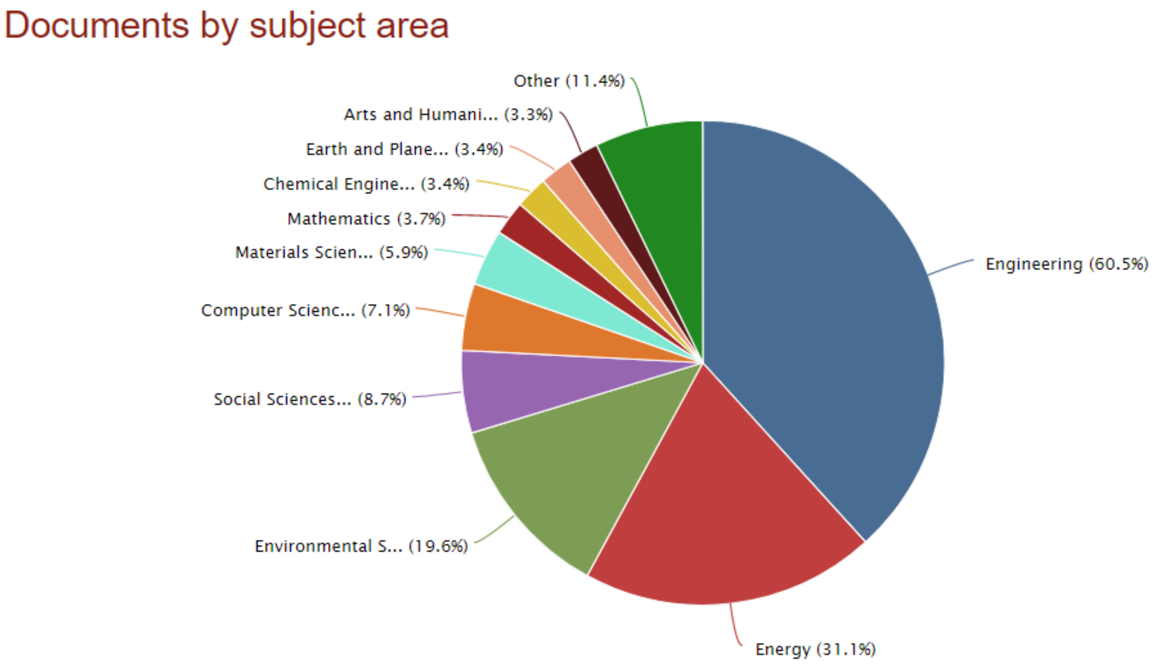


Figure 1.2 Shows the number of scientific works in the literature for PassivHaus by subject area. Date of the search 23/03/2018, source: www.scopus.com.

1.5 Why study indoor air quality in PassivHaus dwellings?

Indoor air quality (IAQ) refers to the indoor concentration of air pollutants that have the potential to harm or detriment human well-being (Jacobs, Kelly and Sobolewski, 2007). Nevertheless, acceptable IAQ is not clearly defined. Some authors suggest that it should be the absence of air contaminants (Rosseau, Bowser and Mattock, 2001), whereas others suggest that small concentrations are permissible as long as they do not harm the majority of the people exposed (ASHRAE 2007). This poses the question of what levels are permissible and how buildings can alter these levels.

Over time, the way we live has changed - and with it the amount of time we spend indoors. It is estimated that in developed countries people spend more than 85% of their time indoors (Klepeis *et al.*, 2001), hence the importance of studying this particular environment. Since the late 1980s, concerns about the amount of time spent indoors, and indoor air quality, have started to rise as their impact on human health has become more evident (Spengler and Sexton, 1987). The need to create binding air quality guidelines for indoor environments was recognised in the early 1990s (Samet, 1993), and in 2000, The World Health Organization (WHO) identified healthy indoor air as a human right (WHO Regional Office for Europe, 2000). While some progress has been made to set IAQ targets and guidance for offices and commercial environments, residential guidance is still absent, and non-regulated. Reasons for the lack of thresholds in dwellings may include the vast array of potential contaminants and analytical equipment to measure them can be intrusive and costly.

Recent interest in the impact of the indoor environment to human health helped to develop studies and building policies, i.e. Action 12 of the EU Environment and Health Action Plan 2004-2012 addressing environmental tobacco smoke and ways to respond to factors that affect IAQ. However, our understanding of the health consequences of indoor air quality is limited, particularly concerning the role of the built environment. Most of the current knowledge that links air pollution to health problems examines pollutants from outdoor sources, yet we still debate the 'safe levels' at which no health effects are likely (Brunekreef and Holgate, 2002), so outdoor pollution cannot be neglected for IAQ studies (Baek, Kim and Perry, 1997; Jones *et al.*, 2000; Kuo and Shen, 2010; Meadow *et al.*, 2014). Linear relationships between indoor and outdoor $PM_{2.5}$ and PM_{10} (Jones *et al.*, 2000; Kuo and Shen, 2010), airborne microbial communities (Meadow *et al.*, 2014) and VOCs (Baek, Kim and Perry, 1997) have been identified. Outdoor conditions remain an important consideration when conducting IAQ studies.

It took several years to realise the impact of radon on human health and the built environment's role, especially ground radon. In 1597 the first lung diseases were noted due to agricultural products; however, it was not until the 1940s when the casual links between ground radon and lung cancer were established (George, 2008). We understand now that radon is found in building materials (De Jong *et al.*, 2006), especially in materials such as concrete and wallboard (Ackers *et al.*, 1985). More importantly, we have a better understanding of how building factors, such as indoor air pressure (Appleton, 2007), permeability of the ground floor, and even building type, location, and occupant lifestyles (Bossew and Lettner, 2007) determine radon levels. Recent research in the field of indoor air pollution attempts to link volatile organic compounds (VOCs) and particulate matter ($PM_{2.5}$) to asthma and sick building syndrome (SBS) in buildings. Recommendations on how to improve IAQ are unequivocal: the most effective method for controlling indoor pollutants is to remove them at the source (Institute of Medicine, 2000). Several design strategies can be used to avoid the accumulation of hazardous chemicals of concern, provide proper ventilation and eliminate spaces and materials that attract or harbour indoor pollution (Sassi, 2006).

Research and knowledge in the field of healthy buildings are gradually increasing. However, an analysis by the author of past studies, presented in Chapter 2 of this study, shows that very limited studies have assessed the indoor environmental performance of PassivHaus dwellings in practice. Likewise, literature about IAQ in PassivHaus is even more restricted, as the majority of the literature in this respect built up significantly from the 2010s. Recent concerns about healthy buildings have started to question the impact of design strategies in low-energy buildings on the indoor environment and on occupants' health (Davies and Harvey, 2008). For instance, investigations have examined the impact of controlled ventilation rates (Seppänen and Fisk, 2004; Wargocki, 2013), MVHR systems (Yu and Crump, 2010), airtightness (Davies and Harvey, 2008), indoor sources (Spengler and Sexton, 1987; Crump, Dengel and Swainson, 2009) and high levels of indoor air pollutants (Uhde and Salthammer, 2007; Bernstein *et al.*, 2008) on human health.

The vast majority of studies that look at air pollution tend to focus on ambient/outdoor concentrations (Chen and Zhao, 2011), highlighting the need for further work to understand the impact of the built environment on IAQ. Home's design, finishes and furnishing can impact on occupants' health. Evidence suggests bedroom indoor environmental conditions, such as temperature, ventilation and IAQ, can have an impact on the quality of sleep. As explained by Wargocki et al. (2018) poor bedroom air quality has a negative effect on sleep whereas a small current of fresh air could improve sleep quality. Indoor sources of pollution vary accordingly to the presence of people and household activities (Jones *et al.*, 2000). Regardless of the sources, the effects of indoor contamination and poor indoor environmental quality are exacerbated by contemporary lifestyles, the consumption and accumulation of chemical products and increasing amounts of time spent at home, which is of special consideration in high-performance buildings where airtightness and ventilation, if not properly addressed, may impair the indoor environment. However outdoor sources have an important effect on indoor air pollution (Chatoutsidou *et al.*, 2015). Outdoor pollution is one of the major contributors to indoor concentrations of air pollutants (Janssen *et al.*, 1998). Therefore, this raises the question of measuring indoor pollution and comparing it with ambient levels to discover the extent to which PassivHaus buildings might protect occupants from, or expose them to, poor IAQ.

Latin American cities are facing air quality problems due to growing urbanisation and growth in transportation networks. Mexico City faces the most dangerous health threat related to air pollution in Latin America (Bell *et al.*, 2006).

The results of previous studies are somewhat inconclusive: while some suggest that PassivHaus design strategies may be beneficial to the indoor environment (Schnieders, 2003; Schnieders and Hermelink, 2006), there have been reservations, especially in terms of thermal comfort (Tabatabaei Sameni *et al.*, 2015). Although, as stated earlier, studies suggest the possibility of adopting the PassivHaus standard in climates, traditions, aesthetics, and regulations beyond those of Central Europe, yet studies on IAQ in PassivHaus buildings in regions with higher air pollution other than Central Europe are very limited. Despite the need for a better understanding of the IAQ impact of sustainable, green, high-performance and net-zero buildings design strategies, the majority of studies have largely focused on energy consumption (Emmerich and Persily, 2011).

Given the reliance on verification achieved via post-completion testing, PassivHaus dwellings are likely to adhere to the strictest levels of airtightness, controlled ventilation rates and the utilisation of MVHR systems, but there remains a fundamental need for research to investigate the impact of IAQ in PassivHaus homes. The impact of low-energy buildings on indoor environment quality remains mostly under-researched (Crump, Dengel and Swainson, 2009; Sullivan *et al.*, 2013) with limited knowledge and skills (Sullivan *et al.*, 2012) in this area. This gap in knowledge was identified by Crump (2009, p.40), who states:

> *"There is an urgent need for research into the performance of highly energy efficient homes with respect to the quality of the internal environment and the impact on the health and wellbeing of occupants."*.

This notion is supported by Mendell (2013), who suggests that further studies in low-energy homes should focus on IAQ by comparing buildings as alike as possible, albeit excluding energy-related factors. This could be strengthened by comparing such buildings with a control group of current building practices and less-energy-efficient dwellings (Crump, Dengel and Swainson, 2009) and the WHO's IAQ guidelines. However, in the author's view, a more exhaustive study would associate the measured data and building design characteristics to occupants' perceptions of IAQ and health.

The current approach to IAQ and occupational health studies is limited by the lack of knowledge on ventilation as well as the underappreciation of the impact of ventilation on contaminant levels (Persily and Levin, 2011; Carrer *et al.*, 2015). It is important to measure indoor contaminant concentrations and describe the measurement method, instruments and estimated uncertainty (Persily and Wargocki, 2016). However, such ventilation and indoor pollution measurements are expensive and invasive. Traditional approach for IAQ investigations requires visits from the researcher to install/uninstall measurement instruments, conduct interviews and collect physical building measurements; which may require several hours and visits, in addition to the initial/hiring costs of instruments. Therefore, existing studies tend to be small and isolated. Additionally, access and availability to traditional IAQ monitors limits the potential of the research.

Studies that have looked into IAQ in energy-efficient buildings usually use highly precise analytical instruments. However, the cost, size, rigidity, process control and requirement for specialised training make them unfeasible for larger/longer studies (Kularatna and Sudantha, 2008). Such instruments suffer from identifiable limitations such as high and periodic maintenance costs, slow response times and large size, thus making them impractical for air quality monitoring (Chou, 2000a), where mobility, accessibility and practicality are required. Consequently, studies rely typically on short-term or spot measurements, resulting in limited IAQ exposure data (White, 2009). Even if these instruments provide high granularity and temporal resolution, one could argue that their accuracy may be considered excessive for IAQ monitoring, where a principal objective is to establish whether or not pollutant concentration exceed specific threshold values. As the performance of low-cost sensors improves, instruments that are compact and robust, and come packaged with versatile applications, could be used as alternatives (Lee, 2001) for monitoring projects. However, their use requires some degree of caution as researchers need to balance the needs, resolution and precision.

Recent developments in technology and communications have led to the development of low-cost sensors that are capable of identifying and measuring a broad range of gases (Chou, 2000b) as well as different sizes of airborne particulates (Wang *et al.*, 2015) with remote real-time data access. Such sensors demonstrate many advantages, including long lifetime, lower cost and compact size (Kularatna and Sudantha, 2008), which could lead to establishing extensive monitoring networks to collect information on real human exposure to air pollutants (Ragazzi *et al.*, 2017) and energy demand associated to the provision of comfortable indoor environment (Parkinson, Parkinson and Dear, 2019). New, low-cost (<£200) monitoring technologies may help building occupants and researchers to understand IAQ, but there is limited information regarding the performance of these low-cost devices in practice. The author has identified a gap in the methodology to obtain more extensive IAQ exposure data. . This study looks at the novelty of approaching IAQ investigations with low-cost sensors, as well as their technologies and advantages for remote monitoring. A secondary area of investigation is the IAQ performance of PassivHaus dwellings in urban environments with extreme – high and low - outdoor pollution.

1.6 Study aim and objectives

This study aims to answer the following research question:

> **To what extent do low-cost IAQ monitors can be used for continuous IAQ monitoring in dwellings?**

To achieve this aim, the following research objectives will be met:

i. To identify IAQ criteria.

ii. To examine the suitability of commercially available low-cost IAQ monitors to quantify exposure to pollutants in real-life residential settings.

iii. To develop a research methodology using low-cost commercial monitors, allowing remote collection of high-quality IAQ data over extended periods of time.

iv. To examine the suitability of online surveys to collect data occupants' perceptions of the indoor environment and building information data.

v. To explore the application and suitability of the methodology to collect IAQ data in dwellings with different levels of sustainability in different locations.

1.7 Thesis structure

This chapter contextualises the external drivers that led to emerging low-energy standards, such as PassivHaus, identifying that most studies focus on energy and CO_2 reductions as drivers for current policies and that there is a lack of IAQ studies. One of the biggest limitations for this type of studies is the current approach to collect IAQ data. This chapter identified a gap in the methodology to collect extensive IAQ data. This chapter also identifies the broad context of the application and suitability of PassivHaus to reduce energy consumption and enhance IAQ.

Chapter 2 discusses current and emerging methods of monitoring IAQ, as well as the appropriateness and challenges of using traditional approaches with highly precise analytical monitors. It also examines the characteristics and limitations of the current methods employed to collect IAQ data, and thereafter it investigates an affordable and practical way to collect these data with low-cost and consumer monitors. In so doing, the advantages of choosing IAQ monitors, their accuracy, limitations and technology are discussed.

Chapter 3 provides the history and building physics behind the PassivHaus standard, the settings of this research to explore the application and suitability of the monitoring IAQ protocol. Studies addressing IAQ in these dwellings are presented, analysed, and discussed, to identify their characteristics and findings. The chapter identifies relevant indoor environmental parameters (temperature, relative humidity and carbon dioxide) and indoor pollutants (particulate matter 2.5 and total Volatile Organic Compounds) and and contextualises them with current routines for IAQ assessment.Chapter 4 outlines the study design to test the methodology a multiple case study that mixes quantitative and qualitative approaches to assess and compare IAQ. In the process, the characteristics, location, parameters, similarities and differences of the case studies are discussed. The challenges of finding suitable case studies through housing associations or architects, and the advantages of low-cost sensing technologies, remote setup, were drivers to develop a monitoring methodology using the Foobot and online surveys to collect IAQ data. This monitoring protocol is based on ASTM-D7297 and ISO:16000-1:2006 standards, to collect physical IAQ data, and The Royal Society of Health Questionnaire to Investigate Sick Building Syndrome to learn about occupants' IAQ perceptions and self-assessed well-being. A pilot study was used to evaluate the research design and refine it accordingly. Finally, this chapter examines the scope, limitations, replicability and quality of this research.

Chapters 5, 6 and 7 present the measured data and its analysis of the case studies in Mexico City, San Francisco and Dunfermline. Data about temperature, relative and absolute humidity, $PM_{2.5}$ and tVOC were collected during 12, 9 and 6.5 months respectively. Additionally, Mexico City's case study collected CO_2 data as a ventilation metric. The occupants' IAQ and thermal perceptions were also evaluated and compared to the physical IAQ data. Data from PassivHaus and control dwellings were compared to ambient levels, which allowed evaluation of the homes' level of protection against, or exposure to the ambient and internal sources of pollution.

Chapter 8 presents the results of the cross-analysis of IAQ measurements, IAQ occupants' perceptions and thermal perceptions of the case studies. Firstly, this analysis compares the level of protection or exposure to air pollutants, removal rates as well as the frequency and severity of pollution peaks in the homes, and secondly contrasts the physical IAQ measurements to the occupants' perception.

Chapter 9 discusses in detail the context and development of the monitoring protocol, as well the performance specifications and suitability for other IAQ studies. Some thoughts and considerations in relation to the use of low-cost sensors/monitors are presented. The implications of the results of the IAQ monitoring campaign are discussed together with further work. . .

Chapter 10 presents the contribution of this study, a novel IAQ monitoring protocol to collect continuous IAQ data. This contribution is presented alongside the study purpose, research implications, further research and the limitations of this work.

1.8 Chapter conclusions

Modern society faces increasing resource competition and the need to create a sustainable built environment as a result of the human impact on the Earth. The built environment is responsible for a large proportion of global energy consumption, especially in the residential sector. Building practices are evolving to achieve ultra-low-energy consumption and high levels of occupant comfort. Whilst they aim to be economical, resource-efficient and resilient to climate change, their design strategies may impact on the quality of the indoor air. Voluntary low-energy building certifications such as BREEAM, LEED and PassivHaus have different approaches to this matter. While BREEAM and LEED have specific criteria and targets for IAQ, PassivHaus remains open in this regard. The current approach to IAQ and occupational health studies is limited by access and availability of IAQ monitors and their characteristics. Moreover, the traditional approach can be considered intrusive and time consuming. Therefore, existing studies tend to be small and isolated. The use of low-cost monitors may be an acceptable option to conduct such studies, nevertheless, researchers need to balance the needs of the research project, the resolution and the accuracy needed. This research looks at the development of a remote monitoring technique using low-cost IAQ monitors and test it in PassivHaus dwellings in differente locations

A research gap in the methodology to study the indoor environment, with emphasis on air quality, in dwellings was identified. This methodology should identify the IAQ criteria that is possible to monitor using low-cost monitors and develop the methodology to deploy the monitors and collect qualitative and quantitative data. In this work, the suitability of this methodology was explored in PassivHaus and control homes in different urban locations. The following chapter will examine the suitability of low-cost IAQ sensors and monitors for quantifying pollution exposure in residences.

Chapter 2 Alternative methods and instruments for IAQ monitoring

2.1 Summary

As awareness of the impact of indoor air pollutants on health increases, new monitoring technologies are being developed to monitor the quality of indoor air. This chapter discusses the application, suitability and limitations of international standards, such as ISO 16000-1 and ASTM D79297, as well the CIBSE KS17 and EPA standard protocols for characterising IAQ. For IEQ studies, with emphasis on air pollution, the wide range of IAQ factors and the desire to simultaneously monitor different rooms pose clear challenges. The use of low-cost IAQ monitors are explored in this chapter as an alternative method for IAQ data collection. Low-cost IAQ monitors may have the benefit of providing corroboration, increased spatial and temporal resolution and thereby improving the robustness of IAQ and health risk assessments. Qualitative data on occupant's perception of the IEQ is explored through survey methods, such as the BUS and CBE methodologies. These surveys have specific sections for IAQ and thermal comfort.Several low-cost IAQ monitors were identified and compared to each other to understand their strengths and limitations, as well as data retrieving options. Based on the awareness, solutions and understanding of the sensors, the Foobot and Netatmo were selected for this study. Measurements of these monitors were compared to conventional monitors suggesting that they are of sufficient accuracy and reliability but can be improved by additional data quality protocols.

2.2 Background

Over the past few years, our understanding of air pollution has increased and with it, awareness of its environmental and human health impacts. As mentioned in the previous chapter, health problems may arise when some of these pollutants are found indoors. Hence, there is a growing demand for indoor pollution studies as well as monitoring and control systems. Standard protocols for IAQ assesment routines, such as CIBSE KS17 and the EPA procols, provide a contexts on what and how to measure to charactrise the IAQ in office buildings. Nevertheless, they require specialised instruments.

Monitoring technologies have been developed to quantify exposure to air pollutants in outdoor environments, but problems may arise when these methods are adapted for indoor use (Jones, 1999). Recent technologies have made it possible to adjust these methods to more suitable techniques for monitoring the quality of the air, developed mainly for safety purposes and then in turn used for research. However, these analytical instruments often require knowledgeable and skilled operators, are generally very expensive and are designed for specific uses. Also, they suffer from identifiable limitations (Chou, 2000a) for IAQ monitoring where mobility, accessibility and practicality are required. The current approach to IAQ data collection has considerable restrictions; for instance, it makes it complicated and expensive to collect IAQ data simultaneously in different rooms and/or across multiple dwellings.

Other approaches, base the IEQ assessment on occupant surveys. They collect occupant perception of the indoor environment and have specific sections for IAQ and thermal comfort. Perhaps, the most prominent of these are the Centre for the Built Environment (CBE, Zagreus *et al.*, 2004) and Building Use Studies (BUS, Leaman *et al.*, 2010) methodologies.

2.3 Current approach to IAQ data collection

Different international standards are available for monitoring and collecting IEQ and IAQ data. The standards discussed herein are only applicable to home indoor environments or indoor spaces that are not subject to health and safety inspections regarding air pollutants (such as offices, educational and recreational spaces).

2.3.1 IEQ occupant perception measurements

IEQ perception surveys collect qualitative data on the subjective evaluation of the indoor environment. Although there are no universally standardised surveys for residential settings, office questionnaires are often their central development core. The questionnaire for studies of SBS (Raw, 1995), CBE (Zagreus *et al.*, 2004) and BUS (Leaman *et al.*, 2010) methodologies are the most common surveys for these kind of surveys. The BUS survey has developed a specific questionnaire for residential purposes; however, there have not been enough studies to populate and validate the benchmarks database properly (Leaman, 2011).

Some of these methodologies use online tools to deploy surveys and collect responses (Peretti and Schiavon, 2011). These surveys often group the questions in sections related to thermal comfort, space satisfaction, lighting, control of building services, design & needs, noise, IAQ and perceived health, among others. However, there is no need to use the whole survey to examine a specific IEQ parameter, as they can be adapted to investigate particular research questions. Nevertheless, there remain problems around contextualising responses, finding a representative period for surveying and extracting meaningful insights from occupants feedback (Nicol and Wilson, 2011). In domestic settings where the sampling (dwelling's occupants) is small, the potential individual differences and circumstances can impact the results. For these reasons, subjective assessments should be corroborated with physical measurements of environmental parameters. The following sections focus on physical measurements; Chapter 4 discusses the survey design and application.

2.3.2 Indoor environment and air pollution measurements

When conducting IAQ assessments, it is essential to evaluate the needs of the study in order to select the best approach. There is, however, no universal standardised routine for IEQ/IAQ assessment as there are several approaches (Parkinson, Parkinson and Dear, 2019) and lack of guidance for residential buildings (Peretti and Schiavon, 2011). Standard routines, such as the CIBSE KS17 (CIBSE, 2011) and the standardised EPA protocol (EPA, 2003) for characterising IAQ, provide an insight of how and which IAQ parameters to measure during a study. The CIBSE KS17 differentiate between those parameters that should always be measured, others that are additionally recommended and those that may be needed for specific studies, whereas the EPA protocol does not make such differentiation (Table 2.1).

Table 2.1 Factors to be measured for IAQ assessment routines.

	CIBSE KS17			
Factor	Always	Additional	If applicable	EPA
Air temperature (θ_{air})	●			●
Operative temperature (θ_{op})		●		
Radiant temperature (θ_r)		●		
Daily temperature rise		●		
Relative Humidity (ϕ)	●			●
Mean air speed (v)			●	
Air turbulence intensity			●	
tVOC	●			●
Main individual VOC	●			●
Formaldehyde	●			●
Aldehydes			●	
Methane			●	
Nitrogen dioxide			●	
Carbon dioxide	●			●
Carbon monoxide	●		●	●
Ozone			●	
Radon			●	●
Particulate matter 2.5µm		●		●
Particulate matter 10µm		●		●
Fungi and bacteria		●		●
Asbestos			●	

Table 2.2 Summary of instrument specifications from the different standards.

	Standard	Instrument requirement - Range [Accuracy]
Air temperature	ISO 7726:2001	10-40°C [±0.5°C *OR* ±0.2°C]
	ASHRAE 55-2017	10-40°C [±0.2°C]
	EPA	-20-60°C [±0.3°C]
Radiant temperature	ISO 7726:2001	10-40°C [±2°C *OR* ±0.2°C]
	ASHRAE 55-2017	10-40°C [±1°C]
Absolute humidity	ISO 7726:2001	0.15-3.0kPA [0.15kPa] -
Relative Humidity	ASHRAE 55-2017	25-95%RH [±5%RH]
	EPA	2-98%RH [±5%RH]
Air velocity	ISO 7726:2001	0.5-1.0m/s [±(0.5+0.05v_a)m/s]
	ASHRAE 55-2017	0.5-2.0m/s [±0.5m/s]
CO_2	EPA	0-3,000ppm [±200ppm]
CO	EPA	2-100ppm [±2ppm]
$PM_{2.5}$ and PM_{10}	EPA	Sample taken on site and analysed on laboratory
VOCs	EPA	Specific VOC 0-20ng/m^3 [±25%]
Formaldehyde	EPA	5-1,000µg/m^3 [±20%]
Radon	EPA	±25% [±20%]
Fungi and bacteria	EPA	Not established

These routines make mention to regulatory documents that share technical aspects for measurements of physical quantities and often include equipment specifications. The most prominent standards fort thermal comfort are the ISO

7726:2001 (ISO, 2001) and the ASHRAE 55-2017 (ASHRAE, 2017). The WHO publications (WHO, 2000, 2010) provide a comprehensive understanding of indoor air pollutants and their health impacts (see Chapter 3) but remain mostly silent on instrument specifications and sampling procedures. Nonetheless, the Standardised EPA protocol for characterising IAQ in Large Office Buildings (EPA, 2003) fills this gap (Table 2.2).

BS EN ISO 16000-1:2006 determines that indoor air pollutant measurements should follow one of two approaches (ISO, 2006):

i. Sampling carried out on site, and subsequent analysis of the sample is carried out in the laboratory, or

ii. Sampling and analysis are performed on site by direct-reading measuring systems.

Current approaches suggest that sampling methods for outdoor air can be used for indoor monitoring, but it should be observed that the measurement equipment should not have a substantial impact on the use of the room because of the instrument size, sampling rate or noise (ISO, 2006). Specific monitors have been developed for indoor use, laboratory conditions and for health & safety purposes. However, the equipment needs to be selected according to specific considerations (ASTM, 2014):

i. Data quality. Usually, higher data quality comes with higher accuracy, precision and detection limits.

ii. Sampling rate and time. The data may require different samplings, such as continuous, point-in-time or integrated, and as such the kind of monitor and method.

iii. Representativeness. The appropriateness of the measurement parameter (aerosol size range, chemical characterisation).

iv. Mode. Active (requiring a pump or aspirator) or passive (relying on diffusion).

v. Output. The data require different approaches according to the guidelines: continuous, point-in-time or time-weighted average.

vi. Data recording. The way the data will be recorded (electronic signals, laboratory tests/reports, field observation).

vii. Mobility. The portability of the instruments (handheld, portable or stationary).

viii. Power requirements. The system may require batteries or standard alternating current.

ix. Calibration. The way the equipment needs to be tested for accuracy, standard atmospheres, co-located, references, laboratory or factory procedures.

x. Equipment costs. The equipment can be purchased or leased.

xi. Facilities costs. Current, new or outsourcing laboratory and other support.

xii. Personnel. The handling of this instrument and monitoring techniques often requires specialised training, and in some occasions, this needs to be subcontracted.

Of particular interest for IAQ data collection are sampling, spatial variation and the mode of sampling, as explained in the BS EN ISO 16000-1:2006 standard (ISO, 2006). Sampling frequency concerns the time related to human activities and ventilation events (window opening or the use of mechanical systems). Short-term sampling should be considered where substances may cause acute health effects, but long-term sampling may be necessary to detect chronic effects on health. On some occasions, continuous recording may serve to collect data on total exposure. However, the researcher needs to bear in mind that sampling duration and analysis may be determined by a standard or a guideline value that has been established with a time interval (i.e. for $PM_{2.5}$ 25µg/m^3 @ 24h). Usually, due to the cost and characteristics of the instruments, the choice between living and sleeping areas in abodes needs to be made. When associations between activities and pollution need to be established, the living area might be the most appropriate (ISO, 2006). However, it depends on the location of sources associated with certain activities. Long-term sampling is constrained by practical considerations, however, for long-term emission sources, bedrooms may be a good starting point, as people usually spend more time in them (ISO, 2006). Regardless of the monitored room, it is important to determine the state of pollution under normal conditions of occupancy, though this comes with the need to record such occupancy conditions and activities. When it is used for short-term assessments, these are useful for gaining insights into changes in ventilation patterns, the conditions of occupancy and activities, as well as seasonal differences

2.3.2.1 Limitations and characteristics

Advances in technologies have made it possible to adapt different monitoring technologies into highly precise monitors suitable for scrutinising the quality of indoor air. For instance, gas chromatographs and mass spectrometers have been developed mainly for safety purposes and research, but they are complex to use (Kumar *et al.*, 2015). Although conventional analytical instruments can be utilised to measure the concentration of indoor air pollutants accurately, they are impractical or inappropriate for the following reasons:

i. They are large in size, emit light and noise, and they have a slow response time (Chou, 2000a), which may not only compromise their mobility but also interfere with occupants' activities (Kumar *et al.*, 2016) and may lead to occupants turning sensors off.

ii. Advanced technologies have made it possible to improve accuracy and data quality. However, they have also increased the initial cost (often to several thousands of GBP), making them prohibitively expensive (Chong and Kumar, 2003; Mead *et al.*, 2013). Additionally, it is costly to maintain and calibrate the equipment (Chong and Kumar, 2003), and most of the time it requires planning, as the instruments need to be returned to the manufacturer.

iii. Highly skilled persons are required to operate and set up the equipment correctly (Chou, 2000a; De Nazelle *et al.*, 2013).

iv. Data storage of analytical monitors is often very limited (Su *et al.*, 2015). In addition, they cannot be used for extended periods of time, which limits the ability to collect data about activity patterns and occupants' exposure to pollutants.

v. The accuracy of these instruments could be considered excessive for IAQ scrutiny, where the objective is to evaluate whether the pollutant concentration exceeds a threshold value (Kumar *et al.*, 2016).

These limitations of current analytical instruments, together with current market demands for IAQ sensors, have motivated researchers to develop and test more practical and affordable solutions for IAQ monitoring. Ideally, IAQ monitors should be small, so that they can be placed across the building without being noticed and avoiding blocking out light or making any noise so that occupants are not disturbed.

2.4 Low-cost IAQ monitors, an alternative tool for research

Since 1990's the use of low-cost sensors and monitors has been explored, especially those measuring realtive humidity and air temperature (Story, Galipeau and Mileham, 1995; Bakker and Huijsing, 1999). They have been used in large-scale monitoring projects (Fu and Hallberg, 2010; Budde, Busse and Beigl, 2012; Wang *et al.*, 2012) to collect environmental and indoor pollution data (Fu and Hallberg, 2010; Budde, Busse and Beigl, 2012; Wang *et al.*, 2012). The need for instrumentation to support large-scale studies, in addition to the current cost and complexity of instruments, has encouraged the development and employment of low-cost sensors (Northcross *et al.*, 2013) for research.

The use of low-cost sensors in pollution exposure/built environment research has a clear advantage to collect more data from a wider population that otherwise with traditional approaches would be difficult. However, their use may have some inconveniences such as the need for additional data quality protocols (Ciuzas *et al.*, 2015) and the risk of data loss if their connection is lost. Additionally, low-cost monitors may also allow for a easier access to peoples homes, as these monitors do not require specialised training they can be delivered to participants to set them up when a visit from the researcher is not possible/appropriate.

There is a general belief that they are not accurate enough for research, but as their accuracy improves low-cost monitors have been considered for IAQ scrutiny in several studies (Kintner-Meyer, 2002; Zampolli *et al.*, 2004; Steinle *et al.*, 2015; Ali *et al.*, 2016; Allen *et al.*, 2016; Chapman, Bell and Bell, 2016; Patel *et al.*, 2017). Recent investigations into the development of sensing technologies for monitoring pollutant gases have consequently improved their performance, resulting in compact, robust and inexpensive alternatives for environmental monitoring (Lee, 2001).

The need for a 'professional' kit of low-cost sensors for IEQ research was the primary diver for the development of the SAMBA device (Parkinson, Parkinson and Dear, 2019). The SAMBA device was developed based on the requirements of the relevant international standards for thermal comfort, IAQ, lighting and acoustics assessments. Therefore, this low-cost monitor is cable of measuring air temperature, radiant temperature, globe temperature, humidity, air velocity, CO_2, CO, $PM_{2.5}$, formaldehyde, sound pressure levels and illuminance meeting the expectation of the performance required for IEQ assessments (Parkinson, Parkinson and Dear, 2019b). Story, Galipeau and Mileham, (1995) looked into the cost-data quality relation of low-cost temperature and relative humidity sensors, suggesting that low-cost sensors are the best accuracy-cost compromise for research.

2.4.1 Accuracy, strengths and limitations

It is common to find different commercially available low-cost sensors in IAQ monitors. Some studies have demonstrated their accuracy, reliability and possible suitability. However, approaching research with low-cost sensors/monitors needs to be done cautiously. Depending on the complexity of the project, a higher set of skills or a more robust data collection method may be required, not to mention the need to prove their accuracy.

Low-cost IAQ monitor manufacturers may include sensors for air temperature, relative humidity, CO_2, $PM_{2.5}$ and tVOC. Low-cost IAQ monitors use microprocessors to collect sensor outputs, convert the data and then store or transmit these data wirelessly to a remote server. Many of these devices may use the same or very similar sensors. However, manufacturers use a variety of algorithms to convert the sensor output into a concentration value for each pollutant. This calibration protocol can have a marked impact on reported precision, accuracy and bias. For instance, the SHARP GPY1010AU0F, a $PM_{2.5}$ sensor, was tested in laboratory conditions. It was found to be accurate, but the study recommended that an improvement to the algorithm could enhance its performance further (Wang *et al.*, 2015). Another study evaluated the same sensor on a monitoring device using a different algorithm, with the results showing better precision and linear responses (Sousan *et al.*, 2017).

A pair of Speck particulate matter monitors was tested against the HHPC-6 and HHPC-6+ in households environments; a high correlation (R^2>0.98) between each pair of Specks and (R^2>0.92) against the HHPC-6/6+ was observed (Taylor and Nourbakhsh, 2015). Dylos DC1700 and Sharp GP and Sharp DN were tested in an environmental chamber, comparing their results with scientific equipment and aerosol photometers by Sousan (Sousan et al. 2016), who found that the performance of these low-cost monitors had a high correlation (R^2>0.99) to the reference instruments and that they are useful in estimating mass concentrations for aerosols at levels relevant to the workplace. Foobot, Speck and AirBeam were also tested in an environmental chamber by the same group. Sousan et al. (2017) found that Foobot had the highest correlation (R^2=0.99) to the reference instrument and the photometer, but they suggested the use of field calibration for the Foobot.

Wang et al. (2015) evaluated three low-cost PM sensors based on light-scattering, among them the Sharp GP2Y1010AU0F, used by Foobot, and found that the GP2Y1010AU0F had the highest linearity with the SidePak-measured concentration (R^2=0.9831 to 0.9838 in three different tests) as well as high sensitivity to smaller particles. The data collected by Wang suggested that the GP2Y1010AU0F could be enhanced by modifying the flow system and amending the algorithm for particle concentrations. Finally, they indicated that this sensor could be used in a wide array of air quality tracking devices, to obtain a significant amount of data to improve air quality. In fact, the use of low-cost sensors, such as the

GP2Y1010AU0F, could have many applications in scenarios that could benefit from particulate matter measurements such as urban/participatory sensing, as well as personal/lifelong and general public/personal information (Budde, Busse and Beigl, 2012).

Manikonda et al. (2016) tested low-cost particulate matter monitors (Spek, Dylos 1100 Pro, Dylos 1700, AirAssure $PM_{2.5}$ IAQ monitor and Air Sense) in an IAQ chamber against widely accepted instruments used for research, finding that they performed with adequate precision when estimating PM exposure. Manikonda and colleagues also suggested that such monitors, if well-calibrated, could be used to quantify the exposure of PM for health effects studies. Other experiments tested the accuracy of the Speck monitor and concluded that it could be suitable for indoor and outdoor PM monitoring programmes; however, they found significant bias at low concentrations, making them unsuitable for measurements in clean environments (Zikova, Hopke and Ferro, 2017).

These sensors started to be incorporated into automated controls for ventilation systems by incorporating the sensor output to ventilation standards (Herberger *et al.*, 2010), thereby reducing energy consumption even further when compared to time-scheduled ventilation (Ulmer and Herberger, 2012). Technology development in low-cost sensors and consumer monitors produces more robust and reliable sensors. Moreover, recent studies have shown that the application of field calibrations can reduce expanded uncertainty for low-cost monitors and sensors. In fact, the outlook for low-cost commercial sensors is promising, especially for NO and PM_{10}, which are already capable of offering information about air quality (Castell *et al.*, 2017).

Other studies may suggest that low-cost monitors require further testing. For instance, Curto et al. (2018) examined the performance of HAPEX Nano, TZOA-R and EL-USB-CO in dwellings. These monitors were selected in 2016 based on their cost, battery-operability, non-filter-based sensors and measurement ranges. The monitors were tested for 5 days in dwellings in Spain and India; they found that their performance was inadequate when compared to more established instruments. However, they suggest that further generation of air pollution sensors should be tested in real conditions, comparing the results of multiple units of the same device.

There are, in fact, many benefits of using low-cost sensors within the building environment research. The strengths of low-cost sensors are the advanced software processing of air quality data, compact size, continuous measurements, easy customisation, deployment, good gas concentration measurement accuracy, high scalability, indoor and outdoor capabilities, low maintenance, low-cost, low-power consumption, possibility for a client-side JavaScript solution, possible auto-calibration and quick responses (Kularatna and Sudantha, 2008; Postolache, Pereira and Girao, 2009; Hasenfratz *et al.*, 2012; Ferdoush and Li, 2014; Wang *et al.*, 2015). However, they may require an additional set of skills, such as knowledge of the components, assembly of the instrument, understanding the algorithms for data interpretation and programming skills to access the data.

Further problems may arise when the system is not working properly, as technical difficulties can arise quite easily. Low-cost monitors, on the other hand, offer the same advantages, but they are “plug-and-play” solutions with the additional benefit of customer support. Additionally, they are compact in size, have a higher grade of design and can be deployed quickly to support better estimates of parameter variations (Abu Al-Haija, Al-Qadeeb and Al-Lwaimi, 2013; Manikonda *et al.*, 2016). However, before using a low-cost sensor or monitor, it is highly advisable to perform an independent assessment of its accuracy. According to Kumar et al. (2016) several aspects of research could benefit from the use of low-cost monitors:

i. Real-time characterisation of indoor concentrations, offering the possibility to compare values with recommended guidelines, such as the WHO guidelines (WHO, 2000, 2010). Moreover, real-time monitoring provides data on peak concentrations, which are frequently hidden in data averaging, thereby increasing the accuracy of health risk assessments.

ii. Through increased spatial resolution, low-cost monitors allow monitoring for significant spatial and temporal variation of indoor pollutants, thus allowing for better understanding of exposure and risk assessments. The robustness of risk assessments is widely improved by a substantial increase of data on smaller spatial scales, whereas conventional instruments are unable to capture simultaneously short spatial variability. However, increased data coverage may cause an additional need for skilled staff to process and interpret the data into useful information.

iii. Reduced uncertainty, because with an increased number of monitoring locations, the uncertainty of the measurement could be linked to the variation in pollutant concentrations by other devices and therefore be avoided (Ciuzas *et al.*, 2015).

iv. With the identification of emitting sources from indoor activities, increased spatial resolution will make it possible to target specific sources by monitoring associated pollutant emissions. This will be of interest in dwellings with cooking stoves, open gas fires, kerosene heaters, biomass and boilers (Hanoune and Carteret, 2015). Moreover, source distribution analysis of indoor pollution, such as VOCs, might be achievable (Poulhet *et al.*, 2015).

v. With air data supply, low-cost monitoring helps gather data on indoor pollution (formaldehyde, VOCs and $PM_{2.5}$ among others), discomfort and heat stress, which are not frequently monitored. Dynamic characterisation of pollutants that help to improve IAQ management (Yu et al. 2013; Ciuzas et al. 2015) may be possible with low-cost sensing technologies.

vi. Improved IAQ management is seen in the increased spatial and temporal coverage of indoor pollution characterisation provided by low-cost monitors. In contrast to what we see from conventional instruments, it will provide more rational and optimised management of ventilation strategies, and prevent wrong decisions and adverse effects on health (M. J. Kim *et al.*, 2014). This will help improve the health of building occupants.

vii. In relation to health benefits, additional spatial and temporal data about indoor pollution exposition will facilitate understanding of health impacts and allow assessments that are not possible with conventional instruments. This will benefit dwellings and building users in terms of existing problems relating to indoor comfort, IAQ, health or energy and environmental problems, especially for low-income households (Kolokotsa and Santamouris, 2015).

2.4.2 Application of low-cost monitors in the building environment

Building environment researchers and maintenance personnel use a wide selection of methods to measure physical indoor conditions. However, the cost of the instruments limit the monitoring points. Low-cost monitors reduce the cost of instruments exponentially and with a small trade-off in accuracy. For instance, Kintner-Meyer (2002) investigated the application of temperature sensors using wireless sensors for the performance of office and commercial buildings with MVHR systems. Inhabitants' exposure to particulate matter in residential buildings has also been monitored with wireless technologies and low-cost sensors (Patel *et al.*, 2017). Low-cost monitors, such as the Dylos DC1700, have been used to quantify personal exposure to particulate matter (Steinle *et al.*, 2015), and the Netamo has investigated the urban heat island effect (Chapman, Bell and Bell, 2016).

Ali et al. (2016) used low-cost sensors to develop the Open Source Building Science Sensors (OSBSS) project, in which they measured air and surface temperatures, relative air humidity, human occupancy, light intensity and CO_2 concentrations, and they also employed an additional data logger to adapt other sensors as required. Furthermore, the authors tested the OSBSS in an educational building in which they had also installed sensors widely used for industry and academic research, demonstrating excellent performance for these low-cost sensors at substantially lower costs. It is usual to find wireless sensor network technologies with open source platforms for mounting low-cost sensors, which allow for measuring the indoor and outdoor conditions of buildings. Sherin & Li (2014) suggest that the use of wireless sensor networks and open source platforms could be extremely useful in monitoring IAQ in buildings, in order to gain a better understanding of the status of air quality, as well as the long-term impact of poor air quality on public health.

Other studies focus on industrial and consumer applications. Zampolli et al. (2004) used a MOx sensor to measure CO, NO_2, VOCs and relative humidity, concluding that the sensors did not suffer from significant degradation, CO and NO_2 had been estimated precisely and that it could be suitable for integration into MVHR systems, as CO and NO_2 concentrations were measured in lower concentrations than the threshold. As the accuracy of low-cost sensors has increased, IAQ consumer monitors have started to be developed and used to obtain information about the quality of air, the results of which have been published for peer review articles.

Semple used low-cost (Dylos DC1700) and scientific (Sidepak AM510) instruments to measure the indoor exposition of second-hand smoke in 34 homes, finding high agreement (R^2=0.86) between both instruments and thereby suggesting the suitability of the Dylos DC1700 for further research projects (Semple *et al.*, 2013). The Sidepak AM510 is a widely accepted instrument for fine dust measurements, but it is costly (>£2,500), noisy and requires some degree of training. The Dylos DC1700, on the other hand, is quieter, much simpler and less expensive (£300). An experiment carried out in the US used Netatmo weather stations to monitor temperature, humidity, CO_2 and sound levels every 5 minutes in different office environments. Netatmo monitors were calibrated and validated using a calibrated TSI Q-Trak 7575 before the experiment and tested at the end with calibration gases to determine if the sensors had drifted during the research. Duplicate CO_2 measures were collected using a TSI Q-Trak 7575 and two K-33s (Allen *et al.*, 2016).

2.4.3 Current low-cost IAQ monitors

A web-based, by the author, search for low-cost monitors available in the US and European markets was conducted between January and February 2016. This research was carried out on the Google database, using the following keywords: "*IAQ monitor home*", "*IAQ monitor reviews*" and "*the best IAQ monitors*". Twenty data entries referring to different devices were found: Air Mentor Pro 8096-AP (nine times), Awair AW6404 (twelve times), Dylos DC1100 Pro (eight times), Foobot FBT0002100 (fifteen times), Netatmo NWS01-EU (ten times), Speck 2.0 SPK18TH (eight times), Withings (three times) and Cube (three times).

Most of the monitors in the market only monitor CO_2, air temperature and relative humidity. While these are key factors in terms of ventilation, monitors that would be suitable for IAQ measurements were required for this research. The Air Mentor Pro 8096-AP, Awair AW6404, Dylos DC1100 Pro, Foobot FBT0002100, Speck 2.0 SPK18TH (available in the US only) and Netatmo NWS01-EU & NIM01-WW are silent and simpler monitors that do not require advanced knowledge for installation. The specifications of the indoor environment parameters measurement are shown in Table 2.3.

Table 2.3 Low-cost IAQ monitors (1). Technical information on the environmental parameters. Ranges: [Minimum-Maximum] Error margin.

Monitor	Indoor Environment parameters and ranges					
	Air temp. (θ_a)	Relative Humidity	$PM_{0.5}$	$PM_{2.5}$	tVOC	CO_2
Air Mentor Pro 8096-AP	[-20-80°C] ±0.1°C	[0-100%RH] ±1.0%RH		[0-300μg/m³] ±1μg/m³	[125-3500ppb] ±1.0ppb	[400-2,000ppm] ±1.0ppm
Awair AW6404	[-40-125°C] ±0.3°C	[0-95%RH] ±3.0%RH		[0-500μg/m³] (not specified)	Not specified	[0-4,000ppm] ±75ppm
Dylos DC1100 Pro			Capable, however not specified.			
Foobot FBT0002100	[-40-125°C] ±0.4°C	[0-100%RH] ±4.0%RH		[0-1,300μg/m³] ±4μg/m³ or ±20%	[125-1000ppb] ±1.0ppb or 10%	*[400-6000ppm] ±1.0ppm or 10%
Netatmo (Main) NWS01-EU	[-0-50°C] ±0.3°C	[0-100%RH] ±3.0%RH				[0-5,000ppm] ±50ppm or 5%
Netatmo (Additional) NIM01-WW	[-0-50°C] ±0.3°C	[0-100%RH] ±3.0%RH				[0-5,000ppm] ±50ppm or 5%
Speck 2.0 SPK18TH	Not specified	Not specified	[0-640μg/m³] (not specified)			
* Foobot lacks of CO_2 sensor, but displays CO_2 equivalents from tVOC.						

Monitor connectivity and remote access was a key for this work. The Dylos DC1100 Pro, for instance, has an internal memory that allows 30 days of data storage, but these data need to be manually downloaded by connecting the device to a PC throughout via a cable and its software. The Air Mentor Pro 8096-AP possess an internal memory of three days, and a smart device (tablet or phone) should be paired with the monitor; otherwise, the data will be lost as new measurements overwrite the old data. Moreover, data from the Air Mentor Pro 8096-AP cannot be downloaded free, as the use of a web dashboard is a service that the developer offers at an additional cost. The Speck 2.0 SPK18TH model has a two-year internal storage facility at one sample per minute. It also possesses cloud storage and possible Wi-Fi connectivity, which needs to be done manually with a USB cable, but once it is completed, it allows for the downloading of information through a specksensor.com account.

Awair AW6040 has Wi-Fi connectivity for cloud storage. However, it requires a subscription to access the web dashboard or API software to download the data. Similarly, the Foobot FBT0002100 has Wi-Fi and cloud storage, and data can be accessed and downloaded from the developer's website with a monthly subscription, or free with an API software. Finally, once the set-up process for the Netatmo NWS01-EU's outdoor and additional modules is complete, it is connected to the internet via Wi-Fi for cloud storage, which the user can access with a my.netatmo.com account and download information free of charge. Table 2.4 summarises data storage and connectivity, but additionally, it shows the size, mass and cost of each of the monitors.

Table 2.4 Low-cost IAQ monitors (2). Data storage, connectivity, dimensions, mass and cost specifications.

	Data storage and connectivity				Size and mass		Cost
Monitor	**Storage**	**Bluetooth**	**Wi-Fi**	**Remote access**	**Dimensions (mm)**	**Weight (g)**	**Price (US dollars)**
Air Mentor Pro 8096-AP	Yes	Yes	No	**Only Bluetooth	106 (H), 115 (W), 44.5 (L)	498.95	$199.99
Awair AW6040	Yes	Yes	Yes	****Cloud	90 (H), 160 (W), 50 (L)	453.59	$199.00
Dylos DC1100 Pro	Up to 30 days	No	No	No	177.8 (H), 114.3 (W), 76.2 (L)	1,133.98	$425.00
Foobot FBT0002100	Yes	No	Yes	***Cloud	172 (H), 71 (D)	475.00	$199.00
Netatmo (Main) NWS01-EU	Yes	Yes	Yes	***Cloud	155 (H), 45 (D)	372.00	$179.00
Netatmo (Additional) NIM01-WW	Yes	Yes	No	***Cloud	105 (H), 45 (D)	299.00	$79.00
Speck 2.0 SPK18TH	Yes	No	Yes	*****Cloud	89 (H), 114 (W), 94 (L)	164.40	$199.00
**Need for an additional phone/tablet device paired via Bluetooth every three days or fewer, so data can be stored on the Cloud.							
***Remote access as long as the instrument is connected to the internet through Wi-Fi. This feature can be free, with a monthly fee or require API software to download the information.							
****Requires API software development to download information.							
*****Requires set-up through free software and a USB cable, allowing for automatically downloading information.							

The user interfaces and aesthetics of the monitors are not essential. Whereas monitor aesthetics is not something that can be easily rated, users are more likely to add to their environment something that has some degree of design. The phone user-interface has a simple design that allows data to be interpreted easily (Table 2.5). The monitors' makers have different ways of comparing measured levels with "safe" levels. These levels are usually different from one to another and use a different global pollution index (Kang and Hwang, 2016) as there is no current universally accepted standards to assess IAQ. These different IAQ indexes vary on criteria, measured pollutants and their magnitude to the index making even more difficult their understanding and direct comparisons from one to another.

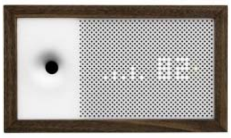
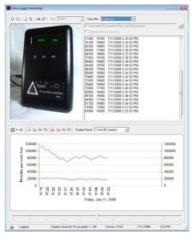
The visualisation of the data in smartphones/tablets allows users to engage more with the indoor environment, especially for health care. Dashboards usually allow users to visualise information through graphs detailing historical levels that can easily be confronted to the threshold guidelines, create historical reports and download/export data into csv files. This may be especially useful to monitor the effects of behaviour changes.

2.4.4 Selection of a suitable IAQ monitor for this study

Precise criteria were considered to determine the suitability of a low-cost IAQ monitor for this study. Awareness (sensors, Table 2.6, and calibration), solutions (data retrieval and accessibility) and understanding (data transparency, good software), availability, data, design, maintenance and health & safety characteristics were taken into account, but one of the most important considerations was remote data accessibility. The Netatmo NWS01-EU and Foobot FBT0002100 sensors were selected for this study, to meet the following criteria based on Chou (2000a) and personal experiences:

- available in the UK and the US,
- capable of being installed in residential areas,
- connectivity & storage,
- dustproof and to an extent water-resistant,
- easy and minimal maintenance,
- easy to operate (no skilled person required),
- flexibility in data download,

Table 2.5 Low-cost IAQ monitors (3). Aesthetics and user interface monitor design.

Monitor	Aesthetics/user-interface design (images were taken from Google image search using the name of the device)		
	Monitor picture	App design	Dashboard design
Air Mentor Pro 8096-AP			
Awair AW6040			
Dylos DC1100 Pro		---	
Foobot FBT0002100			
Netatmo NWS01-EU			
Speck 2.0 SPK18TH			

- good responsiveness and quality of technical support,
- has multisensory systems,
- good longevity,
- low cost (<£200.00, including equipment and software if necessary),
- operationally stable,
- remote access to data and
- rugged and corrosion-resistant.

Table 2.6 Comparison of the instrument specifications between the requirements from the standards, Foobot and Netatmo.

	Standards - Range [Accuracy]	Foobot - Range [Accuracy]	Netatmo (main and additional) - Range [Accuracy]
Air temperature	10-40°C [±0.5°C *OR* ±0.2°C]	-40-125°C [±0.4°C]	0-50ºC [±0.3ºC]
Radiant temperature	10-40°C [±2°C *OR* ±0.2°C]		
Absolute humidity	0.15-3.0kPA [0.15kPa] -		
Relative Humidity	25-95%RH [±5%RH]	0-100%RH [±4.0%RH]	0-100%RH [±3.0%RH]
Air velocity	0.5-2.0m/s [±0.5m/s]		
CO_2	0-3,000ppm [±200ppm]	*400-6000ppm [1.0ppm or 10%]	0-5,000ppm [±50ppm or 5%]
CO	2-100ppm [±2ppm]		
$PM_{2.5}$ and PM_{10}	Sample taken on site and analysed on laboratory	0-1,300µg/m³ [±4µg/m³ or ±20%]	
VOCs	Specific VOC 0-20ng/m³ [±25%] then added for tVOC	125-1000ppb [±1.0ppb or 10%]	
Formaldehyde	5-1,000µg/m³ [±20%]		
Radon	±25% [±20%]		
Fungi and bacteria	Not established		
* Foobot lacks of CO_2 sensor, but displays CO_2 equivalents from tVOC.			

Netatmo NWS01-EU was previously tested elsewhere (Meier *et al.*, 2017; Petersen *et al.*, 2018). Netatmo was found to be accurate, with small drifts in temperature (Meier *et al.*, 2017) and CO_2 (Macnaughton *et al.*, 2016), however, CO_2 was positively dependent to the air temperature on which Netatmo's CO_2 sensor was calibrated (Petersen *et al.*, 2018). At the start of this study (January 2016) tests for Foobot were not available; the section below describes the tests performed to ensure its accuracy.

The Foobot was developed by Airboxlab (Luxemburg) and measures: $PM_{2.5}$, tVOC, CO_2 (equivalent from tVOC, ($CO_{2\text{-equivalent}}$), temperature and relative humidity. The device mechanism is simple: a microprocessor collects electrical outputs from the sensors and converts them into data, which are then transmitted wirelessly to a remote server, where an algorithm is applied to derive the measured concentrations. Data may be lost if the wireless signal is interrupted, as the Foobot does not have internal data storage. The manufacturer hosts a website where the uploaded data can be visualised and downloaded (https://partner.foobot.io/), albeit a monthly subscription was required for this service until October 2018. Before 2018, accessing data for free was possible. Nevertheless, the user needed to develop their software with an application programming interface (API) provided by AirBoxLab, which allows up to 250 daily data requests to the server. AirBoxLab has developed a calibration algorithm for its sensors, details of which are not available to the public (personal communication). Figure 2.1 shows the Foobot and sensors inside the device.

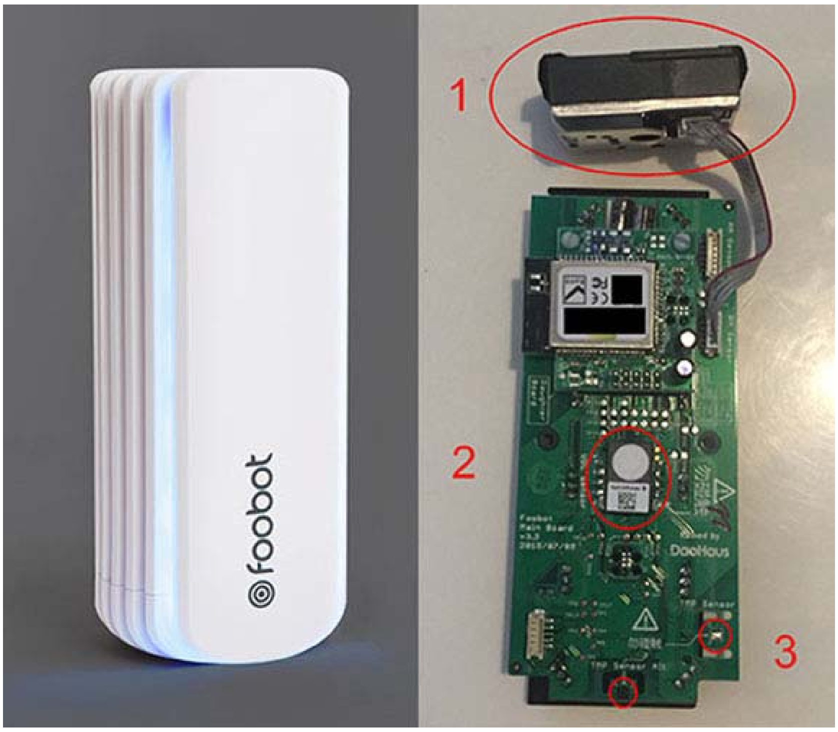


Figure 2.1 Foobot FBT0002100 monitor (left) and Foobot Main Board 3.3 (right) showing the SHARP GP2Y1010AU0F (1), AMS iAQ-CORE-C (2) and SHT20 (3). Left picture from https://foobot.io (last accessed 22/11/2017).

Foobot uses the SHARP GP2Y1010AU0F sensor to measure $PM_{2.5}$. It relies on natural convection to move air passively to the sensor, measuring particles with 0.3µm to 2.5µm diameter (see SENSIRION, (2014) for more information). The Foobot tVOC, sensor AMS iAQ-CORE-C, measures a wide range of VOCs (acetone, alcohols, aldehydes, alkanes, benzene, decane, ethanol, eucalyptol, formaldehyde, hydrocarbons, isoprene, ketones, limonene, phenol, spirits, styrene, toluene, xylene, among others) to predict tVOC. It lacks of CO_2 sensor; however, an algorithm converts tVOC concentrations into a $CO_{2\text{-equivalent}}$ (see AMS, (2015) for more information. The AMS iAQ-CORE-C does not report absolute values for individual VOCs but indicates relative changes in tVOC (Brown, no date). Foobot's air temperature and relative humidity sensor is the SENSIRION SHT20 (see SENSIRION (2014) for more information)..

2.5 Is the Foobot accurate enough?

2.5.1 Test method

The following study was undertaken by the author from the 28th of August 2017 to 1st of September 2017 following the guidelines set in the ASTM D72974-14 Standard Practice for Evaluating Residential Indoor Air Quality (ASTM, 2014) to test the accuracy and suitability of the Foobot for monitoring real-life residential settings. The monitors were located at an approximate height of 0.90 m over the top of a drawer. Care was taken to ensure they were placed away from direct pollutant sources, heat sources and ventilation ducts or openings. Given the nature of the measurements and the desire to ensure that 'typical' conditions were achieved, it was not possible to position the monitors in the centre of the room (see Figure 2.2).

The accuracy of Foobot FBT0002100 air temperature, relative humidity, PM, $CO_{2\text{-equivalent}}$ and tVOC measurements were tested by comparing the measurements of five Foobot to those from GrayWolf TG-502 TVOC, IQ-410 and PC-3016A (Table 2.7), which meet the requirements from the standards and were calibrated by the manufacturer a month before this test. The monitors were set to measure simultaneously at five-minute intervals for 81 hours and 25 minutes (from 28/08/2017 23:50 to 01/09/2017 11:25) in an occupied bedroom (floor area $10.5m^2$) of flat in Glasgow, UK. Occupancy levels and activities were recorded by the occupants in a diary, which was used to contextualise the data and ensure that typical conditions were represented.

Figure 2.2 Test layout of Foobot vs GrayWolf.

2.5.1.1 Statistical analysis

Data from each monitor were exported into Microsoft Excel, for initial inspection, and to SPSS, for statistical analysis. The five-minute data pairs (n=4,895 for each measure) across the study were assigned to either a calibration dataset (n=2,448 for each measure) or a validation dataset (n=2,449 for each measure). The Kolmogorov-Smirnov test rejected the hypothesis of normal distribution. Data were measured at intervals and were found to have a monotonic relationship. Therefore, Spearman's rank-order correlation (r_s) was applied to determine the correlation between the variables from each of the paired devices. This indicates the association from one device to another. The closer r_s is to unity, the more positive and direct the association between devices. Correlations from 0.3 to 0.5 are considered as having a low positive (weak) correlation, 0.5 to 0.7 as a moderate (acceptable) positive correlation, from 0.7 to 0.9 as a high positive (strong) correlation and 0.9 to 1.00 as a very high positive association (very strong) (Mukaka, 2012).

A Spearman's rank-order correlation also determined the uniformity of data from different Foobot devices. Additionally, to compare differences between each of the measurements among the five different Foobot monitors, the Kruskal-Wallis test, which is nonparametric, was applied to determine if there were statistically significant differences between them.

Table 2.7 Manufacturer specifications and characteristics for the GrayWolf instruments.

		GrayWolf (VOC)	GrayWolf ($PM_{2.5}$)	GrayWolf (CO_2)
Model		TG-502 TVOC	PC-3016A	IQ-410
Cost (£)		3,200.00*	2,900.00*	3,200.00*
Air quality parameters	(θ_{air}) °C	[-10°C, 70°C], ±0.3°C		[-10°C, 70°C], ±0.3°C
	%RH	[0-100%RH], ±2%RH, <80%RH, ±3%RH, >80%RH		[0-100%RH], ±2%RH, <80%RH, ±3%RH, >80%RH
	CO_2			[0-10,000ppm], ±50ppm, ±3%rdg
	tVOC	[0.1-10,000.00ppb] ±1.6-2.0ppb**		
	$PM_{2.5}$		[0-4,000,000 particles/ft³] ±5%	
	$PM_{0.5}$		100% for particles >0.45µm	
Remote storage		No	No	No
Internal storage		Yes	Yes, when connected to a tablet	Yes, when connected to a tablet
Wi-Fi connectivity		No	No	No
Remote data retrieving		No	No	No
Recording frequency		1 min	1 min	1 min
Dimensions (mm)		300 (H), 50 (D)	63.5 (H), 127 (W), 222.3 (L)	300 (H), 50 (D)
Weight (gr)		700	1,000	700

*Require additional software (~£1,200.00) and a tablet (>£500.00)
** Isobutylene equivalent.

A regression analysis was performed to improve the accuracy of the Foobot data relative to the GrayWolf data. Field calibration equations were then produced from the calibration dataset, using the results from the GrayWolf instruments as dependent variables and the Foobot as independent variables, following which they were tested on the validation dataset. An analysis in SPSS of the linear, quadratic and cubic models was performed individually for each parameter, to find the most accurate equation. A Bland-Altman analysis was then performed on the validation dataset to examine the correlation and agreement between data generated by the calibration equation and data obtained by the GrayWolf instruments. The Bland-Altman method calculates the mean difference between two methods of measurement (the 'bias') and 95% limits of agreement from the mean difference (1.96 SD) (Myles and Cui, 2007). From this process, a Bland-Altman plot (or difference plot) can be generated as a graphical way of comparing two measurements of the same variable.

Measurement of the extent to which data collectors (raters) assign the same score to the same variable is called 'interrater reliability'. The interrater reliability of the agreement between the data generated by the calibration equation and data from the GrayWolf instruments was tested using the Cohen's kappa test to account for the possibility of agreement happening by chance; essentially, the closer that kappa is to 1.00, the better the agreement.

2.5.2 Results

2.5.2.1 Inter-sensor analysis of Foobot and analytical IAQ monitors

Measurements from the five Foobot FBT0002100 monitors were compared to those from the GrayWolf IQ-410 for CO_2, TG-502 TVOC for air temperature, relative humidity and tVOC and PC-3016A for $PM_{2.5}$. The results showed that the air temperature measurements were very strongly related (r_s=0.833 to 0.926, p<0.001). Despite this, analysis of the temperature data showed that the Foobot underestimated temperature (mean (M)=2.59°C, 95% C.I. from 2.40°C to 2.73 °C;Figure 2.3). This offset, however, may depend on the configuration of the probes, as air temperature readings are influenced by internal heating of the NDIR sensor used for CO_2 (IQ-410) and the PID sensor used for TVOC (TG-502, (GrayWolf, 2018)). Still air conditions exacerbate in still air conditions and it is approximately +2°C (@ θ_{air}=20°C in still air). Knowledge of inter-sensor variability is important to the reliability of sensors in practice. Analysis of the temperature data from the five Foobot FBT0002100 monitors identified very significant uniformity (r_s=0.833 to 0.926, p<.001) and low variability (M=0.16°C, from 0.16°C to 0.33°C) between the different temperature sensors.

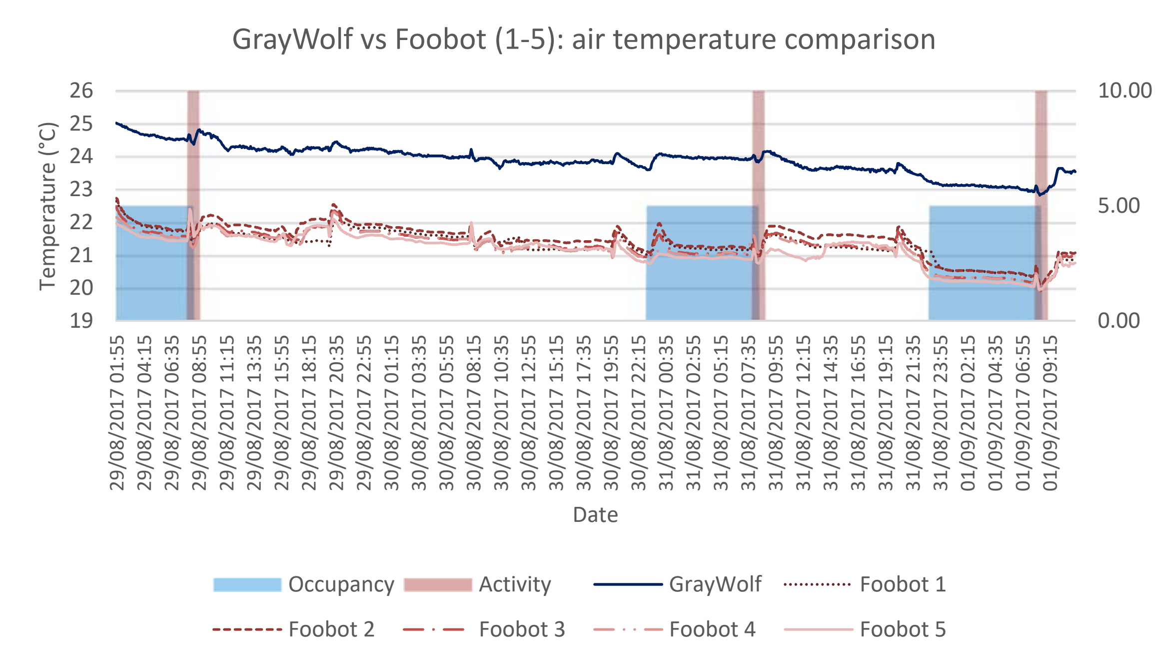


Figure 2.3 Air temperature levels from 29/08/2017 to 01/09/2017 for the Foobot and GrayWolf instruments. Activity describes the morning routine: showering, grooming and changing.

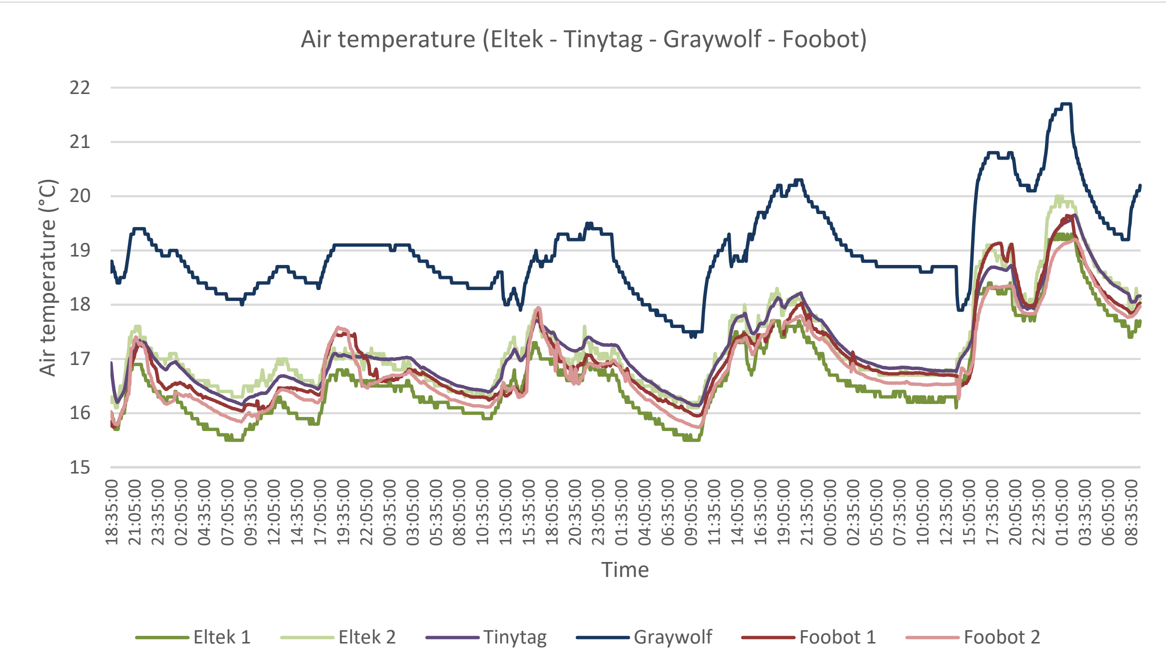


Figure 2.4 Air temperature comparison between Eltek , Tinitag, GrayWolf and Foobot.

Air temperature from the GrayWolf instruments was affected by internal overheating from other sensors, the offset is similar to those suggested by GrayWolf Technical Notes (GrayWolf, 2018). To corroborate offset, two Foobots and GrayWolf TG-503 air temperature were compared using other set of instruments (two Eltek DG47 (θ_{air} -5-40°C [±0.4°C]) and Tinytag Plus 2 TPG-4500 (θ_{air} -25-85°C [±0.1°C]), Figure 2.4). These comparisons found that air temperature from the Eltek to Foobot (-0.24°C, BCa 95% CI [-0.25°C, -0.23°C],

r_S=0.967 and 0.969, p<0.001) and Tinitag (0.39°C, BCa 95% CI [0.36°C, 0.41°C], r_S=0.969 and 0.974, p<0.001) were significantly related to each other with a very low offset.

A very strong relationship (r_S=0.935 to 0.948, p<0.001) was observed for relative humidity measurements from the five Fooboot FBT0002100s and the Graywolf monitors, but very low variability was observed between the Foobot and Graywolf monitors, given that the Foobot FBT0002100 underestimated relative humidity levels by 0.01 %RH (from -0.78 %RH to 1.08 %RH, Figure 2.5). Inter-sensor analysis between the five Foobot monitors showed very strong uniformity (r_S=0.985 to 0.991, p<0.001) and low variability (M=0.52 %RH, from -1.86 %RH to 0.75 %RH) for the relative humidity sensor.

Analysis of the tVOC measurements from the five Foboot monitors and the GrayWolf TG-502 TVOC showed a significant relationship (r_S=0.827 to 0.869, p<0.001). Very low variability between the five Foobot monitors was observed, but Foobot underestimated tVOC levels by 22.12 μg/m^3 (from 12.79 μg/m^{3}to 28.20 μg/m^3, Table 2.8, Figure 2.6). Inter-sensor analysis between the five Foobot monitors showed very strong uniformity (r_S=0.892 to 0.974, p<0.001) and low variability (M=-7.05 ppb, from -15.43 ppb to -1.67 ppb) between the different tVOC sensors.

Table 2.8 Summary statistics for the tVOC calibration dataset.

Instrument	tVOC mean (μg/m^3)	tVOC min (μg/m^3)	tVOC max (μg/m^3)	% time >300 μg/m^3
GrayWolf TG-502 TVOC	176.4	143	549	0.82%
Foobot FBT0002100 A	158.7	125	369	0.41%
Foobot FBT0002100 B	161.3	125	357	0.41%
Foobot FBT0002100 C	164	125	350	0.61%
Foobot FBT0002100 D	165.7	125	376	0.61%
Foobot FBT0002100 E	174.1	125	413	2.25%

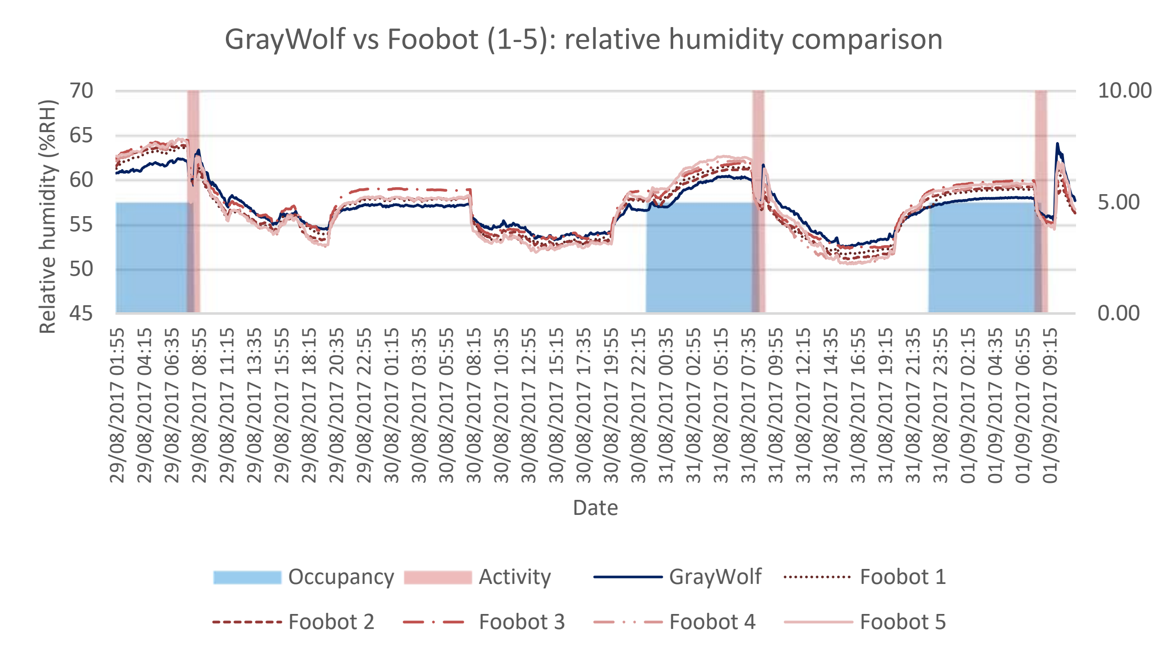


Figure 2.5 Relative humidity levels from 29/08/2017 to 01/09/2017 for the Foobot and GrayWolf instruments. Activity describes the morning routine: showering, grooming and changing.

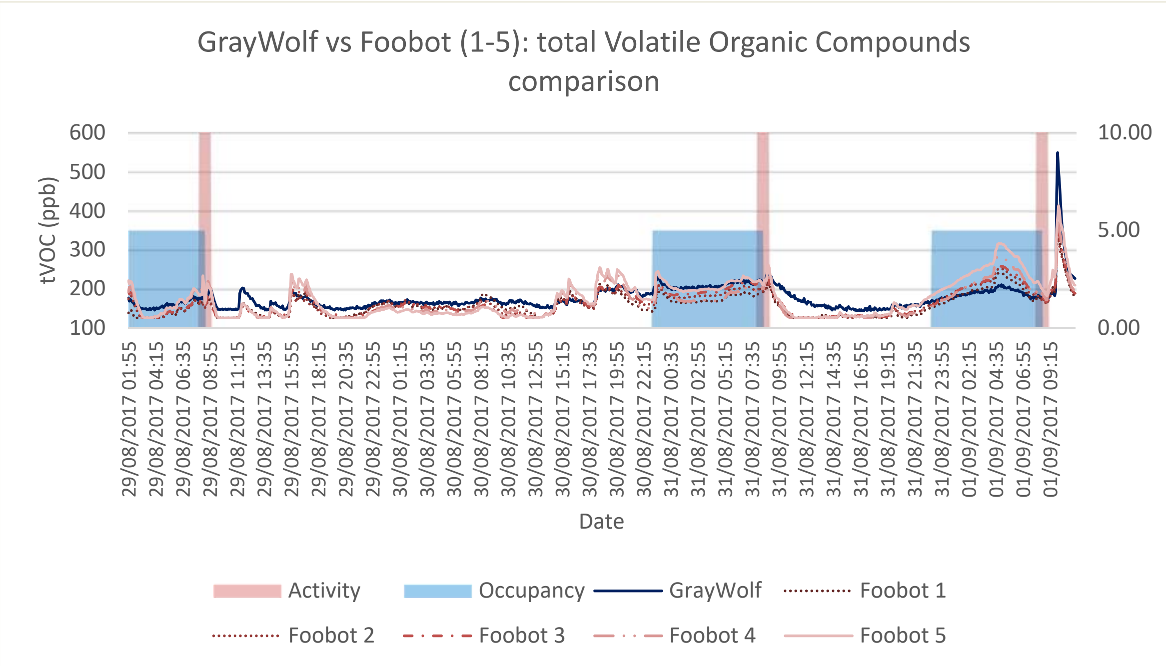


Figure 2.6 Total volatile organic compounds levels from 29/08/2017 to 01/09/2017 for the Foobot and GrayWolf instruments. Activity describes the morning routine: showering, grooming and changing.

Analysis of $CO_{2\text{-equivalent}}$ data from the Foobot monitors and the GrayWolf IQ-410 showed that Foobot CO_2 levels differed. A weak but significant correlation (r_s=0.397 to 0.525, p<.001) was observed, and Foobot monitors underestimated CO_2 concentrations (M=147.08 ppm, from 99.08 ppm to 155.00 ppm, Figure 2.7), a factor which could lead to problems in assessing ventilation based on CO_2 levels. The percentage of time CO_2 >1,000 ppm was considerably different between the

GrayWolf IQ-410 and the five Foobot monitors (Table 2.9). Although the five Foobot monitors showed very similar results between them (r_S=0.892 to 0.973, p<.001).

Table 2.9 Summary statistics for the CO_2 calibration dataset.

Instrument	CO_2 mean (ppm)	CO_2 min (ppm)	CO_2 max (ppm)	% time >1,000ppm
GrayWolf IQ-410 (real CO_2)	727.2	451	1379	20.53%
Foobot FBT0002100 A ($CO_{2\text{-equivalent}}$)	572.2	450	1337	0.72%
Foobot FBT0002100 B ($CO_{2\text{-equivalent}}$)	581.6	450	1294	0.61%
Foobot FBT0002100 C ($CO_{2\text{-equivalent}}$)	591.5	450	1269	0.82%
Foobot FBT0002100 D ($CO_{2\text{-equivalent}}$)	597.7	450	1361	1.84%
Foobot FBT0002100 E ($CO_{2\text{-equivalent}}$)	628.1	450	1496	3.78%

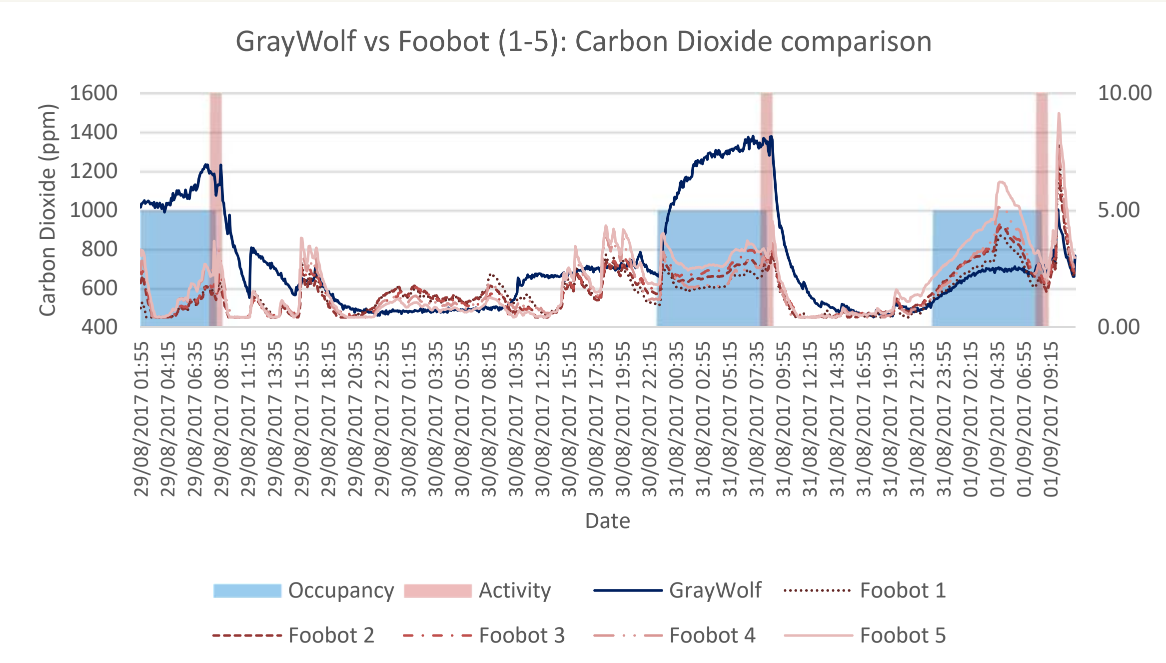


Figure 2.7 Carbon dioxide levels from 29/08/2017 to 01/09/2017 for the Foobot and GrayWolf instruments. Activity describes the morning routine: showering, grooming and changing.

$PM_{2.5}$ measurements from the five Foobot monitors and the GrayWolf PC-3016A were significantly related (r_S=0.787 to 0.866, p<.001) to each other. Despite this, analysis of the data showed that the Foobot overestimated $PM_{2.5}$ concentrations (M=-1.4826 μg/m^3, from -1.4783μg/m^3 to -1.4870μg/m^3, Table 2.10, Figure 2.8). A higher degree of agreement between the types of devices is addressed in the following section. Inter-sensor analysis of the five Foobot monitors showed that there was acceptable uniformity (r_S=0.576-0.843 p<.001) and low variance (M=-1.4826μg/m^3 from -0.0068μg/m^3 to 0.0084μg/m^3) between the different $PM_{2.5}$ sensors.

Table 2.10 Summary statistics for the PM2.5 calibration dataset.

Instrument	PM2.5 mean (µg/m3)	PM2.5 min (µg/m3)	PM2.5 max (µg/m3)	% time >25µg/m3
GrayWolf PC-3016A	6.8438	3.54	35.78	0.82%
Foobot FBT0002100 A	8.3273	3.96	35.7	1.43%
Foobot FBT0002100 B	8.3288	1	44.24	1.43%
Foobot FBT0002100 C	8.3243	3.18	39.06	1.43%
Foobot FBT0002100 D	8.3311	3.48	36.14	1.23%
Foobot FBT0002100 E	8.3224	2.99	42.55	1.33%

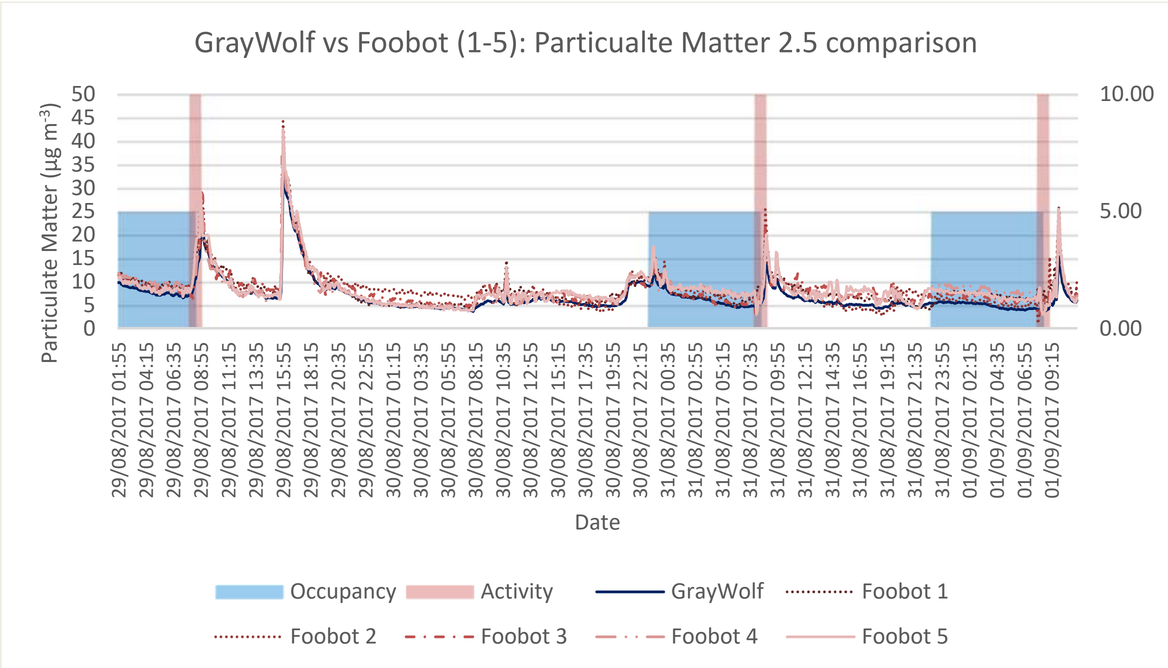


Figure 2.8 Particulate Matter 2.5 levels from 29/08/2017 to 01/09/2017 for the Foobot and GrayWolf instruments. Activity describes the morning routine: showering, grooming and changing.

2.5.2.2 Relationship between the GrayWolf and Foobot monitors

2.5.2.2.1 Total volatile organic compounds (tVOC)

The results from the tVOC measurements showed that Foobot FBT0002100 underestimated tVOC concentrations. Figure 2.9 shows the relationship between the GrayWolf TG-502 TVOC and Foobot FBT0002100 tVOC concentrations from the calibration dataset used to generate a regression equation. The best fit produces an R^2 value of 0.697 and the equation generated by regression is:

$$\boldsymbol{tVOCGrayWolf} = -1.56e^{2} + 4.5(\boldsymbol{tVOCFoobot}) - 0.02(\boldsymbol{tVOCFoobot^{2}}) + 3.57e^{-5}(\boldsymbol{tVOCFoobot^{3}}) \quad \text{(Equation 2.1)}$$

where tVOC is the concentration in ppb. Figure 2.10 shows the Bland-Altman plot comparing the GrayWolf tVOC measurements with those estimated from Equation 2.1 in relation to the five Foobot validation datasets. It shows the mean between the GrayWolf and the Foobot tVOC generated measurements (-0.0148ppb with limits of agreement of -36.7935 to 36.7639 ppb at a 95% confidence interval). A total of 80 (3.26%) data points were outside of the limit of agreement (51 above the upper limit and 29 below the lower limit). This range is significantly lower than the 300 ppb (the World Health Organization (WHO) threshold for tVOC (Koistinen *et al.*, 2008). The plot shows that Foobot FBT0002100 underestimated at high concentrations (>300ppb), and a comparison between tVOC concentrations from the GrayWolf TG-503 TVOC- and the Foobot-generated tVOC showed IAQ information that with very good agreement. The number of data points on which tVOC concentration values exceeded 300ppb is within ±0.71%, as observed in Table 2.11. Agreement of the data points taken from the calibration and validation datasets was also corroborated, and both showed very good agreement on concentrations above 300 ppb: on the calibration dataset, a kappa of 0.75, and on the validation dataset, a kappa of 0.85.

Table 2.11 Summary statistics for the generated tVOC from the validation dataset.

Instrument	tVOC mean (ppb)	tVOC min (ppb)	tVOC max (ppb)	% time >300ppb
GrayWolf TG-502 TVOC	176.4	143	549	0.82%
Generated Foobot A	172.97	149.9	456.59	0.31%
Generated Foobot B	174.09	149.9	416.58	0.41%
Generated Foobot C	175.6	149.9	394.51	0.41%
Generated Foobot D	176.88	149.9	483.35	0.61%
Generated Foobot E	182.53	149.9	658.15	1.53%

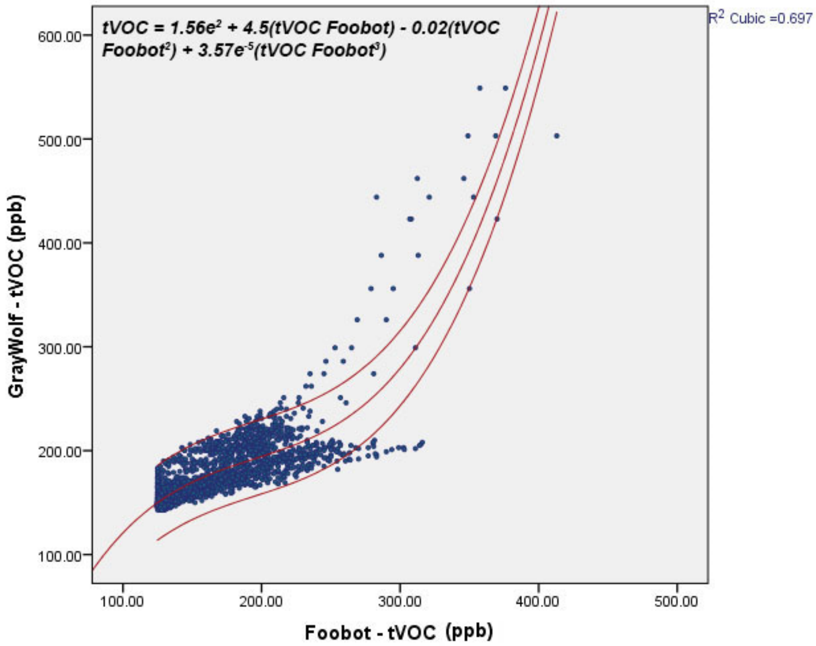


Figure 2.9 Scatter plot of the five-minutes tVOC concentrations measured using the Foobot FBT0002100 and the GrayWolf TG-502 TVOC from the calibration dataset.

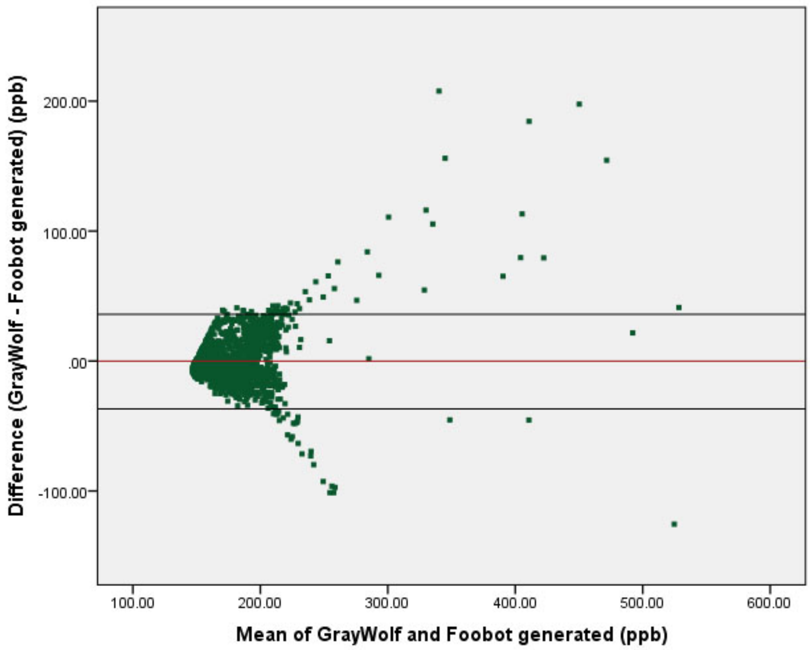


Figure 2.10 Bland-Altman plot of agreement between the GrayWolf TG-502 TVOC and the Foobot-generated tVOC concentrations.

2.5.2.2.2 Carbon Dioxide (CO_2)

Results from the CO_2 measurements showed a weak correlation, as they underestimated CO_2 concentrations. Figure 2.11 shows the relationship between the GrayWolfIQ-410 and the Foobot FBT0002100 CO_2 concentrations from the calibration dataset used to generate the regression equation. The best fit produces an R^2 value of 0.180 and the equation generated by regression is:

$$CO_2GrayWolf = -1.39e^3 + 7.08(CO_2Foobot) - 7.15e^{-3}(CO_2Foobot^2) + 2.29e^{-6}(CO_2Foobot^3)$$ **(Equation 2.2)**

where CO_2 is the concentration in ppb. Figure 2.12 shows the Bland-Altman plot comparing GrayWolf CO_2 measurements with those estimated from Equation 2.2 in relation to the five Foobot validation datasets. It also illustrates the mean difference between the GrayWolf- and the Foobot CO_2-generated measurements (4.1149 with limits of agreement of -457.453 to 465.683 ppm at a 95% confidence interval). A total of 152 (6.21%) data points were outside of the limits of agreement (152 above the upper limit). This range is almost equal to the 1,000ppm (the ASHRAE threshold for CO_2 (ASHRAE, 2007)). A comparison between CO_2 concentrations and the Foobot CO_2 generated to produce information about the ventilation rates showed that there was poor agreement between them. The number of data points on which CO_2 concentration values exceeded 1,000ppm was significantly different from the GrayWolf instruments in relation to those generated by Equation 2.2, as shown in Table 2.12. The agreement of the data points from the calibration and validation datasets was also corroborated. Both showed complete disagreement on concentrations above 1,000ppm: on the calibration dataset, a kappa of 0, and on the validation dataset, a kappa of 0.

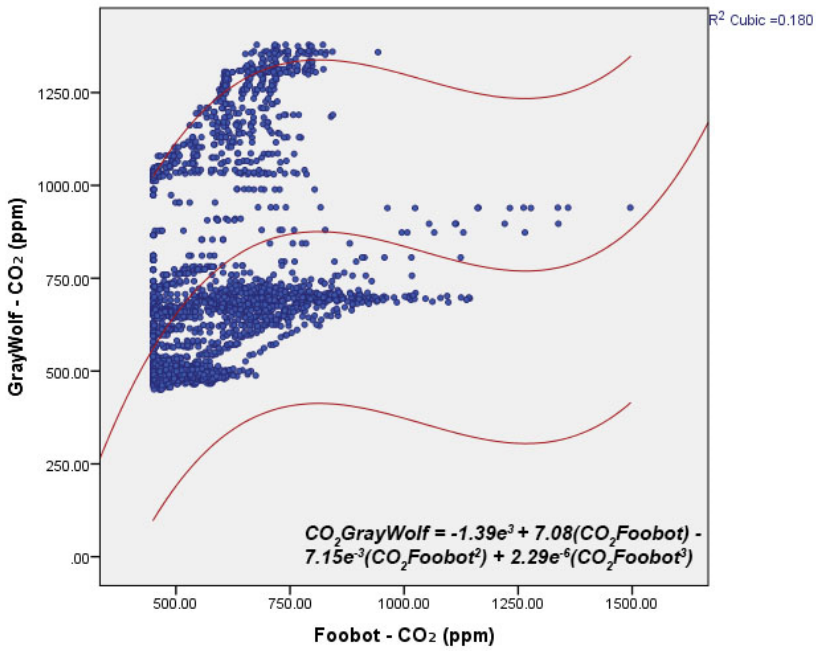


Figure 2.11 Scatter plot of the five-minute CO_2 concentration measured using the Foobot FBT0002100 and the GrayWolf IQ-410 from the calibration dataset.

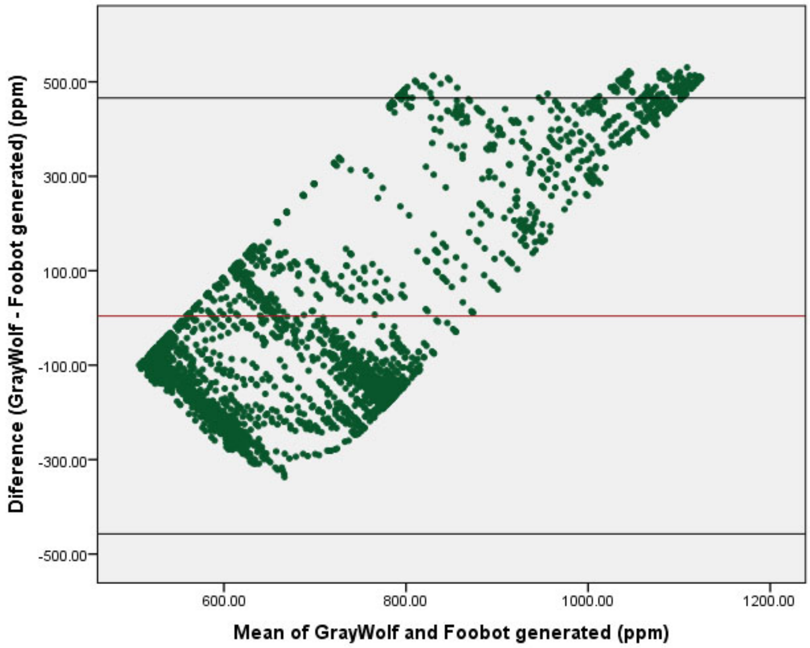


Figure 2.12 Bland-Altman plot of the agreement between the GrayWolf IQ-410 and the Foobot-generated CO_2 concentrations.

Table 2.12 Summary statistics for the generated CO_2 from the validation dataset.

Instrument	CO_2 mean (ppm)	CO_2 min (ppm)	CO_2 max (ppm)	% time >1,000ppm
GrayWolf TG-502 TVOC	727.24	451.00	1,379.00	20.53%
Generated Foobot A	715.86	556.80	870.66	0.00%
Generated Foobot B	720.05	556.80	870.68	0.00%
Generated Foobot C	725.15	556.80	870.68	0.00%
Generated Foobot D	725.05	556.80	870.69	0.00%
Generated Foobot E	729.51	556.80	870.69	0.00%

2.5.2.2.3 Fine particles ($PM_{2.5}$)

The results from the $PM_{2.5}$ measurements showed that Foobot overestimated particle matter concentrations. Figure 2.13 shows the relationship between the GrayWolf PC-3016A and the Foobot FBT0002100 $PM_{2.5}$ concentrations from the calibration dataset used to generate the regression equation. The best fit produces an R^2 value of 0.887 and the equation generated by regression is:

$$\boldsymbol{PM_{2.5}GrayWolf = 0.49 + 0.79(PM_{2.5}Foobot) + 3.76e^{-3}(PM_{2.5}Foobot^2)}$$

(Equation 2.3)

where $PM_{2.5}$ is mass concentration in μg/m^3. Figure 2.14 shows the Bland-Altman plot comparing the GrayWolf $PM_{2.5}$ measurements with those estimated from Equation 2.3 in relation to the five Foobot validation datasets. This shows the mean difference between the GrayWolf- and the Foobot tVOC-generated measurements (-0.0137 with limits of agreement of -2.32 to 2.29µg/m³ at a 95% confidence interval). A total of 100 (4.08%) data points were outside of the limit of agreement (58 above the upper limit and 42 below the lower limit). This range is significantly lower than 25 µg/m³ (the WHO threshold for $PM_{2.5}$ (WHO, 2000)). A comparison between the $PM_{2.5}$ concentrations and the Foobot $PM_{2.5}$ generated to produce IAQ information showed that there was very good agreement between them. The number of data points on which the $PM_{2.5}$ concentration values exceeded the 25µg/m³ was within ±0.21%, as observed in Table 2.13. Agreement of the data points from the calibration and validation datasets was also corroborated. Both showed very good agreement on concentrations above 25 µg/m³: on the calibration dataset, a kappa of 0.9, and on the validation dataset, a kappa of 0.85.

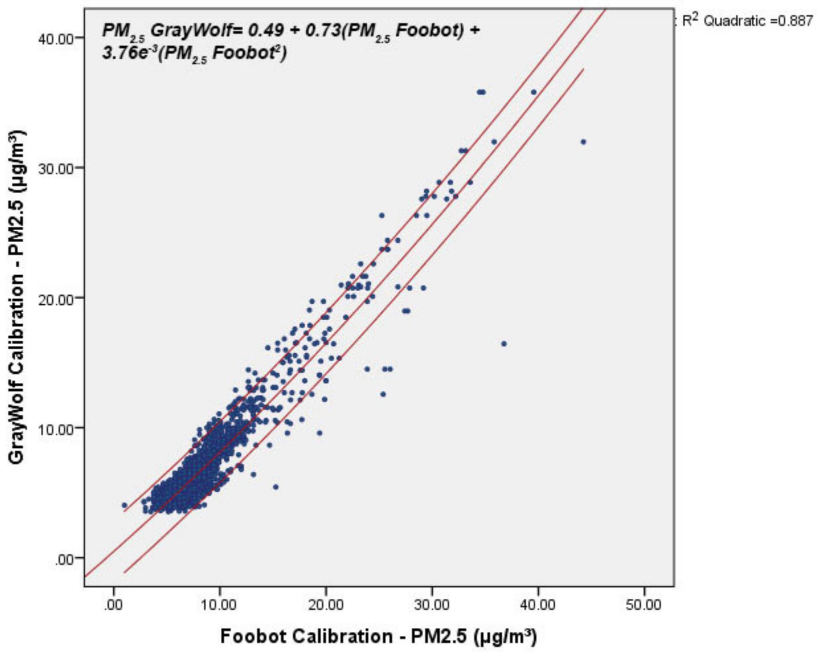


Figure 2.13 Scatter plot of the five-minute $PM_{2.5}$ concentration measured using the Foobot FBT0002100 and the GrayWolf PC-3016A from the calibration dataset.

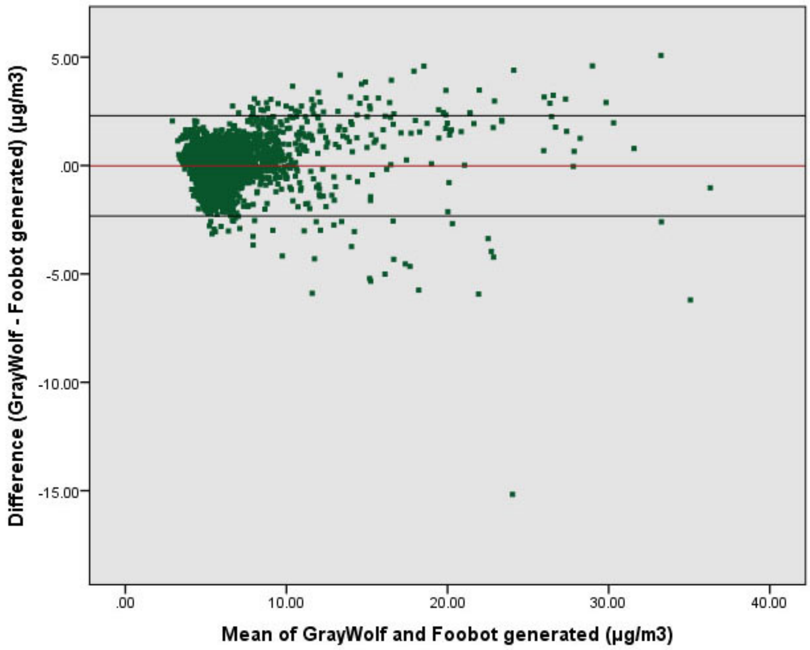


Figure 2.14 Bland-Altman plot of the agreement between the GrayWolf PC-3016A and the Foobot-generated $PM_{2.5}$ concentrations.

Table 2.13 Summary statistics for the generated PM2.5 from the validation dataset.

Instrument	PM2.5 mean (µg/m3)	PM2.5 min (µg/m3)	PM2.5 max (µg/m3)	% time >25µg/m3
GrayWolf PC-3016A	5.3604	1.87	34.52	0.82%
Generated Foobot A	6.8484	3.42	31.18	0.72%
Generated Foobot B	6.8611	1.22	39.95	0.82%
Generated Foobot C	6.8479	2.83	34.57	0.72%
Generated Foobot D	6.8442	3.06	31.62	0.61%
Generated Foobot E	6.8552	2.7	38.18	0.72%

2.5.3 Discussions about the validity and accuracy of the Foobot

Measurements of temporal and spatial changes in indoor contaminant concentrations are vital to gain an in-depth understanding of pollutant characteristics, particularly in dynamic, spatially variable environments such as the home. International standards and IAQ assessment routines, especially for office buildings, require monitoring of several air pollutants (θ_r, O_3, NO_x, CO, Rd, Formaldehydes, among others) that are not monitored by low-cost sensors (θ_{air}, ϕ, $PM_{2.5}$, tVOC, CO_2). Low-cost IAQ monitor's manufacturers opt for a limited number of parameters to lower the costs. While "high-cost" instruments can provide high temporal resolutions of indoor pollutants such as $PM_{2.5}$, PM_{10} and tVOCs, the cost and complexity of these instruments renders the monitoring of spatial and temporal changes on a large scale prohibitively difficult.

This work tries to find a more affordable and suitable instrument to provide IAQ information, which may also enable the simultaneous monitoring of different rooms within the same home. However, it might also facilitate more extensive IAQ monitoring projects looking to characterise pollution and identify potential health risks in indoor building environments with much larger and more statistically significant datasets. A previous experiment in a controlled chamber showed that the monitor could be used to provide mass concentrations of $PM_{2.5}$ (Sousan *et al.*, 2017), but this is the first study to evaluate the accuracy of all measurements (temperature, relative humidity, tVOC, CO_2 and $PM_{2.5}$) made by the Foobot FBT0002100 in real-life residential settings, producing more than 4,800 data points.

Calibration equations for the site were calculated as suggested by Sousan et al., (2017). The equations generated may be influenced by domestic pollution (i.e. pollutants from paint, cleaning and personal care products, household dust, outdoor air and cooking fumes). The density and features of such contaminants will be different depending on the household. Hence, the response of instruments like GrayWolf PC-3016A, TG-502 TVOC, IQ-410 and Foobot FBT0002100 may vary in real-life homes, depending on these and other factors such as monitor location, temperature and humidity. Therefore, to provide the most accurate measurements, an individual calibration equation could be provided for each Foobot and specific contexts, although this may not be possible for large-scale and remote deployable projects. A better alternative for large-scale projects may be to produce a calibration equation for a large set of monitors for each setting (i.e. bedroom, kitchen and living room). Then, in order to reduce the bias of inter-Foobot differences, one could use three monitors within the same space and then employ the mean from the monitors in each room to provide a more robust measurement. This alternative provides not only greater accuracy than the application of a calibration equation, but the redundancy of the acquired data from several monitors also provides higher confidence in and robustness to the dataset.

The validation results showed that there was a very good agreement between the GrayWolf PC-3016A/TG-502 TVOC/IQ-410 and the Foobot FBT0002100 with regard to temperature (Eltek and Tinitag) and humidity. TVOC and $PM_{2.5}$ had very good agreement, when the regression equations were applied. CO_2 concentration levels were not accurate, though, as the Foobot FBT0002100 instrument does not possess a real CO_2 sensor but instead provides a CO_2 equivalent from tVOC levels as an indication. Differences between CO_2 levels from the GrayWolf IQ-410 and the Foobot were clear, as illustrated in Figure 2.7. While the GrayWolf IQ-410 uses non-dispersive infrared spectroscopy technology to determine CO_2 concentrations, the Foobot uses an algorithm to convert tVOC to CO_2 equivalents providing misleading measurements. Differences in the measurements were expected since CO_2 and tVOC are different chemicals and have different sources and compositions. CO_2 concentrations in indoor environments have long been used as an indicator of ventilation (ASHRAE, 2007), and they correlate to human activities and occupancy (Porteous, 2011) but are not related to sources of pollution such as off-gassing from building materials or furniture (Brown *et al.*, 1994), as is the case for tVOC.

The implementation of the algorithm to predict CO_2 is relatively new, and the theory behind it contends that tVOC can be correlated proportionally to CO_2 production, thus providing CO_2- and tVOC-related events at the same time (Herberger *et al.*, 2010). In other words, the algorithm attempts to relate tVOC to CO_2 concentrations in indoor spaces where no human activity takes place (Ulmer and Herberger, 2012). Most of the studies undertaken to correlate CO_2 equivalents to tVOC have been carried in schools, offices, meeting rooms and home environments. For example, Figure 2.15 (Ulmer and Herberger, 2012) compares CO_2 equivalents calculated from tVOC to CO_2. The left graph shows a strong correlation in a meeting room, whereas the right-hand graph show signals that can be attributed to tVOC but differ from CO_2. Implications of this approach may include misleading CO_2 readings that might confuse many new to the IAQ industry; however, it adds the ability to add the sensor output to ventilation standards (Herberger *et al.*, 2010) and implement it for ventilation systems, thereby reducing energy consumption compared to time-scheduled ventilation (Ulmer and Herberger, 2012). However, this approach is a very recent initiative, and so additional development of IAQ modules is needed (Ulmer and Herberger, 2012), especially in residential environments. Airboxlab opted, for two main reasons, for an iAQ-CORE-C sensor to provide tVOC concentrations and an idea of CO_2 instead of real CO_2 measurements. First, they believed that tVOC measurements are more important in evaluating IAQ, as the health impacts of higher levels of tVOC are usually more severe than those from CO_2. Second, the additional cost for the CO_2 sensor may increase the price of the Foobot (personal communication).

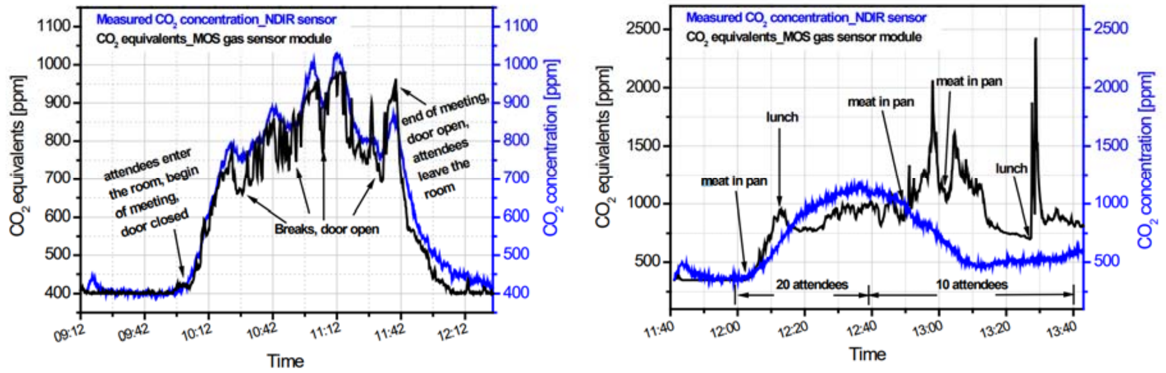


Figure 2.15 The graphs compare the real CO_2 measurements vs CO_2 equivalents from tVOC of a previous study. Real CO_2 (in blue) and CO_2 equivalent from tVOC (in black) in a meeting room (left) and a kitchen (right). Source: (Ulmer and Herberger, 2012)**.**

About 3.2% of the tVOC measurements and 4.1% of $PM_{2.5}$ were outside of the limits of agreement when an upper and lower bound of a 1.96 standard deviation (SD) of the difference was applied. There is, however, a concern as to whether or not the 1.96 SD limits are appropriate for assessing the impact of pollution on human health (Bland and Altman, 2010). For this reason, the 1.96 SD was transformed into pollution concentrations to ensure these bounds were either the same or lower in terms of range to those thresholds set by the WHO, which resulted in tighter ranges. The 1.96 SD for $PM_{2.5}$ resulted in a range from -2.3245 $\mu g/m^3$ to 2.2971 $\mu g/m^3$ ($\pm$2.2932 $\mu g/m^3$ from the mean), and from -36.7935 ppb to 35.9668 ppb for tVOC ($\pm$36.5920 ppb from the mean). An examination of the instruments employed to produce IAQ information reinforced this conclusion, as the quantitative information provided by the different instruments demonstrated high agreement. Variability between the percentage of time above threshold values as determined using data from the Foobot and the GrayWolf monitors was generally small and was considered to be unlikely to produce major changes in IAQ assessments.

The findings show that the Foobot FBT0002100 provided sufficiently accurate results for evaluation of IAQ in occupied dwellings and that the information provided could identify trends and exposures above thresholds within a small margin of error. The Foobot does not make any noise and the light can be dimmed or turned off during normal operation, however, if problems with the internet connection arise the Foobot has a light signal. So, the Foobot can be used to perform simultaneous measurements of the indoor environment inside homes, including sensitive spaces such as bedrooms. This should minimise changes in participants' behaviour in response to their awareness of being observed, minimising the Hawthorne effect (Landsberger, 1958) and the risk of occupants disconnecting the monitors. Moreover, the cost, size, mobility and the easy deployment of the Foobot FBT0002100, combined with its accuracy, make it a useful tool for evaluating occupant pollutant exposure in research and large-scale monitoring campaigns looking to collect high-density temporal and spatial data on indoor pollutant concentrations in a wide range of households at local, regional and national levels. This information could be used to acquire more comprehensive information on indoor pollutant concentrations, in order to understand better temporal and spatial changes and pollutant-activity relationships in the home. There is, however, an important limitation of the Foobot monitor for studies that require a wider consideration of air pollutants and outdoor measurements (that cannot be obtained from outdoor monitoring networks). Due to its characteristics, the Foobot cannot be used outdoors - it still requires a plug and extreme temperatures and humidity may damage the sensors, and such it is not possible to take comparative outdoor measurements.

This study suffers from some identifiable limitations. First, there was no comparison or control group in an environmental chamber. Environmental chamber experiments would include the use of calibration gases and aerosols, allowing comparison with a wider range of highly accurate instruments. However, the purpose of this study was to evaluate the intended purpose of low-cost monitors in field conditions. Additionally, sensor's drift over the time was not evaluated, as these kind of studies require longer testing periods in addition to controlled environments. Second, it was assumed that GrayWolf PC-3016A/TG-502 TVOC/IQ-410 provided accurate temperature, humidity, CO_2, CO, VOCs and $PM_{2.5}$ concentrations. While the devices were tested and calibrated by the manufacturer a month before this study, this still represents a potential error. Third, we assumed that the monitors were left in place throughout sampling. We asked the participants not to handle the devices, but the light and noise produced by the

GrayWolf instruments might cause occupants to relocate them, though there was no evidence of this.

2.6 Chapter conclusions

The findings highlight the challenges of current approaches to measuring and collecting indoor air pollutant exposure data, and so an alternative is presented. Traditional analytical instruments are impractical and costly, and often their accuracy is much higher than required to assess indoor pollution levels. Low-cost IAQ monitors provide information about the quality of indoor air and have the advantages of reduced size, less noise and ease of deployment. The accuracy of low-cost sensors and monitors in quantifying exposure to pollutants (gases and fine particles) has improved drastically over the last few decades. Moreover, the addition of different technologies, such as wireless data retrieving, smartphone visualisation and wireless communication with home devices (including heating and mechanical ventilation systems), have made them even more practical for home users, manufacturers and researchers. The use of low-cost monitors has the potential to collect much larger datasets in short- and long-term studies can help to assess changes in concentrations that may result from changes in ventilation patterns, conditions of occupancy and activities as well as potential for behavioural changes.

Low-cost IAQ monitors offer real-time characterisation of indoor pollutants, increased spatial and temporal resolution and reduced uncertainty, whilst facilitating the collection of larger datasets providing information about emitting sources and activities of indoor pollutants that are not often monitored. For this study, the Foobot FBT0002100 was selected due to its accuracy level, which is appropriate for the purposes of this study, the ability to measure different indoor pollutants and environmental parameters and remote data retrieval among other characteristics. Temperature, relative humidity, $PM_{2.5}$, tVOCs and CO_2 measurements of the Foobot were compared to those from conventional IAQ monitors (GrayWolf TG-502 TVOC, GrayWolf PC-3016A and GrayWolf IQ-410). Foobot FBT0002100 was found to have significant agreement with the GrayWolf instruments, for temperature (r_s = 0.832–0.871), relative humidity (r_s = 0.935-0.948), tVOC (r_s = 0.827–0.869) and PM2.5 (r_s = 0.787– 0.866) data. Air temperature was found to be underestimated by 2.59°C to the GrayWolf and by 0.39° to the

Tinytag and overestimated by 0.24°C to the Eltek. The calibration equations produced for tVOC (R^2 = 0.697) and PM2.5 (R^2 = 0.887) reduced variability between the monitors and improved their accuracy when compared to the GrayWolf instruments.

Foobot's lack of a specific CO_2 sensor and estimated tVOC from CO_2 provided misleading concentrations. However, the results showed that this does not affect the accuracy of the other sensors. Foobot CO_2 reading were deemed not reliable and, therefore not used in this study. Netatmo was used instead to provide real CO_2 measurements. This study did not evaluated Netatmo's performance as this has been tested elsewhere (Meier *et al.*, 2017; Petersen *et al.*, 2018).

The key findings of this chapter have been published in a peer-reviewed journal publication (see (Moreno-Rangel et al. 2018)). The following chapter will describe in detail the PassivHaus approach, identify and discuss PassivHaus IAQ studies and give an overview of IAQ parameters and guidelines.

Chapter 3 PassivHaus and Indoor Air Quality

3.1 Summary

Rising awareness of the impact of the building environment on climate change, in addition to rising energy prices, has stimulated the development of low energy design. One of the most successful examples of this is the PassivHaus approach, which relies on proven building science to reduce energy consumption to a minimum. However few studies have assessed IAQ in PassivHaus dwellings, and of those that have done so, their primary purpose is often to understand the impact of the building fabric and technologies on energy conservation, and they pay little attention to IAQ issues. Some aspects of IAQ, such as ventilation rates, are often the matter of PassivHaus studies. However, others such as source control are not so common as they are out of the PassivHaus scope.

PassivHaus had started to become more widespread, and now, PassivHaus dwellings have started to be developed in areas where energy consumption may not be the significant driver. While weather conditions limit the potential for energy saving, indoor air quality and environmental performance become more critical in PassivHaus in this context. Nevertheless, these issues are also essential in locations where energy performance is a driver for PassivHaus. Few studies have compared measured levels of indoor pollution in PassivHaus dwellings to conventional buildings, or the occupants' perceptions and well-being, such studies are often based on short-term measurement of environmental parameters in a limited number of dwellings or based on virtual simulations. The PassivHaus design strategies that might have an impact on IAQ are discussed here within the body of knowledge and the relevant literature.

This chapter also defines how this research will use the term 'acceptable IAQ' based on the World Health Organization (WHO). It also identifies the indoor environmental and air pollutant thresholds – and their impact on human health - used in this study.

3.2 PassivHaus background and concept

The PassivHaus concept is an evolution of passive solar architecture and super-insulated homes developed in Sweden, whose national interest in reducing space heating and improving the U-values of building fabrics, windows and doors was evident in the Swedish SBN1975 Building code. This had numerous implications, but one of the most important was the commercial development of triple glazing windows (Adamson, 2011), along with further developments in insulation, thermal bridging, airtightness and controlled ventilation. Bo Adamson investigated the trade-offs from super-insulated buildings to the conventional central heating systems of Swedish homes in the 1960s – experiments that would eventually become associated with the PassivHaus standard (Hopfe and McLeod, 2015).

The actual term 'PassivHaus' is forged from a research idea generated in 1988 by Professor Bo Adamson from Lund University (Sweden) and Professor Wolfgang Feist from the Institute for Housing and Environment (Germany, Wang *et al.*, 2017). In 1990, as a result of their early experiments, the first PassivHaus dwellings were built in Darmstadt, Germany, and later, in 1996, the Passive House Institute (PHI) was established. Since then, the PHI has researched super-insulation in different climates, building construction techniques and building components, such as doors, windows and ventilation systems.

A Passive House, or 'PassivHaus', which is the original German term, is (PHI, 2017b):

> "*[…] a building, for which thermal comfort (ISO 7730) can be achieved solely by post-heating or post-cooling of the fresh air mass*[2]*, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air*".

In this research, 'PassivHaus' will refer to the building concept definition above, with a few exceptions, where the term *Passive House* is used explicitly to name some research projects or when quotations are used. This distinction is made, as the words "passive house" could also refer to buildings that use passive or solar

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[2] As defined by the DIN1946, the PassivHaus definition by the PHI does not include the DIN1946. However, ventilation calculations are based on this German standard of ventilation.

design techniques to achieve low-energy consumption or higher indoor environmental quality but do not necessarily adopt solutions or certifications for the PassivHaus standard.

The PassivHaus standard is based on five fundamental concepts: super-insulation, thermal bridge-free construction, an airtight building envelope, use of high-performance doors and windows and MVHR systems. Also, the building must comply with strict design criteria listed in detail on the Passive House Planning Package (PHPP) version 9 (Feist *et al.*, 2015). Energy-efficient electric appliances and lighting are essential to achieve the low-primary energy demand required to obtain certification. As part of the certification process, the PHPP analysis and post-completion tests (blower door and ventilation rates) are verified by a PassivHaus certification body. In recent years, the PHI has developed new standards: EnerPHit, the standard for refurbishment projects, PassivHaus Plus, for near-zero-energy buildings, and PassivHaus Premium, for positive energy buildings and PassivHaus Classic.

The principal criteria for PassivHaus certification are presented in Table 3.1. Possibly the most crucial factors are heating load and heating demand so that the building does not require conventional heating approaches to maintain thermal comfort levels (Schnieders and Hermelink, 2006). Indoor thermal comfort is the centre from which the PassivHaus develops. The supply-air heating load should not exceed $10W/m^2$ in order that a comfortable indoor climate ($\theta_{op} \leq 25^{\circ}C$) can be maintained without conventional heating. Thus, thermal comfort is taken into account in line with the peak supply-air heating load, by considering the volumetric capacity of the system, supplied flow rates ($30m^3/h$ per person), indoor temperatures and treated floor area in the project (Feist *et al.*, 2015). Excellent indoor environment comfort is linked directly to energy efficiency as an incentive; the PassivHaus standard originated as an ultra-low-energy concept rather than as a way to reduce CO_2 emissions. By prioritising energy-efficient design, the PassivHaus standard addresses energy demand reduction and thermal comfort, unlike other low-carbon standards which may advocate low-carbon heating standards, such as LEED or BREEAM.

Table 3.1 Overview of the principal PassivHaus certification criteria for Central European climates. Adapted from: (Hopfe and McLeod, 2015)

PassivHaus certification criteria (residential)	Cool-moderate climate (Central Europe)	
Specific heating demand	≤ 15	kWh/(m^2a)
OR Specific heating load	≤ 10	W/m^2
Specific cooling demand	≤ 15	kWh/(m^2a) + 0.3 W/(m^2aK). DDH
OR Specific cooling load	≤ 10	W/m^2
AND Specific cooling demand	≤ 4	kWh/(m^2a) .σ_e + 2 • 0.3 W/(m^2aK). DDH-75 kWh/(m^2a)
Specific total primary energy demand	≤ 120	kWh/ m^2/a
Airtightness n_{50}	≤ 0.6	h^{-1} (@*50Pa*)
Overheating frequency	10%	Percentage of time with operative temperature above 25°C
DDH refers to Dry Degree Hours. σ_e Annual mean external air temperature (°C).		

Ventilation in PassivHaus buildings is based on the German DIN1946 standard. It states that CO_2 peaks levels should be no higher than 1,500ppm. Mechanical ventilation removes the moisture when the infiltration air volume flow is insufficient to remove it (Guillén-Lambea, Rodríguez-Soria and Marín, 2016) – this would require a (total) outdoor airflow of 5-10 l/s per person (18-36m^3/h per person, 0.3-0.6h^{-1}, (Feist *et al.*, 2005)).

PassivHaus was developed for buildings in Central European countries. However, as the standard has become more popular, structures are now being built in climates that differ considerably from Germany or anything found in Europe. As of March 2018, the PassivHaus database (PHI, 2014) had registered 212 buildings outside of Europe, built predominantly in the US (92), Canada (42), New Zealand (22), Japan (21) and China (16).

3.2.1 Building form

PassivHaus buildings may have freedom in design, but their shape, size and orientation need to be planned carefully, as they have a significant impact on energy consumption. For instance, the ratio of surface area of the building envelop to the volume (A/V ratio) of the building places a considerable load on heating and cooling demands, regardless of the thermal transmittance value (U-value) of the building envelope (Hopfe and McLeod, 2015). In low-energy buildings, the more compact the building, the less energy it requires. However, PassivHaus buildings reduce energy consumption by avoiding energy (heat or cooling) losses through the building envelope. Therefore, the higher the A/V ratio, the higher potential for heat transfer. So small buildings have greater disadvantages, while larger buildings may have a lower A/V penalty for complex forms.

3.2.2 Super-insulation

As suggested by the early work of Bo Adamson, PassivHaus buildings use super-insulation to decrease heat transfer through the opaque building envelope. Super-insulation is essential when the difference between indoor and outdoor temperatures is high, but as this difference reduces, it becomes slightly less necessary, as there is no need to maintain an indoor temperature different from outdoors (Wassouf, 2014). An extensive range of thermal insulation is available to achieve typical U-values (0.10-0.15W/m^{2}K) required for PassivHaus (Schnieders, 2003), although foam insulations should be avoided where possible, as they might compromise safety in terms of IAQ and fire (Woolley, 2017). External insulation in PassivHaus is typically between 20-40cm thick, and pipework and ductwork must be insulated as well, to avoid condensation and heat loss from the pipes.

3.2.3 Thermal bridge-free construction

A thermal bridge is a part of the building envelope that conducts heat between indoor and outdoor environments, causing internal condensation and dampness. Therefore, thermal bridges may become a source of unquantified thermal loss and contribute as much as 50% of the transmission heat in PassivHaus buildings (Schnieders, 2009) and condensation depending on the θ_{ai}, θ_{surf} and air moisture content. Thermal bridges need to be modelled and assessed carefully at the design stage through virtual simulation, with software such as THERM. However, time can be saved by replicating any of the reference detail sources for PassivHaus, such as the IBO Book (Waltjen *et al.*, 2009; IBO, 2017).

The most common types of thermal bridges are ‘constructional’, whereby a construction material penetrates the insulation. Other options include geometric thermal bridges, caused by the shape of the building (i.e. corners), point thermal bridges, caused by structural connections or insulation fixing, and linear thermal bridges, caused by a gap between the edges of two pieces of insulation or when one building material meets another (Cotterel and Dadeby, 2012).

3.2.4 Use of high-performance doors and windows

The main reason for using high-performance doors and windows is to eliminate the risk of condensation and mould growth, reduce drafts and radiant temperature asymmetry while simultaneously achieving acceptable thermal comfort. PassivHaus windows, including frames, are designed to make the most of solar gains, thus helping to warm the building. They have two or three layers of glass, usually clear, which can be filled with different gases. The G-value is the solar heat transfer that enters through a proportion of the window in comparison to the energy that reaches the window, and so a higher G-value means higher solar transmission. A suitable PassivHaus window (<0.8W/m^{2}K) may have a higher U-value than PassivHaus walls (0.10-0.15W/m^{2}K), and so they should be used carefully. PassivHaus windows are usually limited to 0.8W/m^{2}K (Feist *et al.*, 2015); however, this can change in warmer climates (PHI, 2011; Schnieders, Feist and Rongen, 2015). As with windows, doors must have a U-value of 0.8W/m^{2}K and be airtight. Window sizing is an important issue, in PassivHaus dwellings windows tend to be small to reduce heat loss and solar gains, however, this has an impact on the opening size and ventilation that may lead to overheating (Tabatabaei Sameni *et al.*, 2015).

Installation is as important as the characteristics of the windows and doors. A correctly installed window will avoid thermal bridge losses while improving the overall U-value by up to 50%. If they are positioned "*within the insulation plane of the thermal envelope and that insulation overlaps the frame as far as possible, the thermal bridge loss coefficient of installation can be 0* (Schnieders and Hermelink, 2006, p. 154)." PassivHaus approved windows are the best way to optimise solar gains.

3.2.5 Airtightness of building envelope

The building envelope adheres to high levels of airtightness, thereby avoiding thermal losses through infiltration. The most common uncontrolled air leakage occurs due to poorly installed windows, doors, suspended floors, services (pipes and ducts), internal partitions, ventilation systems, small cracks and holes in the building envelope and poorly designed construction systems (NHBC Foundation, 2009). To achieve good airtightness, air barriers that seal construction joints and penetration across the envelope are indispensable (Sherman and Chan, 2004).

The airtight barrier also works as a vapour control layer, in that on the warm side of the building (usually on the inside), this layer protects the insulation and building structure from interstitial warm air and moisture. An additional wind barrier layer, usually on the outside of the building fabric, is placed in position to stop cold air entering the building. Both layers are a requirement and should be appropriately marked in the design. In PassivHaus buildings, the airtightness target is defined by the number of air changes per hour at a reference of ±50 Pascal (n_{50}) (see (McLeod *et al.*, 2014) for more details). The on-site airtightness test (blower door test) measures total leakage through the building envelope. An under-pressure and over-pressure blower door test are part of the PassivHaus certification process. The airtightness result must achieve an n_{50} $\leq 0.6h^{-1}$ @50Pa (Schnieders and Hermelink, 2006).

In PassivHaus homes, the heat losses are reduced by improving the airtightness of the building, which improves the energy conservation (PHI, 2017). However, as a consequence of the high airtightness achieved has an impact on IAQ, the hourly air change is reduced around 27% of its volume (Badescu and Sicre, 2003). Thus the need to achieve ventilation with MVHR systems with low air velocity to ensure proper heat distribution.

3.2.6 Mechanical ventilation with heat recovery (MVHR) systems

An MVHR system's primary purpose is to provide a continuous supply of fresh air while optimising occupant comfort by recovering heat from extracted air (Schnieders and Hermelink, 2006), thereby reducing energy (heat or cold) losses and protecting against outdoor air pollution (Hopfe and McLeod, 2015). PassivHaus air change rates are usually between $0.25h^{-1}$ and $0.40h^{-1}$, according to IAQ requirements (Feist *et al.*, 2005) and should not exceed $30m^3/h$/person (PHI, 2017). Lower rates may compromise the health of the occupants and higher ones may result in dry air. The supply air is delivered to the living areas (rooms where the occupants spend extended periods of time, i.e. bedroom and living rooms) and extracted from wet rooms (rooms where occupant activities may produce increased moisture or odours, i.e. bathroom and kitchen). The recommended extract air flow (m) rates from wet rooms are 60m^3/h for kitchens, 40m^3/h for bathrooms and 20m^3/h for other rooms (i.e. WC, store rooms). However, some house may have low occupancy and relatively low wet rooms. PassivHaus dwellings should also meet a minimum whole-house air change rate per hour (ach/h) of 0.3. So that PassivHaus dwellings should be designed to meet:

- Fresh air demand: 30m^3/h x number of occupants.
- Recommended minimum extract rate from wet rooms (kitchen + bathroom): 60m^3/h + 40m^3/h.
- Minimum air change rate: 0.3ach/h x treated floor area x floor to ceiling height (maximum of 2.5m height).

Table 3.2 MVHR requirements for certification as "Passive House suitable component – heat recovery device". Adapted from (PHI, 2015b)**.**

Passive House - comfort criterion	Minimum supply air temperature ($\theta_{supply\ air}$) ≥ 16.5°C at θ_{ao}=-10°C.
Efficiency criterion, heat ($\eta_{HR,eff}$)	The efficiency dry heat recovery must be higher than 75% with balanced mass flows at external temperatures (θ_{ao}) of between -15°C and 10°C and dry extract air (ca. 20°C) $$\eta_{HR,eff} = \frac{(\theta_{extract} + \theta_{exhaust}) + \frac{P_{el}}{m \cdot C_{\rho}}}{(\theta_{extract} + \theta_{exhaust})}$$
Electrical efficiency criterion	At the designed mass flow rate the total electrical power consumption of the ventilation device may not exceed 0.45W per (m^3/h) of transported supply flow.
Balancing and controllability	Outdoor air and exhaust air mass flows must be balanceable for the rated air flow rate, with controllability of at least three levels (basic ventilation (10-80%), standard ventilation (100%), increased ventilation (130%)).
Sound absorption	Noise level in installation room < 35 dB(A), in living areas < 25dB(A), in functional areas < 30dB(A).
Room air hygiene	Outdoor air filter at least F7, extract air filter at least G4.
Frost protection	Frost protection for heat exchanger without supply air interruption, frost protection for an air heater in case of failure of the extract fan or frost protection heater coil.

Any MVHR system installed in PassivHaus need to meet the requirements and pass the certification tests (detailed in (PHI, 2015b)). A summary of the criteria is detailed in Table 3.2.

When planning the use of MVHR systems in PassivHaus homes, the ventilation should be designed to i) achieve the required ventilation rate in the intended rooms, thus balancing the MVHR unit and the system pressure loss; ii) minimise the noise nuisance; iii) be easy access for maintenance; and iv) achieve the required ventilation in the most energy-efficient way. To help in this process the PHPP 'Ventilation Protocol worksheet' should record supply and extract air demands across the house, as well as the distribution of the airflow volume rate entering and leaving each room together with the control range of the airflow volumes, energy efficiency requirements, noise protection and filters. Finally, each of these parameters should be tested and entered on the PHPP 'Ventilation commissioning worksheet'. Therefore, airflow measurements should be taken at low, normal and maximum air flow rates and be recorded. If noise levels are a problem, the system should be rebalanced at a lower pressure.

The design, installation and commissioning of an MVHR system make up a significant part of the overall performance of the ventilation system and may help to save up to 90% of heat (Bere, 2013). The ventilation ducts should be insulated and sealed to prevent energy losses through air leakages (Balvers *et al.*, 2012), as energy savings are linked to the ratio of heat saved and energy consumed by the system. Ventilation behaviour – MVHR or window opening - strongly influence the PassivHaus' energy performance. Window opening increases the ventilation rates, but may interfere with humidity and temperature as well as decreasing the performance of the heat recovery (Schnieders and Hermelink, 2006). The operation and implications of MVHR ventilation to IAQ, as well as the flow rates, are presented later in this chapter.

3.2.7 Energy-efficient electric appliances and lighting

Once heat and cooling demands are met and efficient technologies for domestic hot water are implemented, electrical appliances are the most significant component of any final energy demand in dwellings: "*It is a part of the Passive House philosophy that efficient technologies are also used to minimize the other* *sources of energy consumption in the building, notably electricity for household appliances* (Schnieders and Hermelink, 2006, p. 152)." Hot water connections for washing machines and dishwashers, airing cabinets, fluorescent lamps and LED bulbs are examples of techniques that may help to reduce energy consumption, without sacrificing comfort (Schnieders, 2003; Schnieders and Hermelink, 2006).

3.2.8 Thermal comfort and risk of overheating overheating

In PassivHaus buildings, thermal comfort is achieved through the use of super-insulation, high levels of airtightness, MVHR systems, optimising the solar and internal heat gains and solar shading. PassivHaus dwellings are designed to avoid or minimise temperature stratification and draughts. Temperature stratification refers to the vertical air temperature difference ($\Delta\theta_{air}$), the PassivHaus criterion establish that vertical $\Delta\theta_{air}$ should not be higher than 2°K between 0.1m and 1.1m height measured from a distance of 0.50m from the window. PassivHaus dwellings achieve this by maintaining uniform internal surface temperatures (θ_{si}). Airtightness is key to reduce undesired air leakages and draughts, as they could cause occupants to feel colder than the internal air temperature (θ_{ai}) suggests. Airtightness, low U-values on construction elements and low temperature stratification help to reduce draughts of 0.15m/s in PassivHaus (@ θ_{op}<22.5°C) (Hopfe and McLeod, 2015).

Overheating is, perhaps, the main concern in terms of thermal comfort in PassivHaus dwellings (McLeod, Hopfe and Kwan, 2013; Ridley *et al.*, 2013). The PHI classify the thermal comfort in 5 different categories based on the frequency of overheating beyond the threshold of an θ_{op} of 25°C during the occupied period (Table 3.3). In order to mitigate overheating is necessary to avoid solar radiation, plan the configuration, orientation and size of windows, provide of adequate shading, among other techniques. Nevertheless, overheating in PassivHaus dwellings has been documented (Ridley *et al.*, 2013; Foster *et al.*, 2016). Evidence suggests this may be due to occupant behaviour (i.e. external blinds not deployed, windows not being opened at night), hence such techniques are not always implemented as designed.

Table 3.3 Assessment criteria of the frequency of overheating in PassivHaus buildings. Adapted from (Feist et al., 2015).

% of time of θ_{op} >25°C	Assessment
>15%	Catastrophic
10-15%	Poor
5-10%	Acceptable
2-5%	Good
0-2%	Excellent

3.3 Shaping the PassivHaus standard

Since 1990, when the first PassivHaus was built, many studies have been published on the concept. Over the last three decades, especially in the last ten years, many lessons have been learned from new and refurbished PassivHaus buildings, and the approach has been adapted for different climates. There are many studies on PassivHaus; however, findings from the most recent studies that have contributed to the development of PassivHaus as we know it today are discussed below.

Perhaps one of the most significant studies is the Cost-Efficient Passive Houses as European Standards (CEPHEUS) project (2000-2002), which provides evidence on the concept's performance. Two-hundred and twenty-one dwelling units were built as part of fourteen projects in five European countries (Figure 3.1), the primary goal of which was to understand the PassivHaus standard in relation to different social, environmental, economic and sustainable contexts, emphasising particularly on the technical feasibility and cost-effectiveness of reducing energy consumption (Schnieders, 2003). The CEPHEUS project measured the energy performance and thermal comfort of 100 dwelling units.

The airtight test showed that only nine of the projects had >0.6 h^{-1}, but it was noted that this could be remediated by further work between the junctions (Schnieders and Hermelink, 2006). The results of energy monitoring showed that energy consumption for heating was about 80% less compared to conventional new reference buildings and that the discrepancies between the heating loads measured and those simulated with the PHPP were minimal. On the subject of final and primary energy consumption, a reduction of 50% was reported against conventional new buildings (Schnieders, 2003; Schnieders and Hermelink, 2006).

Most of the studies evaluated whether or not energy savings could repay the additional investment for PassivHaus, however indoor temperature measurements and building user surveys were also undertaken. The results of the temperature measurements showed that PassivHaus could be maintained in a comfortable range during summer. Shading elements and occupancy ratios also have an essential impact on thermal comfort (Schnieders, 2003). Schnieders & Hermelink (2006) discuss some recommendations to maintain user satisfaction, most of which are related to user behaviour and the ventilation system's use and its maintenance. Users reported to be satisfied with their dwellings, but the lack of radiators to control heating caused some anxiety. About 50% reported feeling better than before and that their comfort increased compared to their previous home, due to thermal improvements, easy ventilation controls and good air quality (Schnieders and Hermelink, 2006).

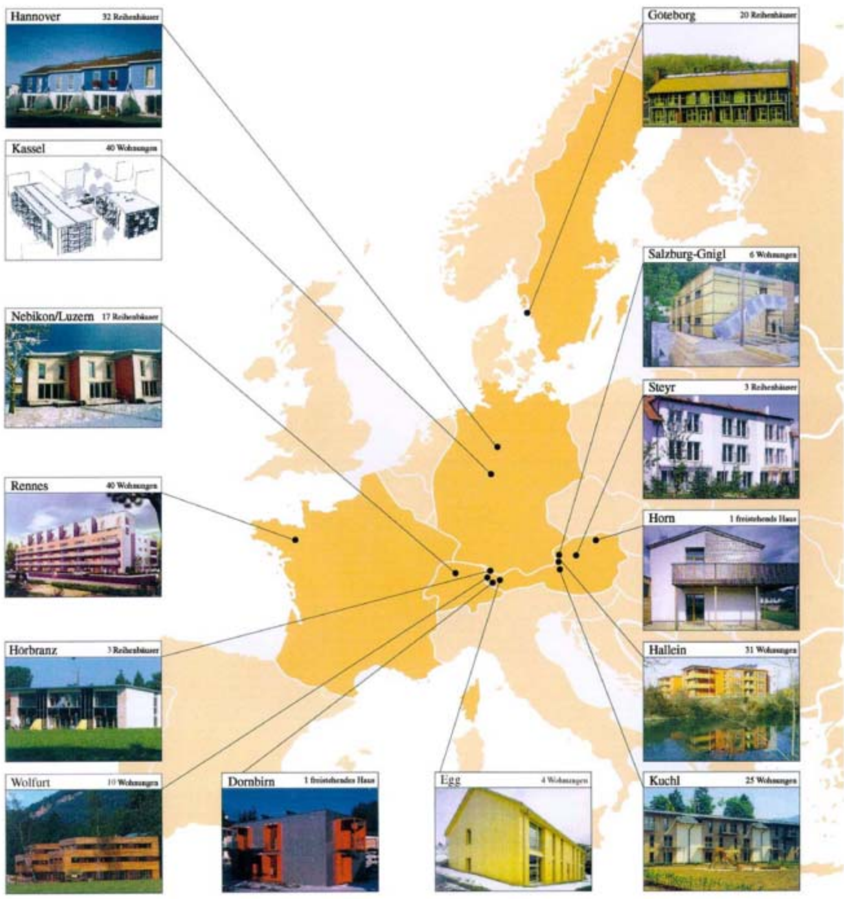


Figure 3.1 Location of the CEPHEUS projects. The CEPHEUS project was carried out in France, Switzerland, Germany, Austria and Sweden. Source: (Schnieders and Hermelink, 2006).

The Passive House Institute published the Passive House for Different Climate Zones (PHI, 2011) in November 2011. This project aimed to demonstrate through dynamic building simulations the success of the PassivHaus standard in achieving ultra-low-energy consumption and high indoor comfort, regardless of the location, and to determine the influence of individual on-site parameters. The locations were selected according to two main factors: representative climates and expected new and renovation construction over the following decades. By demonstrating how PassivHaus could be built in extreme weather locations, there was an expectation that the same would be right in less demanding climates (PHI, 2011).

The report shows in detail the application of PassivHaus in:

- Yekaterinburg (cold climate), where they reduced the heating demand to 22.4kWh/m^{2}a. While this is greater than the 15kWh/m^{2}a, they considered acceptable as it was already less than 4% of a standard building in the same climate. The most critical factors in the design are the building's compactness, extremely good airtightness, a great MVHR efficiency and overnight ventilation via windows. Table 3.4 shows the characteristics of the model.

- Tokyo (subtropical warm climate), they reduced the heating demand to 14.5kWh/m^{2}a (~7% of a standard building) and the cooling demand to 7.1 kWh/m^{2}a (~68% of a standard building) using climatisation by air supply. They found that compactness had a positive aspect, as well as separating the cooling and dehumidification functions. Table 3.4 shows the characteristics of the model.

- Shanghai (subtropical warm climate), PassivHaus achieved a heating demand of 11 kWh/m^{2}K (~7% of a standard building) and cooling demand of 11.4 kWh/m^{2}K (~30% of a standard building) using climatisation by air supply. Special care is required regarding the glazing ratio as this may tend to reduce the energy demand during summer, especially south-facing windows. However, larger surfaces will increase the cooling load. Therefore, movable outdoor shading is highly recommended. Table 3.4 shows the characteristics of the model.

- Las Vegas (hot and dry climate), the model reduced the heating demand to 14.5 kWh/m^{2}a (~14% of a standard building) and cooling demand to 15.2 kWh/m^{2}a (~21% of a standard building) using climatisation by air supply. Overnight ventilation in building with higher thermal mass can reduce further the cooling demands; however, the cooling load might not be affected due to critical periods of heat because of the high outdoor temperatures. Compactness, insulated walls and ceilings affect the heating and cooling loads positively. Table 3.4 shows the characteristics of the model.

- Dubai (hot and humid climate), no heating was needed, but the cooling demands were high (37.7 kWh/m^{2}a). Using climatisation by air supply, this was ~18% less of a normal building. They noted that the airtightness and MVHR system were key factors to reduce the energy consumption and that the use of humidity recovery in the MVHR system is highly desirable due to dry outdoor conditions. Reducing the windows to the minimum required for lighting and outdoor views will result in even lower cooling demands. Compactness is not important as in colder climates. Table 3.4 shows the characteristics of the model.

- Singapore (tropical climate) was incorporated by a different study Schnieders et al. (2015). Similarly to Dubai, no heating was needed, but cooling demand was reduced to 38.5 kWh/m^{2}a using climatisation by air supply. Airtightness and MVHR system were key factors to achieve less energy consumption. Further savings can be achieved by separating the cooling and dehumidification systems. Table 3.4 shows the characteristics of the model.

The findings suggest that in extremely cold climates, the additional cost of reducing heating demand down to the PassivHaus standard would not pay for the energy savings. Contrastingly, in tropical regions with slight seasonal variations, and where no heating is needed, the annual cooling demand can be significant. The economic analysis showed that, in fact, solutions that go beyond the functional PassivHaus level (i.e. external shading) are the best economic option for tropical regions as low heating and/or cooling loads can be achieved with almost no insulation (PHI, 2011).

Table 3.4 Characteristics of the models in different climates. Adapted from (PHI, 2011; Schnieders, Feist and Rongen, 2015)

	Yekaterinburg	Tokyo	Shanghai	Las Vegas	Dubai	Singapore
Wall: U-value (kWh/m^{2}a); thickness (cm)	0.064; 50	0.202; 15	0.202; 15	0.125; 25	0.125; 25	0.20; 8
Roof: U-value (kWh/m^{2}a); thickness (cm)	0.042; 80	0.155; 20	0.155; 20	0.200; 15	0.155; 20	0.28; 15
Window frame: U-value (kWh/m^{2}a)	0.67	0.72	0.72	1.6	1.6	1.6
U-/g-value glazing	0.51; 0.52	1.19; 0.6	1.19; 0.6	1.19; 0.31	0.70; 0.25	1.10; 0.23
Shading	None	Movable	Movable	None	Immovable	Immovable
Airtightness (n_{50}, h^{-1} @50Pa)	0.3	0.5	0.5	0.5	0.5	0.5
MVHR efficiency (%)	92	85	85	85	85	85
Humidity ratio of ventilation	0.60	0	0.6	0.8	0.8	0.8
Hear recovery bypass	None	Controlled	None	Controlled	None	None
Overnight ventilation via windows	Yes	No	No	Yes	Yes	No
Climatisation via air supply	Yes*	Yes	Yes	Yes	Yes	Yes
Operation of cooling	No	Continuous	Continuous	Cycling	Continuous	Continuous
Humidity control for cooling	No	Yes	Yes	No	Yes	Yes
* Plus bathroom radiators						

Passive House Regions with Renewable Energies (PassREg) was an EU project with the aim of implementing nZEB in Europe. It tested the use of renewable energy produced on site in PassivHaus buildings with the vision to make the building operationally zero-energy on an annual basis. The secondary objectives were to make PassivHaus components more accessible, improve training materials and boost the market with sustainable products and technologies (Hopfe and McLeod, 2015). Ten European countries participated in this project, which led to the new PassivHaus certifications (PassivHaus Premium, Plus and Classic) (PHI, 2015a).

The project centred its attention on incorporating renewable energies into the buildings, and so a guide was developed summarising the experiences of each country, which would, in turn, help local decision-makers implement PassREg solutions, set the best practice and solutions for each country and the incorporate renewable energies into the PHPP. To achieve the desired target for nZEB in Europe, political actors, architects and tradespersons need to know about PassivHaus plus renewable energy, while suitable financial incentives for investors are needed (PHI, 2015a).

Finally, the EuroPHit project aimed to demonstrate step-by-step refurbishment using PassivHaus principles so that existing buildings could also meet the European target for nZEB buildings by 2020. This resulted in the PHit certifications (Premium, Plus and Classic), which offer solutions for thermal protection for existing buildings. The minimum standards for all energy-relevant building components and energy demands are slightly higher than those for new PassivHaus buildings, as existing structures have residual thermal bridges and other prevailing problems. The process for retrofitting is explained in detail in (PHI, 2016).

3.4 Indoor air quality: what is it?

Several definitions of "*acceptable/healthy IAQ*" have been suggested over the years, and these have evolved as our understanding of indoor air has expanded. In the past, healthy IAQ was linked to outdoor air, building design and indoor pollution control (WHO, 1991). There was an accepted belief that clean outdoor air secured a healthy indoor air environment (WHO, 1991) and that human bio-effluents were the most significant indoor pollutants (Mølhave *et al.*, 1997). These assumptions might be still applicable today; however, we now understand that the quality of the air is far more complex than these simple aspects.

The number of airborne contaminants and air pollution sources found indoors is considerable, and yet very few of them have been adequately characterised (Katsouyanni *et al.*, 2004). For instance, over 900 different pollutants, ultrafine particles and biological materials identified in building fabrics (SCHER, 2007) are present in the air we breathe (Jacobs, Kelly and Sobolewski, 2007). Porteous *et al.*, (2014) that occupant activities such as passive indoor drying has the potential to impact IAQ, they suggest that moisture levels are likely to boost dust mite populations and airborne mould spores. Jacobs (2007, p.p. 977) defined indoor air pollution as "*[…] chemical, physical or biological contaminants in the breathable air inside a habitable structure […]*" with the potential to harm the well-being of its occupants. Therefore, an IAQ definition should take into consideration the health and comfort of occupants. For instance, appropriate IAQ is defined by Rosseau (2001, p.p. A-3) as the "*absence of air contaminants which may impair the comfort on health of building occupants*," though the author recognises that air free from all contaminants is difficult to achieve, but it should nevertheless be understood as "*the absence of pollutants which can affect the health of typical occupants.*" The American Society of Heating, Refrigeration and Air-cooling

Engineers' (ASHRAE 2007, p.3) definition of acceptable IAQ is a more suitable one for high-occupancy buildings:

> *"[…] air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with a substantial majority (80% or more) of the people exposed do not express dissatisfaction."*

3.4.1 Health effects of indoor air pollutants

Given the broad range of indoor pollutants and their sources, greater understanding of their effect on human health is valuable. Indoor air pollution has been classified as a threat to human health (Berglund *et al.*, 1992) and a disease burden (Smith and Mehta, 2003) as part of the WHO Global Burden of Disease Comparative Risk Assessment. There is a concern about emissions from building materials, furniture and chemical consumer products used indoors (Jacobs, Kelly and Sobolewski, 2007) and occupant behaviours (Porteous *et al.*, 2014) that have been observed in modern buildings (Zhang and Smith, 2003). It is vital, therefore, to comprehend the concentration, duration and frequency of exposure to certain pollutants (Jones, 1999), in order to explain the impact on health and its association with the prevalence of illnesses. Unfortunately, health risks associated with indoor air pollution have not received adequate attention from building designers.

The following section addresses the IAQ parameters investigated in this study. This review is not intended to be exhaustive, but it does seek to explain why particular parameters were selected and to discuss the benchmarks used for this work. There is, however, detailed literature on understanding the effect of indoor air pollutants on human health (See for example Berglund et al., 1992; Federal-Provincial Advisory Committee on Environmental and Occupational Health, 1989; Katsouyanni et al., 2004; Samet, 1993; Uhde and Salthammer, 2007; WHO, 2010, 2000; World Health Organization Europe, 2009). For information about IAQ in homes, see CIBSE (2011), and for ventilation, see Wargocki (2016).

3.4.2 Indoor air quality parameters

Standard protocols to measure IAQ in homes are limited, however, there are some that have been developed for office buildings such as CIBSE KS17 (CIBSE, 2011) and EPA Protocol for characterising IAQ in Large Office Buildings (EPA, 2003); there is also the WELL Building Standard (International Well Building Institute, 2019) which focuses on commercial and institutional buildings. Each of the standards contemplate different factors on their routines for IAQ assessment, however, the three of contemplate the physical measurement of θ_{air}, relative humidity, total volatile organic compounds, carbon dioxide, carbon monoxide and particulate matter (2.5µm and 10µm, Table 3.5). Whereas these routines are used to evaluate physical IAQ factors, others such as the BUS Methodology (Leaman, 2011), the Questionnaire for Studies of Sick Building Syndrome (Raw, 1995), CBE survey (Zagreus *et al.*, 2004), SCATs (Mccartney and Nicol, 2002) and HOPE (Bluyssen, Aries and Dommelen, 2011) are used to investigate occupant perception of the indoor environment quality with dedicated sections for thermal comfort and IAQ.

Table 3.5 Summary of measured factors for routine IAQ assessment compared to those measured by low-cost monitors. Based on (EPA, 2003; CIBSE, 2011; International Well Building Institute, 2019).

Factor	CIBSE KS17			WELL standard	EPA	Low-cost monitors (commercial)
	Always	Additional	If applicable			
Air temperature (θ_{air})	●			●	●	●
Operative temperature (θ_{op})		●		●		
Radiant temperature (θ_r)		●				
Daily temperature rise		●				
Relative Humidity (ϕ)	●			●	●	●
Mean air speed (v)			●			
Air turbulence intensity			●			
tVOC	●			●	●	●
Main individual VOC	●				●	
Formaldehyde	●			●	●	
Aldehydes			●			
Methane			●			
Nitrogen dioxide			●	●		
Carbon dioxide	●			●	●	●
Carbon monoxide	●		●	●	●	
Ozone			●	●		
Radon			●	●	●	
Particulate matter 2.5µm		●		●	●	●
Particulate matter 10µm		●		●	●	
Fungi and bacteria		●			●	
Asbestos			●			

3.4.2.1 Temperature

Even though the aim of this study is not primarily to investigate thermal comfort, indoor temperatures were measured, because while temperature is not a pollutant per se, it may have an exacerbating impact on indoor material emission rates (Haghighat and De Bellis, 1998), perceptions of IAQ (Fang, Clausen and Fanger, 1998) and health in terms temperature extremes (Neill and Ebi, 2009). Studies have demonstrated that comfort diminishes with high temperatures, causing especially sleep disturbance and thereby resulting in reduced productivity, diminished attentiveness and impaired judgement (Peacock, Jenkins and Kane, 2010). Problems surrounding overheating in low-energy dwellings have been measured (McGill *et al.*, 2016) and contextualised with regard to IAQ measurements (McGill et al. 2015).

One of the most accepted definitions of overheating is "*[…] the phenomenon of excessive or prolonged high temperatures in the home, resulting from internal or external heat gains, which may have adverse effects on the comfort, health or productivity of the occupants*" (Zero Carbon Hub, 2015, p. 11). Different criteria are utilised to assess the risk of overheating, either through static or dynamic values, as explained below. However, there is no universal definition under which overheating can be said to occur (Zero Carbon Hub, 2012), and neither has an accepted standard for the domestic sector been established (Zero Carbon Hub, 2012, 2015). A new method to standardise the assessment of overheating, the CIBSE TM59, based on the CIBSE Guide A and CIBSE TM52 criteria (described below) as the main criteria for overheating, was presented in 2017. The TM59 states that dynamic simulation of the building construction and shading provision should be modelled as proposed using hourly intervals. Additionally, standard occupancy profiles, ventilation assumptions, window operation are proposed and assessed with the TM52 criteria. However, "[…]*real proof will come in future when the units tested are built and occupied* (Bonfigli *et al.*, 2017, p. 1)." Whereas virtual simulations were out of the aims of this study, the overheating frequency was assessed following the TM52 criteria as described below.

Overheating is not just a function of high temperature, as there are other factors involved (Nicol, 2004), especially in buildings without mechanical cooling (Nicol and Humphreys, 2002). The adaptive approach, as explained by CIBSE Guide A

Section 1.6, takes into consideration the outdoor temperatures of previous days and therefore is considered a dynamic benchmark. The Chartered Institute of Building Service Engineers (CIBSE) criterion is calculated according to the maximum/minimum acceptable operative temperature (θ_{ap}) and the daily mean outdoor air temperature (θ_{ao}) range from the (CIBSE, 2013) TM52 category II (normal expectation for new buildings and renovations):

- $\boldsymbol{Upper\ limit}: \boldsymbol{T_{max} = 0.33T_{rm} + 18.8 + 3}$ **Equation 3.1**
- $\boldsymbol{Lower\ limit}: \boldsymbol{T_{min} = 0.33T_{rm} + 18.8 - 3}$ **Equation 3.2**

where T_{min} and T_{max} represent θ_{ao} and T_{rm} the θ_{ao}.

The adaptive approach uses exponentially-weighted outdoor running mean temperatures (T_{rm}) during the monitoring period as a way to define the acceptable temperature range. T_{rm} is calculated from the following equations:

$$\boldsymbol{T_{rm} = (T_{od-1} + T_{od-2} + T_{od-3} + T_{od-4} + T_{od-5} + T_{od-6} + T_{od-7})/3.8}$$ **Equation 3.3**

$$\boldsymbol{T_{rm} = (1 - \alpha)T_{od-1} + \alpha T_{rm-1}}$$ **Equation 3.4**

where T_{od-1} represents the daily mean θ_{ao} for the previous day, T_{od-2} the day before and so on, T_{rm-1} is the exponentially-weighted running mean for the previous day and constant α is 0.8.

The adaptive method presented in the TM52 characterises overheating in a building or room when it fails any two of the following criteria:

- **Hours of exceedance.** This criterion sets a limit for the number of hours that the θ_{op} can exceed the threshold comfort temperature. Therefore, it refers to the temperature difference between the θ_{op} and the maximum acceptable temperature (ΔT). This value should not be greater than or equal to 1°C during the non-heating season (May to September) for any more than 3% of the occupied hours of this period.

- **Daily weighted exceedance.** This criterion refers to the severity of overheating within any one day, which is as important as the frequency of overheating. The criterion is passed when the daily limit for weighted exceedance (W_e) during occupied hours is less than or equal to the daily limit. W_e is calculated using the following equations:

$W_e = \sum(h_e \times WF)$ **Equation 3.5**

$\therefore W_e = (h_e \times 0) + (h_{e1} \times 1) + (h_{e2} \times 2) + (h_{e3} \times 3)$ **Equation 3.6**

- **Upper-temperature limit** refers to the maximum daily indoor θ_{op} for a room/building. Hence, ΔT should not exceed 4°C at any time.

Other overheating methods are based on static benchmarks. The PHI set a benchmark for overheating at θ_{op} of 25°C for more than 10% of the year (Bere, 2013; Hopfe and McLeod, 2015). Other work by CIBSE sets overheating criteria based on θ_{op} at 25°C in living areas and 23°C in bedrooms at no more than 5% of the occupied hours, and the other benchmark is set at no more than 1% of the annual occupied hours over θ_{op} of 28°C for living areas and 26°C for bedrooms (CIBSE *et al.*, 2006). Although factors such as air speed, θ_{air} and θ_r are used to estimate the θ_{op}, for practical purposes θ_{air} can be used to assess overheating (Dengel *et al.*, 2016). Similarily, the EN 15251:2007 (CEN EN, 2008) and CIBSE TM52 (CIBSE, 2013) standards state θ_{op} should be measured with a globe thermometer, otherwise θ_{air} can be used in long-term measurements. Therefore, in this study θ_{air} is used to perform overheating assessments. Due to the different overheating benchmarks, no specific temperature threshold was stipulated in this study, but an assessment of the dynamic and static benchmarks is presented.

3.4.2.2 Relative humidity and absolute humidity

In IAQ studies, relative humidity help to identify the risk of mould growth, dampness or the proliferation of house dust mites and other invertebrates. Moreover, relative humidity has an impact on indoor material emission rates (Haghighat and De Bellis, 1998) and the perceptions of IAQ (Fang, Clausen and Fanger, 1998) in a manner similar to temperature. Relative humidity is the "*[…] ratio of water vapour pressure to the saturation of water pressure (over water) at a gas temperature*" (Vaisala Oyj, 2013, p. 3).

Usually, IAQ should be "dry and cool" for material emission (VOCs, ozone and particulate) testing (Wolkoff and Kjærgaard, 2007) in climatic chambers, but in real-life situations, building occupants may develop symptoms of irritation. Recent studies have determined that low indoor relative humidity levels may cause some Sick Building Syndrome symptoms (SBS), such as eye irritation, dry skin and mucosal irritation (Doty *et al.*, 2004). For instance, relative humidity below 20%RH has been associated with eye irritations and dry skin (Arundel *et al.*, 1986), and levels below 30%RH may produce respiratory ailments as a consequence of dry mucous membranes (Burton, 1962). Additionally, Sunwoo et al. (2006) indicate that 40%RH is healthier than 30%RH for eyes and upper airways.

Elevated levels of relative humidity are related to mould growth, allergenic mites and fungi, as well as concentrations of formaldehyde, sulphur, nitrogen dioxide acids and salts in the air (Arundel *et al.*, 1986). Berglund et al. (1992) suggest that the risk of mould growth increases in levels above 70%RH, although laboratory studies indicate that mould growth will occur at 75-95%RH, depending on the substrate (Nielsen *et al.*, 2004; World Health Organization Europe, 2009). At normal temperatures, mould can propagate in some common building materials found in dwellings, if the internal surface humidity is 78%RH or higher (Johansson, Svensson and Ekstrand-Tobin, 2013), while according to CIBSE (2015), mould growth corresponds to indoor relative humidity levels of 70%RH.

It has been demonstrated that maintaining levels below 60%RH also helps avoid house dust mite proliferation (Wolkoff and Kjærgaard, 2007). Models such as the critical equilibrium humidity (CEH) measure for house dust mite populations (Arlian, 1981; Cunningham, 1996; de Boer and Kuller, 1997; Ucci *et al.*, 2011) and the population equilibrium humidity (Crowther *et al.*, 2006) con be used to predict the effect of house dust mite population of any combination of relative humidity and θ_{air}. Thus, it can be used to assess the likelihood of house dust mite existence in real settings. Although these models only require the input of θair and relative humidity (ϕ), they were developed taking into account different parameters such as θ_{ai}, θ_s, v, ϕ, vapour pressure and human interactions among other factors explored in detail elsewhere (Pretlove *et al.*, 2005).

The CIBSE recommends levels of 40-70%RH for home spaces, or optimally 65%RH for a comfortable temperature (CIBSE *et al.*, 2006). The United States Environmental Protection Agency (EPA) advises home users to keep relative humidity levels below 60%RH, ideally 30-50%RH (EPA, 2012). For the purpose of this study, a benchmark of 40-60%RH is used, as this is considered the most appropriate to fit with both CIBSE and EPA recommendations. However, as relative humidity levels depend on temperature, in that a high level of water vapour in the air can be found in moderate relative humidity levels (Vaisala Oyj, 2013). Absolute humidity is the measurement of water vapour in the air, regardless of temperature. When assessing the indoor environment, psychrometric charts can be used to investigate the behaviour of the air, showing the properties of the θ_{air}, relative humidity and moisture content on which one can define a comfort area. The CIBSE KS20 states that the psychrometric conditions for comfort are based on θ_{air} and relative humidity (CIBSE, 2012). Therefore, in this study uses ideal (θ_{air}=20˚C-25˚C, and ϕ=40%RH-60%RH) and extended (θ_{air}=18˚C-28˚C, and ϕ=30%RH-70%RH) psychrometric conditions for comfort for living rooms (Figure 3.2) and ideal (θ_{air}=18˚C-23˚C, and ϕ=40%RH-60%RH) and extended (θ_{air}=16˚C-25˚C, and ϕ=30%RH-70%RH) for bedrooms. The calculations for the psychrometric charts on this work were developed using the calculations described in the CIBSE Guide C (CIBSE, 2007).

Psychrometric conditions can also be used to evaluate the condensation risk using dew point temperature (θ_{dp}). If the incoming air (θ_{air}) is warm enough and enters in contact with cold surfaces (θ_s) this could cause the air to reach the θ_{dp} and condensate over the surface. Over time this moisture can cause mould, damage the building and IAQ problems.

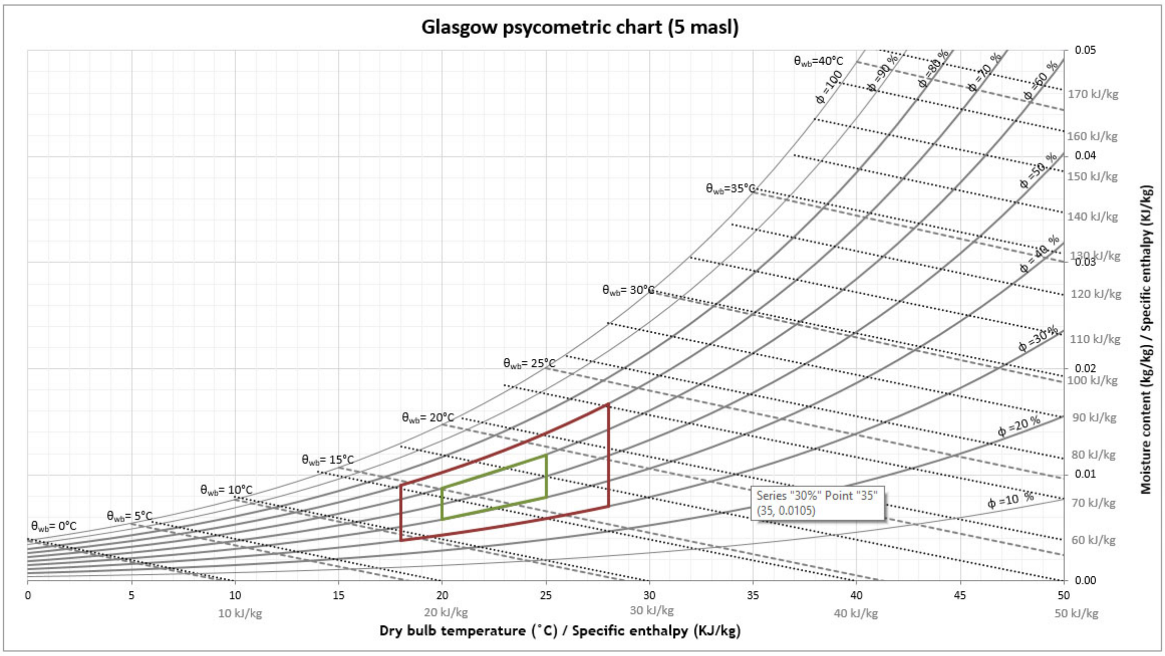


Figure 3.2 Psychrometric chart showing the comfort parameters used in this study for temperature and relative humidity.

Since the early 1980s, absolute humidity has been used as a way to assess the risk of house dust mites (Korsgaard, 1983), which are found more commonly in areas of high humidity (Murray, Ferguson and Morrison, 1985; Sears *et al.*, 1989). As explained by Korsgaard (1983) and Korsgaard & Hallas (1979), at absolute humidity levels above 7g/kg (or 1.13kPa), mite proliferation is likely to occur, while higher exposure of 100 mites/g of dust is commonly observed at 7g/kg (B. J. Hart, 1998). However, this criterion should be used with caution, as this result was obtained at a temperature ranging from 20-22°C (Arlian, 1992), which is usually found in homes. The PassivHaus standard states that humidity above 12g/kg has to be limited to 20% of the occupied time without active cooling, or 10% if active cooling is used (Brimblecombe and Rosemeier, 2017). Due to the difference in both benchmarks, an assessment of absolute humidity is presented as both 7g/kg and 12g/kg – the first one to assess the possible impact on human health and the second to assess the PassivHaus criterion.

Absolute humidity, or water pressure saturation, is calculated as follows (Vaisala Oyj, 2013):

$$A = C\left(\frac{P_w}{T+273.15}\right) \text{ (where } P_w \text{ is given in Pa)} \qquad \textbf{Equation 3.7}$$

$$P_w = (P_{ws})\left(\frac{RH}{100}\right) \text{ (where } P_w \text{ is given in hPa)} \qquad \textbf{Equation 3.8}$$

$$P_{ws} = (a)10^{\left(\frac{mT}{T+T_n}\right)} \qquad \textbf{Equation 3.9}$$

Therefore, if Equation 3.8 and Equation 3.9 are substituted in Equation 3.7:

$$A = C\left(\frac{\left((a)10^{\left(\frac{mT}{T+T_n}\right)}\right)\left(\frac{RH}{100}\right)}{T+273.15}\right) \qquad \textbf{Equation 3.10}$$

Where:

A	=	Absolute humidity
P_w	=	Water vapour pressure (Pa)
C	=	Constant 2.16679gK/J
T	=	Air temperature (θ_{air}, °C)

P_{ws} = Water saturation vapour pressure (hPa)

RH = Relative humidity (%RH)

a = Constant 6.116441 for temperatures between -20°C and 50°C

m = Constant 7.591386 for temperatures between -20°C and 50°C

T_n = Constant 240.7263 for temperatures between -20°C and 50°C

3.4.2.3 Carbon dioxide

Levels of CO_2 correlate with pollution related to human occupancy, but they may be disassociated from other sources of pollution, such as off-gassing from building materials. Levels of CO_2 are commonly used as indicators of ventilation (Porteous, 2011) and IAQ (Curwell, March and Venables, 1990). However, CO_2 itself is not considered an indoor air pollutant (Satish *et al.*, 2012) despite adverse impacts on human well-being and productivity being observed (Kajtar *et al.*, 2006). A frequent practice is to use CO_2 as an indicator of ventilation rates (Wargocki, 2013), and levels below 1,000ppm are associated with adequate solutions in this regard (Porteous, 2011) as human bio-effluents were considered the most significant pollutant of indoor air (Mølhave *et al.*, 1997). CO_2 levels are often used as an indicator of IAQ levels (Persily, 1996, 1997). This practice is still present today, especially when investigating crowded living environments (Wang *et al.*, 2017). However, studies have now demonstrated that several parameters influence CO_2, i.e. its disposal, building openings and heat (Steiger, Hellwing and Junker, 2008). Therefore, a more sensible practice is to use CO_2 as a metric of outdoor air ventilation (Sundell *et al.*, 2011).

Porteous (2011) found that CO_2 concentrations above 1,000ppm are related to poor ventilation, which corresponds with a ventilation rate of 8l/s (28.8m^3/h, Appleby, 1990) in residential buildings. Indoor CO_2 concentrations above 700ppm of the outdoor level are considered as acceptable indoor concentrations (ASHRAE, 2007), but this is based on the assumption that outdoor CO_2 levels are indeed acceptable (typically 300-500ppm). Controlled ventilation is necessary to meet this target, especially in low-energy buildings with high levels of airtightness (SCHER, 2007). The EN 13779:2007 (CEN EN, 2007a) classifies the quality of indoor air in occupied zones based on four IDA categories depending on the CO_2 above the outdoor air and recommended outdoor air rates (Table 3.6). Normal outdoor

CO2 levels can reach 400ppm (CEN EN, 2007a; CIBSE *et al.*, 2015); although, in city centres, 500ppm is a more realistic assumption (CIBSE *et al.*, 2015; CIBSE, 2016). Using the IDA 2 values and 500ppm, as the outdoor baseline, would result in CO_2 levels between 900-1,100ppm (1,000ppm default value) for indoor spaces.

Table 3.6 IDA categories based on the EN 13779:2007.

Category	CO_2 levels above of outdoor air (ppm)		Rate of outdoor air per person (m^3/h)			
			Non-smoking areas		Smoking areas	
	Typical range	Default value	Typical range	Default value	Typical range	Default value
IDA 1 (high IAQ)	≤400	350	>54	72	>108	144
IDA 2 (medium IAQ)	400-600	500	36-54	45	72-108	95
IDA 3 (moderate IAQ)	600-1,000	800	21.6-36	28.8	43.2-72	57.6
IDA 4 (low IAQ)	>1,000	1,200	<21.6	18	<43.2	36

The 1,000ppm benchmark is supported by associations between CO_2 levels, ventilation rates and impacts on health. Ventilation rates of 10l/s (36m^3/h) per person may be effective in reducing the prevalence of SBS and occupant dissatisfaction with IAQ (Godish *et al.*, 1996). Wargocki (2016, p. 114) states that "*ventilation rate in homes is associated with health in particular with asthma, allergy, airway obstruction and SBS symptoms […] ventilation rates above 0.4h^{-1} or CO_2 below 900ppm in homes seem to protect against health risk.*" For the purpose of this study, the CO_2 threshold is classed as 1,000ppm as no outdoor measurements were possible.

3.4.2.4 Particulate matter 2.5µm

'Particulate matter 2.5' ($PM_{2.5}$) is a term used to refer to ultrafine particles or droplets that are 2.5µm or less in diameter. Their composition varies, but it includes materials referred to as dust, smoke, soot (AQEG, 2012), mineral ash dispersed into the atmosphere (i.e. coal, oil ash, metal oxides, calcium carbonate, sodium, chlorides, pollen, mould spores) and other airborne matter (i.e. hair, fur, fleece, vegetable fibres, such as cotton, flax and hemp) and silicate materials (i.e. zeolites, sepiolite clays), textile fibres (i.e. nylon, polypropylene, glass and ceramic, silicates, asbestos, Crump *et al.*, 2002). The impact of airborne particulate matter on human health is linked directly to the size of the particles (Harrison *et al.*, 2010). Continuous exposure to $PM_{2.5}$ may impair people's health, in that respiratory disease outcomes correlate significantly with exposure to $PM_{2.5}$ concentrations (Harrison *et al.*, 2010).

The literature indicates that $PM_{2.5}$ is suspected of causing cataracts, irritation, reddened eyes, runny noses and respiratory irritations, cancer, cardiovascular problems (Mott *et al.*, 1997; Bruce, Perez-Padilla and Albalak, 2000; Secretaria de Salud, 2014; Bernnan, 2015) and hypertension (Holguín *et al.*, 2003). Moreover, $PM_{2.5}$ can penetrate deep into the human respiratory system, thereby causing increases in hospital admissions and premature deaths (WHO, 2000).

As concern for the effects of $PM_{2.5}$ on human health increases (Kampa and Castanas, 2008), especially in the case of residential buildings (Crump, Dengel and Swainson, 2009), different thresholds have been set for its exposure. For instance, Laxen et al. (2010) suggest that there is currently no safe level in the short or the long term. Daily average exposure recommendations might be as low as 8µg/m^3 (Environment *et al.*, 2003) or as high as 25µg/m^3 (Commission, 2015), but there is a general consensus that levels above 25µg/m^3 are considered harmful to human health (WHO, 2000). For this reason, this study sets the $PM_{2.5}$ exposure benchmark at 25µg/m^3 over 24 hours (10µg/m^3 per year).

3.4.2.5 Total Volatile Organic Compounds

Volatile organic compounds are a large, diverse and ubiquitous group of compounds that will vaporise at room temperature. The indoor VOC mixture is often known as 'total volatile organic compounds' (tVOCs), which the WHO classes as organic compounds with a boiling point of 20-100°C to 240-260°C (WHO, 1989). In the past, VOCs were difficult to consider separately as human health hazards, but their effects on health were studied as a mixture (tVOC, WHO, 1997). Therefore, studies made associations between health and the temporary exposition of tVOC (Molhave, Jensen and Larsen, 1991), as well as their severity (Molhave, 1991). Nowadays, individual VOCs, such as formaldehyde and benzene, are associated with significant health risks (WHO, 2010), and guidelines have been developed to target specific VOCs instead of tVOCs (Berglund *et al.*, 1997; Mølhave *et al.*, 1997; Teichman and Howard-reed, 2016).

Exposure to VOCs can lead to acute and chronic health effects (Maroni, Seifert and Lindvall, 1995), such as respiratory conditions, neurotoxicity, lung cancer and eye and throat irritation (Hodgson *et al.*, 1991; Molhave, 1991; Molhave, Jensen and Larsen, 1991; Maroni, Seifert and Lindvall, 1995; Mølhave *et al.*, 1997). Neurological impacts include fatigue, headaches, dizziness, nausea, lethargy and depression (Guo *et al.*, 2004). The WHO has published guidance for safe levels of individual VOCs (see (WHO, 2000, 2010), and for a detailed list of individual VOC exposure limits, see CIBSE (2011) and Health and Safety Executive (2011)). There are different guidelines for tVOC concentrations in non-industrial environments, from 25µg/m^3 (Berglund *et al.*, 1997) up to 500µg/m^3 (Delia, 2012); however, there is a general acceptance that 300µg/m^3 over an 8-hour period should be adopted as a maximum level (ECA, 1992), which equates to UK guidelines (HM Government, 2013).

TVOC concentrations are usually higher in new buildings, as they emanate from construction materials as well as building contents (Brown *et al.*, 1994). Indoor organic compounds are released from a variety of building materials (vinyl tiles, coving, carpets, linoleum, particleboard and power cables) and construction consumer products (paints, paint thinners, paint strippers, adhesives, caulks and cleaners), but they are also related to human activities (frying food, smoking, dry-cleaned clothing, deodorisers, showering, moulds, pesticides and personal care products (Zhang and Smith, 2003)).

To convert tVOC concentrations from ppb to µg/m^3, the following formula is used:

$$Concentration\ (\mu g/m^3) = Concentration\ (ppb) \times \frac{Molecular\ mass\ (g/mol)}{Molecular\ Volume\ (L)}$$

Equation 3.11

where molecular volume is 24.45 L (assumptions @ 1atm and 25°C).

Molecular mass for tVOC is variable (40-150g/mol) according to the composition, but a value of 40g/mol was used for purposes of conversion, as assumed in experiments by Khan and Ghoshal (2000).

3.4.2.6 IAQ benchmarks summary

A comprehensive method to assess IAQ requires addressing building products and furnishing emissions evolving beyond the current CO_2 approach; this requires a list of target pollutants associated with concentration guidelines (Emmerich and Persily, 2011). A summary of the assessment of IAQ guidelines used in this study is presented in Table 3.7.

Table 3.7 Summary of the IEQ and IAQ thresholds used in this study.

IAQ factor	Benchmark	
	Range/Concentration	Exposure
Temperature static factors		
PassivHaus	25°C	10% of the year
CIBSE A	23°C (bedroom), 25°C (living areas)	5% of annual occupied hours
CIBSE B	26°C (bedroom), 28°C (living areas)	1% of annual occupied hours
Temperature dynamic factor		
CIBSE	T_{max} = 0.33 T_{rm} + 18.8 + 3 T_{min} = 0.33 T_{rm} + 18.8 – 3 T_{rm} = (T_{od-1} + 0.8 T_{od-2} +0.6 T_{od-3} +0.5 T_{od-4} +0.4 T_{od-5} +0.3 T_{od-6} +0.2 T_{od-7})/3.8	C1: $\Delta T \leq 1$°C @ <1% of the time C2: $W_e = \Sigma(h_e \times WF)$; $W_e \leq 10.5$ C3: $\Delta T \leq 4$°C at any time
Relative humidity	40-60%RH @ 18-23°C (bedroom) 20 -25°C (living areas)	Ideal limit
	30-70%RH @ 16-25°C (bedroom) 18 -28°C (living areas)	Extended limit
Absolute humidity	7g/kg (8.42g/m^3) and 12g/kg (14.44g/m^3)	20% of occupied hours (for the 12g/kg)
Carbon dioxide	1,000ppm	
$PM_{2.5}$		
$PM_{2.5}$	25µm/m^3	24 hours mean
$PM_{2.5}$	10µm/m^3	1 year mean
tVOC	300µg/m^3	8 hours mean

3.5 Indoor air pollution: where does it come from?

As homes adopted higher standards of insulation, airtightness and ventilation to reduce energy consumption and heat losses, the outdoor-indoor air exchange decreased. The combination of low ventilation rates and the increased use of chemicals and synthetic building materials has resulted in elevated concentrations of chemical emissions, such as VOCs and human bio-effluents (Zhang and Smith, 2003). In buildings, contaminant emissions are varied in their sources, which are often affected by ventilation and other dynamic interactions (Godish *et al.*, 1996). Perhaps the most effective way to control and reduce indoor pollution is to control these sources (Fanger, 2006). Therefore, once the health risk has been identified, it is a fundamental requirement to identify them accordingly. Sundell (2004) suggests that building factors that may impact on IAQ are dampness, ventilation, building materials and indoor air chemistry. However, "*…we 'know' that building characteristics such as 'dampness', a low ventilation rate and certain building (furnishing) materials are important, but we really do not know how, or why*" (Sundell, 2004, p. 57). The following paragraphs are dedicated to providing a general overview of where "we" believe pollution originates.

3.5.1 Sources of indoor air pollution

There is an extensive collection of scientific literature on sources of air pollution ("Air Pollution in Mexico City, Facts and Stats," 2011; Bruce et al., 2000; Champion et al., 2015; Coward et al., 2001; Crump et al., 2009, 2002; Dimitroulopoulou et al., 2005; Guardino Solá, 1998; Holguín et al., 2003; Mott et al., 1997; Rojas, 2014; WHO, 2010, 2000; Yip and Madl, 2000). Airborne contaminants often include combustion products, allergens, volatile organic compounds, tobacco smoke and gases from building materials, furnishing, cleaning and personal care products (Jacobs, Kelly and Sobolewski, 2007). A summary of sources and emissions is provided in Table 3.8.

According to Maroni et al. (1995) the concentration of airborne contaminants depends on:

- the volume of air contained in the indoor space
- the rate of production or release of the pollutant
- the rate of removal of the pollutant
- the rate of exchange with the outside atmosphere
- outdoor pollutant concentration.

- **Table 3.8 Sources and emissions of air pollution. Adapted from Crump et al. (2009) and Spengler and Sexton (1987).**

Sources	**Emission**
Building materials and elements	
Fire retardants	Asbestos
Insulation	Asbestos, formaldehyde
Boilers	Carbon monoxide
Stoves	Carbon monoxide
Gas or kerosene heaters	Carbon monoxide
Particleboard and plywood	Formaldehyde
Furnishing	Formaldehyde
Air conditioning systems	Micro-organisms
Adhesives and solvents	Volatile organic compounds
Paint	Volatile organic compounds
Building materials (concrete, stone)	Volatile organic compounds, radon
Internal surfaces	Fungal spores
Human-related (activities and occupants)	
Respiration	Carbon dioxide
Combustion (cooking, fireplace)	Carbon dioxide, volatile organic compounds, particulates.
Fuel burning	Carbon monoxide, nitrogen dioxide, polycyclic aromatic hydrocarbons, sulphur dioxide
Tobacco smoke	Carbon monoxide, volatile organic compounds, particulates, polycyclic aromatic hydrocarbons
People	Micro-organisms
House Dust	Allergens
Domestic animals	Allergens, micro-organisms
Cleaning products	Volatile organic compounds
Outdoors	
Motor vehicles (in garages)	Carbon dioxide, nitrogen dioxide
Outdoor air	Biological particles, benzene, nitrogen dioxide, particulates, pollens, sulphur dioxide
Trees, grass, weeds and plants	Pollens, fungal spores
Soil	Radon, fungal spores

3.5.1.1 Outdoor pollution as an IAQ problem

Previous studies that associate health impacts to air quality have focused on ambient pollution (Bruce, Perez-Padilla and Albalak, 2000), and yet not adequately addressed (Zhou, Li and Wang, 2018), with little attention to indoor pollutants exposure and their impact on health. Of great importance to this study is the urban air pollution, which is related to fossil fuels' combustion for transport, power generation and other human activities. The characteristics of its composition in a specific location depend on relative contribution of human activities, technologies and the geo-climatic factors (Cohen *et al.*, 2004), but the most common pollutants are SO_2, NO_x, CO, O_3, PB, benzenes, $PM_{2.5}$ and PM_{10} (Amato *et al.*, 2010). These depend on the land use, population density and traffic patterns (Wang *et al.*, 2013), especially in developing cities where it is common to observe separation of housing, employment, leisure and services.

Outdoor air pollution plays a major health challenge in modern societies, and has been linked to cancer (Cohen, 2000), asthma (Guarnieri and Balmes, 2014), stroke and heart disease (Brook *et al.*, 2010), diabetes (Eze *et al.*, 2015), obesity (Weichenthal, Hoppin and Reeves, 2014) and changes linked to dementia (Chen *et al.*, 2017). These effects occur across a lifetime, especially to vulnerable populations (babies, children and older people) or simply to people living in deprived areas or near busy roads. However, the effects of air pollution are also related to climate change, placing the food, air and water supplies at risk (Royal College of Physicians, 2016). As a response to the Royal College of Physicians Report in 2016, recognition of air pollution has increased, as has the need for action at local and national levels. However, immediate actions have yet to materialise (Royal College of Physicians, 2018). The report calls for new and more ambitious targets for reduction in air pollution, a framework for introducing 'clean air zones', incentives for zero emissions transport, and increase investment for 'active transport', which should help address the growing concern of air pollution in cities. While we find the best solution to address ambient air pollution and reduce contaminants levels, the need for ventilating our homes is still present. Some mechanical ventilation systems offer air filtration, but the association of fresh air with outdoor air is a deep belief in modern societies. Moreover, natural ventilation in polluted environments may lead to ingress of ambient air pollution indoors exacerbating IAQ problems.

3.6 Indoor air quality in PassivHaus dwellings

New buildings, regardless of whether or not they are PassivHaus, are expected to improve energy efficiency without jeopardising indoor environmental quality. Nonetheless, high-performance buildings should provide better indoor environment (thermal comfort, IAQ, noise, among others) than conventional buildings. While energy consumption is an important aspect of abodes, other aspects such as health, comfort and occupant satisfaction are less well known (Fanger, 2000; Emmerich and Persily, 2011). Although the indoor environment in

PassivHaus has been addressed in many studies, most of this work tends to focus on offices or educational buildings (Eicker, 2010; Cablé, Hammer and Mysen, 2016) with very little focus on IAQ (Wang *et al.*, 2017). Additionally, very little has been done to investigate the interaction between energy efficiency and indoor environmental quality in PassivHaus applications (Wang *et al.*, 2017), particularly IAQ in dwellings. The effect of energy-efficient homes on human health and well-being remains under-researched (Crump, Dengel and Swainson, 2009; Sullivan *et al.*, 2013).

Mendell (2013) suggests that further studies in low-energy homes should focus on IAQ, comparing buildings as alike as possible but excluding energy-related factors. This may help understand further some of the design strategies in PassivHaus dwellings – reduced ventilation rates (Seppänen and Fisk, 2004; Wargocki, 2013), airtightness and the use of mechanical ventilation (Yu and Crump, 2010) might have an adverse impact on IAQ, especially when combined with high levels of pollution (Uhde and Salthammer, 2007; Bernstein *et al.*, 2008).

Studies that look at IAQ in PassivHaus dwellings tend to use CO_2 levels as an indicator of IAQ, but very few of these address other air pollutants. The author identified Thirty-five studies examining IAQ in PassivHaus dwellings, and they either examined occupants' perceptions through building user surveys, indoor air contaminant concentrations via physical IAQ measurement or virtual simulations of indoor pollution (Table 3.9 part 1-3). Other journal publications based on a literature review as a research method, such as Berge and Mathisen (2015), Sabouri and Femenias (2012) and Wang et al. (2017), were not included but scrutinised to expand the sources.

Building systems not only help to achieve low-energy consumption, but they should also provide favourable IAQ and healthier environments. To achieve these aims, it is critical to adhere to best practices in terms of design through to construction and even occupant education (Kovesi *et al.*, 2009; Weichenthal *et al.*, 2013). Yet, other simulations and field research have adverse results (Emmerich *et al.*, 2005; Milner *et al.*, 2014; Wilson *et al.*, 2014), and perhaps the most significant challenge for energy-efficient buildings related to IAQ are these kinds of contradictory findings.

Table 3.9 Part 1. Publications about IAQ in PassivHaus dwellings. Black marks refer to studies that collected data through building user surveys or physical IAQ monitoring, while those in red used virtual simulation.

				Purpose of the study					Data collection																Duration					Energy efficiency			Type of building				
									Building User Survey						Environmental/air pollutants measurements											Seasons											
	Study	Country	Climate	Energy	Thermal comfort	IAQ	Other comfort aspects	Other*	Satisfaction	Well-being	Thermal comfort	IAQ	Other environmental comfort	Other**	Temperature***	Relative Humidity***	Absolute humidity***	CO2***	PM2.5***	tVOC***	Individual VOC***	Other****	Outdoor data	Computer simulations	Temporality	Winter	Spring	Summer	Autumn	PassivHaus	Other low-energy building	Conventional building	Dwellings	Offices	Educational	Other	Number of buildings/units
1.	(Beamer *et al.*, 2003)	USA	Not specified	•	•	•		•			•	•		•	•	•		•				•	•		1w	•				•			•				6
2.	(Brunsgaard *et al.*, 2012)	Denmark	Temperate		•	•	•				•	•	•		•	•		•				•			3y	•	•	•	•	•			•				3
3.	(Cablé, Hammer and Mysen, 2016)	Norway	Cold		•	•				•	•	•		•	•			•							3d	•	•			•					•		1
4.	(Dan *et al.*, 2016)	Romania	Temperate	•				•							+	+		+				•			2y	•	•	•	•	•			•				1
5.	(Derbez *et al.*, 2014)	France	Continental Oceanic Mediterranean		•	•									•	•		•	•	•	•	•			2w†	•		•		1	2	4	•				7
6.	(Eicker, 2010)	Germany	Warm/temperate	•				•							•							•			2y	•	•	•	•	•				•			1
7.	(Feist *et al.*, 2005)	Austria, France[NM], Germany, Sweden[NM], Switzerland	Cold Temperate Continental Oceanic	•	•	•		•							•	•						•			2.5y	•	•	•	•	•			•				100 + 121 NM
8.	(Figueiredo *et al.*, 2016)	Portugal	Mediterranean	•	•										•								•	•	3m	•			•	•			•				1
9.	(Firlag and Zawada, 2013)	Poland	Temperate	•	•										•							•		•	1y	•	•	•	•	•			•				1
10.	(Fischer, Langer and Ljungström, 2014)	Sweden	Oceanic		•															•	•	•	•		1w				•	•			•				1
11.	(Fokaides *et al.*, 2016)	Cyprus	Subtropical		•										•	•								•	11m	•	•	•	•	•			•				1
12.	(Foster *et al.*, 2016)	Scotland	Temperate Oceanic		•	•								•	•	•	•	•				•	•		1y					•			•				5
13.	(Georges, Berner and Mathisen, 2014)	Norway (4 locations)	Cold	•	•										•							•		•	1y	•	•	•	•	•			•				1
14.	(Guillén-Lambea, Rodríguez-Soria and Marín, 2016)	Germany, France, Spain, UK, USA	Several (2 Germany, 7 France, 12 Spain, 2 UK, 8 USA)	•				•														•		•	1y	•	•	•	•	1		•	•				6

* CO2 emissions (Beamer et al. 2003; Dan et al. 2016), life-cycle cost analysis (Dan et al. 2016), ventilation (Eicker 2010; Feist et al. 2005; Guillén-Lambea et al. 2016).
** Occupant behaviour (Beamer et al. 2003; Foster et al. 2016), occupant experiences (Beamer et al. 2003; Foster et al. 2016).
*** Highly precise and analytical monitors (scientific monitors) (•); low-cost monitors (+).
**** Building fabric data (Beamer et al. 2003; Feist et al. 2005; Foster et al. 2016) or other environmental factors (daylight, noise (Brunsgaard et al. 2012; Derbez et al. 2014)), energy consumption (Dan et al. 2016; Eicker 2010; Feist et al. 2005), solar radiation (Dan et al. 2016), energy simulation (Firlag & Zawada 2013; Georges et al. 2014; Guillén-Lambea et al. 2016), temperature simulation (Firlag & Zawada 2013; Georges et al. 2014), ventilation (Foster et al. 2016), ventilation simulation (Guillén-Lambea et al. 2016), fabric envelope simulation (Guillén-Lambea et al. 2016), Ozone, NO_2, acetaldehyde, peroxyacetyl (Fischer et al. 2014)
† Plus three weeks of pre-occupancy monitoring.
[NM] Non-monitored buildings.

Table 3.9 Part 2. Publications about IAQ in PassivHaus dwellings. Black marks refer to studies that collected data through building user surveys or physical IAQ monitoring, while those in red used virtual simulation.

	Study	Country	Climate	Purpose of the study: Energy	Purpose: Thermal comfort	Purpose: IAQ	Purpose: Other comfort aspects	Purpose: Other*	Data collection – Building User Survey: Satisfaction	BUS: Well-being	BUS: Thermal comfort	BUS: IAQ	BUS: Other environmental comfort	BUS: Other**	Environmental/air pollutants measurements: Temperature***	Env: Relative humidity***	Env: Absolute humidity***	Env: CO2***	Env: PM2.5***	Env: tVOC***	Env: Individual VOC***	Other****	Outdoor data	Computer simulations	Duration: Temporality	Seasons: Winter	Seasons: Spring	Seasons: Summer	Seasons: Autumn	Energy efficiency: PassivHaus	Energy efficiency: Other low-energy building	Energy efficiency: Conventional building	Type of building: Dwellings	Type: Offices	Type: Educational	Type: Other	Number of buildings/units
15.	(Kaunelienė *et al.*, 2016)	Lithuania	Oceanic Continental			•								•	•	•		•		•	•	•	•		7d		•	•			•		•				11
16.	(Langer *et al.*, 2015)	Sweden	Oceanic			•									•	•		•		•		•			1-2w	•			•	20	21		•				41
17.	(Langer *et al.*, 2016)	France	Temperate Continental Oceanic			•						•		•	•	•		•	•	•	•	•	•		7d	•	•	•	•	Not specified			•				56 7
18.	(Less *et al.*, 2015)	USA	Mediterranean			•		•				•		•	•	•		•	+			•	•		6d	•	•				•		•				24
19.	(Liang *et al.*, 2017)	England	Temperate maritime	•	•	•									• •(red)	•		•					• •(red)	•(red)	1y	•	•	•	•	•		•	•				2
20.	(Mahdavi and Doppelbauer, 2010)	Austria	Oceanic	•	•	•		•	•	•	•	•			•	•		•							5m	•	•	•		2	2		•				4
21.	(McGill, Oyedele and Keeffe, 2015)	England	Temperate maritime		•	•		•		•	•	•	•		•	•		•			•		•		1d	•		•		2	5		•				7
22.	(Mihai *et al.*, 2017)	Romania	Humid continental	•											• •(red)	•		•				• •(red)		•(red)	6m 1y (red)	•(red) •	•(red) •	•(red)	•(red) •	•(red)			•(red) •				1
23.	(Mlecnik *et al.*, 2012)	Netherlands	Maritime		•	•	•		•		•	•	•	•												•		•		7	83		•				90
24.	(Paliouras *et al.*, 2015)	Denmark	Temperate	•	•									•	• •(red)	• •(red)		• •(red)				• •(red)		•(red)	30d 30d (red)		•			•			•				1
25.	(Ridley *et al.*, 2013)	England	Temperate maritime	•	•		•		•		•	•		•	•	•		•				•	•		1y	•	•	•	•	•			•				1
26.	(Ridley *et al.*, 2014)	Wales	Maritime	•	•	•		•	•		•	•		•	•	•		•				•	•		2y	•	•	•	•	•			•				2
27.	(Rojas *et al.*, 2016)	Austria	Humid continental		•	•			•		•	•			•	•		•		•			•		2y†	•†		•†		18	6		•				24

* Ventilation (Ridley *et al.*, 2013, 2014; Less *et al.*, 2015), CO_2 emissions (Mahdavi and Doppelbauer, 2010; Ridley *et al.*, 2014), embodied energy (Mahdavi and Doppelbauer, 2010), construction cost (Mahdavi and Doppelbauer, 2010), noise (Mlecnik *et al.*, 2012), controllability & information (Mlecnik *et al.*, 2012), compare the PHPP predictions to the measured data (Ridley *et al.*, 2013, 2014), commissioning (Ridley *et al.*, 2013).

** Building construction characteristics (Mlecnik *et al.*, 2012; Less *et al.*, 2015; McGill, Oyedele and Keeffe, 2015; Kaunelienė *et al.*, 2016), occupant behaviour (Ridley *et al.*, 2013, 2014; Less *et al.*, 2015; McGill, Oyedele and Keeffe, 2015; Paliouras *et al.*, 2015; Kaunelienė *et al.*, 2016; Langer *et al.*, 2016), demographics (Ridley *et al.*, 2013, 2014; Less *et al.*, 2015), energy savings (Mlecnik *et al.*, 2012), information (Mlecnik *et al.*, 2012).

*** Highly precise and analytical monitors (scientific monitors) (•); low-cost monitors (+).

**** Microbiological flora (Langer *et al.*, 2015), NO, NO_2, NO_x, aldehydes, $PM_{0.1}$ (Less *et al.*, 2015) energy simulation (Paliouras *et al.*, 2015; Liang *et al.*, 2017; Mihai *et al.*, 2017), indoor environment not specified (Liang *et al.*, 2017), energy (Ridley *et al.*, 2013, 2014; Paliouras *et al.*, 2015; Liang *et al.*, 2017; Mihai *et al.*, 2017), formaldehyde (McGill, Oyedele and Keeffe, 2015), luminosity (Mihai *et al.*, 2017).

† Temperature, relative humidity and CO_2 measured two months each year, but only during winter. Temperature and relative humidity for three months during summer and winter each year.

Table 3.9 Part 3. Publications about IAQ in PassivHaus dwellings. Black marks refer to studies that collected data through building user surveys or physical IAQ monitoring, while those in red used virtual simulation.

	Study	Country	Climate	Purpose of the study					Data collection																Duration					Energy efficiency			Type of building				Number of buildings/units
									Building User Survey						Environmental/air pollutants measurements											Seasons											
				Energy	Thermal comfort	IAQ	Other comfort aspects	Other*	Satisfaction	Well-being	Thermal comfort	IAQ	Other environmental comfort	Other**	Temperature***	Relative humidity***	Absolute humidity***	CO2***	PM2.5***	tVOC***	Individual VOC***	Other****	Outdoor data	Computer simulations	Temporality	Winter	Spring	Summer	Autumn	PassivHaus	Other low-energy building	Conventional building	Dwellings	Offices	Educational	Commercial	
28.	(Schnieders, 2003)	Austria, France[NM], Germany, Sweden[NM], Switzerland	Cold Temperate Continental Oceanic	•	•	•		•	•		•	•			•	•						•			2.5y	•	•	•	•	•			•				100 + 121 [NM]
29.	(Schnieders and Hermelink, 2006)	Austria, France[NM], Germany, Sweden[NM], Switzerland	Cold Temperate Continental Oceanic	•	•	•		•	•		•	•			•	•						•			2.5y	•	•	•	•	•			•				100 + 121 [NM]
30.	(Schnieders, Feist and Rongen, 2015)	Russia Japan China USA United Arab Emirates Singapore	Cold Subtropical warm Hot and dry Tropical	•	•	•		•							•	•								•	1y	•	•	•	•	•			•			•	7
31.	(T. R. Sharpe *et al.*, 2014)	Scotland	Temperate Oceanic		•	•		•							•	•	•	•				•			7m	•	•	•	•	5	21		•				26
32.	(Thunshelle and Hauge, 2016)	Norway	Humid continental		•	•				•	•	•	•	•												•	•	•		•					•		1
33.	(Truong and Garvie, 2017)	Australia	Oceanic	•	•	•		•							•			•				•			1y	•	•	•	•	•			•				1
34.	(Tuohy, Murphy and Deveci, 2012)	Scotland	Temperate Oceanic		•	•		•							•	•		•				•	•		1y					•	•	•	•				3
35.	(Wallner *et al.*, 2015)	Austria	Oceanic			•									•	•		•		•	•	•			2y†		•	•		•	•	•	•				123
36.	(Wallner *et al.*, 2017)	Austria	Oceanic			•		•	•	•	•	•		•	•	•		•		•	•	•			2y†		•	•		•	•	•	•				123
37.	(Wang *et al.*, 2018)	China	Severe cold		•	•		•				•		•	•	•		•	•			•			5m	•				8	8		•				16

* Cost-effectiveness (Schnieders, 2003; Schnieders and Hermelink, 2006; Schnieders, Feist and Rongen, 2015), ventilation (T. R. Sharpe *et al.*, 2014), compare the PHPP predictions to the measured data (Tuohy, Murphy and Deveci, 2012), self-reported health perceptions (Wallner *et al.*, 2017).
** Building characteristics (Thunshelle and Hauge, 2016), knowledge of energy-efficient buildings (Thunshelle and Hauge, 2016), noise (Thunshelle and Hauge, 2016), demographic characteristics (Wallner *et al.*, 2017; Wang *et al.*, 2018)
*** Highly precise and analytical monitors (scientific monitors) (•); low-cost monitors (+)
**** Energy (Schnieders, 2003; Schnieders and Hermelink, 2006; Tuohy, Murphy and Deveci, 2012; Schnieders, Feist and Rongen, 2015; Truong and Garvie, 2017), airtightness (T. R. Sharpe *et al.*, 2014), operation schedules (Tuohy, Murphy and Deveci, 2012), mould spores (Wallner *et al.*, 2015, 2017), dust mite allergens (Wallner *et al.*, 2015, 2017), radon (Wallner *et al.*, 2015, 2017), air supply (Wallner *et al.*, 2015, 2017), noise (Wallner *et al.*, 2015; Wang *et al.*, 2018), air velocity, PM_{10} (Wang *et al.*, 2018).
[NM] Non-monitored buildings.
† CO_2, temperature and relative humidity only one week each year and the other parameters one spot measurement once a year.

Twenty of the thirty-seven IAQ studies in PassivHaus dwellings have been undertaken in cold, oceanic, maritime and Mediterranean weathers, mostly in European countries. Very few had been carried out on warm and humid climates and even many of those are located within continental European countries. In fact, only six of the studies were carried out in non-European countries. This demonstrates the need to address IAQ studies worldwide focusing on different climates. Table 3.9 also shows clear evidence of the need to study IAQ beyond CO_2. Eleven publications, two of which used the same dataset, collected IAQ data other than CO_2. Moreover, only six studies measured two or more IAQ parameters in addition to CO_2, and only four of these studies associated physical IAQ measurements with occupants' perceptions. Another noteworthy finding is related to the temporality of data collection, in that most of it varies from one spot measurement to two weeks of continued monitoring at 1 min, 5 min or 30 min intervals. As exposed by White (2009), the actual monitoring approaches draw conclusions from limited IAQ exposure data.

Berge and Mathisen (2015) found that MVHR systems in residential buildings, PassivHaus among them, are suitable for providing heated air, without adverse effects on comfort and health. The authors linked high satisfaction with perceived IAQ and thermal comfort to air-heating in comparison to other heating strategies, and they also determined that some limitations in planning, installation, use, maintenance or inadequate system application exist if a building's heating system is based purely on air-heating. Therefore, air-heating should be supplemented with an additional heat source in bathrooms and the possibility to adjust the temperature in the bedroom independently from other rooms. Occupants' perceptions of dry air, especially during winter, were noted as a possible weakness of this approach. Wang et al. (2017) support these findings and emphasise that energy efficiency and favourable IAQ in PassivHaus buildings, through the appropriate adjustment and optimisation of MVHR systems and sun-shading systems, is achievable.

Twenty of the thirty-five studies concluded that PassivHaus dwellings have reported acceptable levels of IAQ (Beamer *et al.*, 2003; Feist *et al.*, 2005; Mahdavi and Doppelbauer, 2010; Eicker, 2010; Tuohy, Murphy and Deveci, 2012; Ridley *et al.*, 2013; Fischer, Langer and Ljungström, 2014; Wallner *et al.*, 2015, 2017; Langer *et al.*, 2015; Less *et al.*, 2015; Cablé, Hammer and Mysen, 2016; Rojas *et* *al.*, 2016; Thunshelle and Hauge, 2016; Dan *et al.*, 2016; Fokaides *et al.*, 2016; Kaunelienė *et al.*, 2016; Mihai *et al.*, 2017; Truong and Garvie, 2017). Studies that compared PassivHaus to conventionally built dwellings found better levels of IAQ in the PassivHaus alternatives (Derbez et al. 2014; Guillén-Lambea et al. 2016; Langer et al. 2015; Mahdavi & Doppelbauer 2010; McGill et al. 2015; Rojas et al. 2016; Tuohy et al. 2012; Wallner et al. 2015; Wallner et al. 2017). However, overheating problems and dry indoor environments have also been observed (Ridley *et al.*, 2013, 2014; Figueiredo *et al.*, 2016; Fokaides *et al.*, 2016; Rojas *et al.*, 2016).

Fischer et al. (2014) measured indoor pollutants in empty, pre-occupied PassivHaus dwellings to observe indoor emissions from building materials. They found that PassivHaus' wooden building materials with air change rates of $0.5h^{-1}$ had the potential to achieve good IAQ. The quality of the indoor environment in newly built PassivHaus dwellings was compared to other new low-energy homes (Langer *et al.*, 2015). The authors found comparable or better indoor environments in PassivHaus than in other homes, especially in relation to IAQ, as buildings achieved higher air changes rates. Concentrations of formaldehyde were lower in PassivHaus, but drier environments and high tVOC levels were also observed in Langer's study. Drier environments have also been reported in other PassivHaus dwellings, especially during winter (Wallner *et al.*, 2015, 2017; Rojas *et al.*, 2016), which was associated with high temperatures (Rojas *et al.*, 2016) and the use of MVHR systems (Wallner *et al.*, 2017). Although the air has been reported as dry in Lancaster co-housing PassivHaus dwellings, the BUS surveys could not identify weather or not this was perceived negatively or positively by the occupants (Stevenson and Johnston, 2013). Simulation and laboratory studies demonstrated that pre-heated air had no adverse effects on IAQ or thermal comfort and was associated with high occupant satisfaction (Berge and Mathisen, 2015); therefore, occupant behaviour and incorrect use of the system may lead to dry environments. Feist et al. (2005) carried out a comprehensive study of over 100 PassivHaus dwellings and found comfortable temperatures and acceptable levels of CO_2 was possible with pre-heated air systems such as MVHR units.

The evidence is therefore that PassivHaus residences should achieve acceptable IAQ by following the mandatory certification criteria. However, these are affected by IAQ practices for source control, local exhausts, continuous ventilation, filtration, commissioning and occupant education (Less *et al.*, 2015). However, overall IAQ performance depends on outdoor air quality, indoor emissions, ventilation (design, use and maintenance) and air exchange rates. It is also clear that occupants play an essential role, and so efforts should be made to give them the correct information about effective operation of systems and the impact of certain behaviours, which in turn may improve overall IAQ performance. There is some concern about the effects of human activities and behaviours in PassivHaus homes. A study that compared the performance of PassivHaus dwellings before and after being occupied suggested that human activities may increase alkanes, benzene, aldehydes and $PM_{2.5}$ temporarily, compared to the pre-occupancy period, but mean indoor pollution emissions from building materials were higher during the pre-occupancy study and decreased over time. For instance, $PM_{2.5}$ levels increased during the occupancy period and were associated with the infiltration of outdoor $PM_{2.5}$ during summer and human activities during winter (Derbez *et al.*, 2014). In fact, "*the variance of almost all[…] indoor air pollutants can be explained by their outdoor concentrations and the presence of human occupants and their related activities rather than by building characteristics* (Langer *et al.*, 2016, p. 90)." However, geographical location and building characteristics may have an impact on indoor temperature, relative humidity, air exchange rate and concentrations of formaldehyde (Langer *et al.*, 2016).

Several of these studies addressed IAQ issues, but for many of them their primary research objective was to associate the building fabric to energy consumption, and CO_2 emissions related to PassivHaus (Eicker, 2010; Mahdavi and Doppelbauer, 2010; Firląg and Zawada, 2013; Ridley *et al.*, 2013, 2014; Dan *et al.*, 2016; Figueiredo *et al.*, 2016; Liang *et al.*, 2017; Mihai *et al.*, 2017; Truong and Garvie, 2017). All of the studies produced equivalent results, with PassivHaus reducing primary energy consumption (42-90% lower) and CO_2 emissions (25-78% lower) for conventional buildings, and IAQ being rated by the occupants as acceptable. PassivHaus' rigorous design and construction methods along with post completion testing and verification, especially those related to the building fabric (e.g. air tightness testing), are key components in ensuring that energy target are achieved. Moreover, the strict controls used in the construction phase are, in a way, a form of warranty that the building will perform as designed and that its results can be replicated. Guerra-Santin et al. (2013) looked at the construction process for two PassivHaus residences. They found that rigorous monitoring control during construction, and the commitment of the design team, are key factors in achieving PassivHaus standards and that undertaking monitoring activities, such as thermal building surveys, and tests, such as the blower door tests, at the right time, are essential to ensure that the building meets expectations. As PassivHaus dwellings have proven to achieve better air quality by following the certification criteria, future buildings may achieve comparable results.

The recent concern in healthy buildings has opened up questions about the impact of some design strategies in PassivHaus buildings on the indoor environment and occupants' health (Davies and Harvey, 2008). The following section addresses in greater detail the impact of airtightness, controlled ventilation rates and MVHR systems in low-energy buildings, focusing on PassivHaus.

3.6.1 PassivHaus' design strategies and their impact on IAQ

3.6.1.1 Airtightness

The primary purpose of airtightness in PassivHaus buildings serves two primary purposes: energy conservation and protection of the building fabric (Schnieders and Hermelink, 2006). Leaking building envelopes may lead to a series of problems, such as condensation on indoor surfaces, draughts, cold air above the floor level and increased energy consumption. High levels of airtightness, such as those in PassivHaus structures (≤0.6h^{-1} @50Pa), may help to avoid condensation and conserve energy. However, studies have opposing results as to whether it may be either beneficial (Sherman and Chan, 2004; Berge and Mathisen, 2015; Less *et al.*, 2015; Szirtesi *et al.*, 2018), or detrimental (Mendell, 1993; Godish *et al.*, 1996; Seppänen, Fisk and Mendell, 1999; Seppänen and Fisk, 2002; Davies and Harvey, 2008; Carrer *et al.*, 2009) for buildings and occupants' health.

A study that measured IAQ and several indoor air pollutants in 24 homes in California found that IAQ was better in those that had higher levels of airtightness. In fact, the 7 PassivHaus dwellings were the tightest, but they also had the best practices to control IAQ (Less *et al.*, 2015). However, they noted that if these practices – source control, local exhaust, continuous ventilation, filtration, commissioning and occupant education – were not included, IAQ may be compromised to some extent. Another study that looked at two homes with n_{50} of 0.89-1.60 h^{-1} and mechanical ventilation, and a control house with n_{50} 7.13 h^{-1} and natural ventilation, found no differences in the concentrations or composition of $PM_{2.5}$ (Szirtesi *et al.*, 2018).

Other studies have addressed airtightness in PassivHaus applications, seeking to relate energy to the building fabric. Lordache et al. (2016), looked at this issue over the construction in final phases. They found that the pressurisation test in the final phase was higher (4.37%) than during the construction phase. On the one hand, better finishing on the walls and windows improved airtightness, but MVHR wall penetrations and terminals reversed performance improvements. Similar studies have been conducted in different climate locations, albeit without addressing IAQ issues in particular (Fu, Qian and Wang, 2017; Guillén-Lambea, Rodríguez-Soria and Marín, 2017). The impact of airtightness on heat demand was studied in single-family and multi-family homes PassivHaus residential buildings (Vlk and Novák, 2017). The authors found that the impact of air leakage from the building envelope had a higher impact compared to internal leakage. However, internal leakages in the multi-family dwelling may cause IAQ problems, affect the performance of the ventilation system and reduce fire safety. As explained by Sherman and Chan (2004), when poor airtightness allows air to be drawn in from contaminated areas, IAQ can be reduced, as the infiltrating air is unfiltered, and in some cases, the building envelope may be a source of pollution because of mould or toxic materials. Therefore, airtightness is important because it not only affects building energy consumption, but it may also provide increased comfort levels, which have a positive impact on occupants' perceptions of the indoor environment. The need to reduce energy consumption has led to more airtight buildings, which still require proper ventilation.

As new homes are becoming more airtight, less reliance can be placed on the building's air permeability to achieve this aim (Bone *et al.*, 2010). The provision of ventilation is therefore imperative, as there are consequences for the health of occupants when adequate ventilation is not achieved (Bornehag *et al.*, 2005; Wargocki, 2013). As energy-efficient homes are made more airtight, indoor pollution sources may take on particular significance in relation to IAQ, unless ventilation is adequate (Energy Saving Trust, 2006), which is necessary in order to achieve and maintain satisfactory and effective ventilation levels of IAQ (Davies and Harvey, 2008).

3.6.1.2 Ventilation rates

Removing indoor sources of pollutants is an efficient way of controlling IAQ (WHO, 1989). However, designers and contractors do not always pay attention to materials emissions in part due to lack of clear or mandatory labelling and in any case, pollutants may be introduced in other ways such as furnishings or cleaning products, and so ventilation becomes the primary mitigation method to control indoor pollution. In PassivHaus dwellings, ventilation via MVHR system is used mainly for heating, but it also acts as a way to contain, dilute and remove indoor pollution and humidity (Brimblecombe and Rosemeier, 2017) to acceptable levels (Seppänen and Fisk, 2004). For instance, the quality of the air in PassivHaus, with other low-energy homes and conventional houses in Sweden has been compared. The study found that whereas tVOCs were slightly higher in PassivHaus abodes, but not significantly different from other houses, concentrations of specific VOCs and formaldehydes were lower in the PassivHaus. PassivHaus dwellings were also characterised by a significant reduction of microflora (related to mould or water-damage) compared to conventional homes and outdoors, thereby indicating comfort and a healthier indoor environment (Langer *et al.*, 2015). Langer's study suggests that the better IAQ in PassivHaus residences is down to their relatively high air exchange rates.

Reducing ventilation rates to conserve energy is likely to affect human health (Howieson, Sharpe and Farren, 2013). As explained by Wargocki (2013, p.114):

> "*Ventilation rates above 0.4* h^{-1} *or* CO_2 *below 900ppm in homes seem to protect against health risks[...], [as v]entilation rate in homes is associated with health in particular with asthma, allergy, airway obstruction and SBS symptoms[...]. Increasing ventilation rates in homes reduces house dust mites known to cause allergic symptoms.*"

The commonly accepted threshold below which associations may occur is 0.5ach^{-1} (Dimitroulopoulou, 2012), which may help to control moisture, but may differ from other widely known thresholds (CO_2<1,000ppm or 8l/s, Porteous 2011)).

PassivHaus ventilation rates are set according to the German standard DIN1946-6, which establishes flow rates between 0.5 and 1.0ach^{-1} (Deutsches Institut für Normung e. V, 2012). The mean ventilation rates for PassivHaus structures are determined for IAQ requirements, with the minimum being a supply flow of 30m^3/h (8.33l/s) per person, thus allowing the system to have at least 0.2h^{-1} air changes when there is no occupancy in the building (Feist *et al.*, 2005). Limited evidence shows that ventilation rates in homes below 0.5ach^{-1} may degrade occupants' health, as they are associated with a higher likelihood of exacerbating the symptoms of asthma and allergies from indoor pollutants (Sundell *et al.*, 2011).

Data are limited regarding the health effects associated with ventilation rates in houses (Spengler, 2012); however, as explained by Seppänen and Fisk (2004), "*as the limit values of all pollutants are not known, the exact determination of required ventilation rates based on pollutant concentrations and associated risks is seldom possible.*" Different studies suggest that low ventilation rates not only result in increased concentrations of indoor-generated pollutants, but they are also associated with SBS symptoms, comfort, health effects and reduced productivity in non-industrial buildings (Seppänen, Fisk and Mendell, 1999; Wargocki *et al.*, 2002). An increase in SBS symptoms was associated with low ventilation, with human responses to low ventilation rates likely to affect IAQ perceptions and productivity (Seppänen and Fisk, 2004), causing inflammation, asthma, allergies and short-term sick leave in office-buildings (Wargocki *et al.*, 2002).

There is a wide range of research findings on whether or not PassivHaus ventilation rates might be appropriate to maintain acceptable IAQ. For instance, it has been reported that PassivHaus with air change rates of 0.5h^{-1} has the potential to achieve good IAQ (Fischer, Langer and Ljungström, 2014). Others suggest that whereas PassivHaus ventilation may be sufficient to comply with regulations or provide occupants with breathable air, it might not be enough to remove concentrations of VOCs, particulates and other hazardous chemicals (Woolley, 2017). Low ventilation rates (Bornehag *et al.*, 2005) and dampness (Bornehag, Sundell and Sigsgaard, 2004) have been associated with asthma, rhinitis and eczema in Swedish homes, so higher ventilation rates are highly desirable.

A comparison between the USA, European and PassivHaus ventilation standards found an apparent lack of ventilation guidelines for the latter example (Guillén-Lambea, Rodríguez-Soria and Marín, 2016). Ventilation rates (8.3-8.9l/s or 30-32m^3/h person) required for PassivHaus dwellings account for the entire building only, whereas local guidelines might suggest different air flows (exhaust and supply), depending on the room. However, perhaps this opens up the possibility for PassivHaus to adapt to local regulations.

A frequent practice is to use CO_2 as an indicator of ventilation rates (Sundell *et al.*, 2011; Wargocki, 2013), and levels below 1,000ppm are associated with adequate solutions in this regard (Porteous, 2011). PassivHaus studies that have measured CO_2 concentration often find contradictory evidence. For instance, Dan et al. (2016) measured CO_2 concentrations in a Romanian PassivHaus abode and found that ventilation levels led to CO_2 below 800ppm. Beamer et al. (2003) measured CO_2 concentrations in PassivHaus dwellings in the US and found that absolute levels remained below 1,000ppm (between 810 to 832ppm); exceptions were when the house was occupied with more people than for what it was designed (hosting a dinner party, for instance).

Another study measured CO_2 concentrations in two PassivHaus homes in Wales over two years (Ridley *et al.*, 2014). The dwellings were designed to meet the EN 13779 (CEN EN, 2007b) "IDA 3 – moderate IAQ." In one of the houses, the MVHR unit met 99.9m^3/h for four occupants (24.98m^3/h per person), and bedroom CO_2 concentrations exceeded 1,400ppm over 12.9% and 1,000ppm over 36% of the time over the two years. The second dwelling achieved a ventilation rate of 122.2m^3/h for three occupants (40.73m^3/h per person), and bedroom CO_2 levels exceeded 1,400ppm only 0.1% and 1,000ppm over 9.5% of the time over the two years. Eight PassivHaus flats were compared to eight conventional flats in China (Wang *et al.*, 2018). The authors found that ventilation levels of 30m^3/h (8.33l/s) per person or higher were sufficient, thereby concluding that PassivHaus dwellings achieve acceptable CO_2 levels. CO_2 concentrations in the PassivHaus flats were between 622 and 841ppm, whereas four of the conventional flats in the study exceeded 1000ppm.

Other studies present contradictory evidence. For instance, Brunsgaard et al. (2012) measured three PassivHaus units in Denmark, and while summer CO_2 levels were acceptable, during winter they exceeded the threshold (660ppm above the outdoor (outdoor average 370ppm)) in two of the homes. However, they noted that the occupants would open the windows during summer. McGill et al. (2014) monitored UK PassivHaus dwellings over one day during summer and another day during winter. Whereas the limited measurements may not be enough to generalise, they present evidence that PassivHaus buildings may have poor ventilation, especially social housing, as the CO_2 levels were often exceeded when the rooms were occupied. However, they concluded that this could be down to some deficiencies in the MVHR system, including a lack of occupant knowledge.

3.6.1.3 Mechanical ventilation with the heat recovery (MVHR) system

Ventilation in PassivHaus homes, in most cases, is achieved through a balanced system of extracting and supplying fresh air, aligned with heat recovery. MVHR is "[…] *dimensioned for air flow rates according to IAQ requirements. Also, for IAQ reasons, air recirculation is not considered*" (Feist *et al.*, 2005, p. 1194). Feist et al. (2005) suggest that MVHR systems provide acceptable ventilation levels, high levels of comfort and energy reduction while achieving acceptable IAQ. An MVHR is a 'whole-house' ventilation system, on which fresh air circulates from the supply zones (living areas and bedrooms) to the extract zones, usually the wet and smelly spaces (kitchen, toilets and bathrooms) so that the whole house is continually refreshed with clean, filtered outdoor air. This is achieved through 'transfer paths' an undercut on the doors of at least 20mm or adapting the architrave at the door head. The heat recovery element is the key factor for this ventilation strategy, as the incoming air is pre-heated by the extracted air on a counter-flow heat exchanger chamber without mixing them. There are several components of the MVHR systems (Cotterel and Dadeby, 2012):

- Central unit, where two fans (extract and supply) push the air through the air filters to the heat exchanger. The unit needs to be heavily insulated. See Table 3.2 for specifications for the MVHR unit in Passivhaus.

- Condensate drain, as heat is taken out from the exhaust air and becomes cold, it is no longer able to hold the same moisture content and the water vapour becomes liquid that needs to be taken off from the central unit.

- Frost protection, the air supply to the central unit needs to be protected from air freezing preventing undesired condensation in the unit.

- Air filters, the central unit incorporates two paper filters – an F7 for outside incoming air and a G4 for extract air returning to the unit preventing fine particles or insects from getting into the heat exchanger. Their main purpose is to protect the central unit; however, secondary effects such as air clean from dust and pollen are advantageous for IAQ. An additional filter is needed in the kitchen exhaust, to protect the ducts from grease.

- Intake and exhaust ducts, these are the ducts that connect the unit to the outdoor and ideally, they should have the same orientation. The best practice is to use a wider grille than the duct to protect the duct at the end, separate at least 2m the ducts to avoid short circuits and place them at least 3m above the ground level (EN 13779:2007). If the unit is located inside the thermal envelope, the insulation they require insulation of at least 20-25mm.

- Supply and extract ducts, they connect the unit to the rooms. The pipes should be smooth internally, of short distances and airtight. If the unit is located outside of the thermal envelope, they require a minimum of 100mm for warm ducts and 50mm for cold ducts 50mm.

- Sound attenuator, noise protection between the unit and the first supply and extract terminals. Room noise levels should not be higher than 35dB(A) in the room containting the MVHR, 30dB(A) in functional rooms and 25dB(A) in living areas This can be achieved with the use of sound attenuators, usually 90cm length for supply ducts and 60cm for extract ducts immediately after the MVHR. For the intake and exhaust ducts 60cm between the MVHR and the outside. It is also desirable to provide noise protection between an adjacent room on a duct run.

- Supply and extract air terminals, the supply nozzles primary function is to distribute the air to the room evenly and should not be placed near to a transfer path or extraction zone allowing most of the air flow. In PassivHaus the speed of the air jetted by the valves should not be superior of 1m/s and they should be located on or at no more than 20cm from the ceiling. Similarly, the extraction valves are required to be placed on or close to the ceiling to remove moisture and odours. Valves can be regulated to extract or supply more or less air.

- Summer bypass, this allows the incoming air to be delivered without passing through the heat exchanger during warmer weather.

- Central control unit, this allows controlling all the settings and functions of the unit. The minimum level of control should include fan control for the three set speeds (trickle, normal and boost), individual control fan for commissioning, as well as indicator for filter replacement, fan failure, frost protection and summer bypass modes.

MVHR systems are one of the most common applications in energy-efficient dwellings (Sullivan *et al.*, 2012) and a usual requirement for PassivHaus buildings. Their installation has been associated with lower CO_2 concentrations (Fehrm, Reiners and Ungemach, 2002), improved IAQ (Hekmat, Feustel and Modera, 1986; Seppänen, 2008) and thermal comfort (Mardiana-Idayu and Riffat, 2011), as well as energy savings (Hekmat, Feustel and Modera, 1986; Mardiana-Idayu and Riffat, 2012), especially in PassivHaus residential buildings (Dodoo, Gustavsson and Sathre, 2011). However, these outcomes depend on favourable ambient conditions and operating parameters (Mardiana and Riffat, 2013).

Limited data are available on whether the effectiveness of MVHR systems to provide ventilation and control IAQ is adequate or not. Some studies suggest that they may actually exacerbate, rather than resolve, IAQ problems (Woolley, 2017). In fact, a significant concern of sizing residential MVHR units has been noted in current PassivHaus practices, as they deliver the same background ventilation regardless of occupancy levels (Foster *et al.*, 2016). It is clear that in order to benefit from the above, MVHR systems should be adequately designed, commissioned, installed, maintained and operated. A recent study of 54 homes in the UK, in which MVHR systems often did not perform as intended, found numerous problems related to installation, commissioning stages, operation and performance (Sharpe *et al.*, 2016). These findings are similar to earlier studies investigating MVHR deficiencies (Hill, 1998; Pluijm, 2010; Balvers *et al.*, 2012).

McGill et al. (2015) suggest if proper instructions and guidance are given, problems in installation and commissioning could be prevented, thus averting problems with operation and performance. Recent studies have also identified incidences of overheating in PassivHaus (Mlakar and Štrancar, 2011; Sharpe *et al.*, 2016; Morgan *et al.*, 2017), with complaints regarding the noise of the MVHR (Bone *et al.*, 2010; Pluijm, 2010; Mlecnik *et al.*, 2012; Sharpe *et al.*, 2016), cold draughts (Sharpe *et al.*, 2016) and occupants' experiences when interacting with the ventilation unit (Tuohy, Murphy and Deveci, 2012). These problems may lead to the intermittent or seasonal use of MVHR systems as one of the many occupant responses to such deficiencies. Performance shortcomings in PassivHaus projects were observed less often than in homes without the certification but with MVHR systems installed (Sharpe *et al.*, 2016), due to the rigorous certification process. However, Sharpe et al. (2016) concluded that despite the shortcomings listed above, MVHR systems could result in better levels of ventilation and lower energy consumption compared to naturally ventilated houses, but the context for this may be even worse ventilation in non-MVHR houses.

MVHR systems, regardless of the building type in which they are installed, perform better with higher levels of airtightness (Manz *et al.*, 2000; Tommerup and Svendsen, 2006). However, this raises other issues, as mechanical ventilation systems are associated with VOCs and other chemical pollutants emitted by system components and ductworks (Seppänen and Fisk, 2004). Moreover, the correct filters must be used to protect the system components and reduce indoor exposure to pollutants of outdoor origin. Szirtesi et al. (2018) studied PassivHaus structures employing grade G4 filters and without secondary filters instead of the F7 suggested by the PassivHaus, finding that $PM_{2.5}$ was inadequately filtrated and, in addition to the indoor sources, resulted in higher concentrations.

Wallner et al. (2017)studied naturally ventilated and MVHR-equipped dwellings to find associations between SBS symptoms, CO_2 and formaldehyde levels. They found that associations were observed regardless of the type of ventilation. A recent study in office environments shows that a significant pollution load may originate from air-handling systems (0.04-0.27olf/m^2) (Wargocki, Wyon and Fanger, 2000), but a significant proportion of VOC emissions may be due to reduced maintenance and cleaning. This hypothesis is supported by other studies that associate indoor air problems with the cleanliness of ventilation systems in offices (Crandall, Sieber and Malkin, 1996) and homes (Balvers *et al.*, 2012). System design, construction, operation and maintenance have been associated with increases in the prevalence of SBS symptoms (Seppänen and Fisk, 2004). Therefore, buildings with better ventilation system operation and maintenance have lower associations with SBS symptoms (Burge, 2004). Recent studies, however, have demonstrated the difficulties involved in regular maintenance and cleaning. For instance, Crump et al. (2009) explained the limited options for filter replacements for ventilation units in the UK. Balvers et al. (2012) studied 150 homes with MVHR systems and found that the most common problem was general maintenance and cleaning. In total, 66% of the homes did not undertake annual maintenance, visible dirt was found in 43% of the homes, 77% had dust and dirt on the ducts and 67% had visible dirt from material construction.

Occupant interaction with the system is a critical dimension. Tuohy et al. (2012) identified common problems in PassivHaus units but observed that occupants are often unaware of how to use the controls or replace the filters. The inadequate user understanding and awareness about the MVHR operation and control, combined with habitual behaviours (e.g. unexpected window openings), leads to misuse (Gupta, Kapsali and Howard, 2018).

Occupants' perceptions of IAQ and self-reported health may improve in dwellings ventilated with MHVR systems. Wallner et al. (2017) studied occupants' health, well-being and house satisfaction experiences in 123 dwellings (PassivHaus, other low-energy homes – with MVHR systems – and conventional homes – without MVHR systems), finding that the overall health status of young people in dwellings with MVHR ventilation was not significantly higher than those without, but self-reported health was indeed better in dwellings with MVHR for children and adults. However, adults living in homes with MVHR systems reported a higher prevalence of dry eyes (19.4%) compared to the control group (12.5%), which was associated with low levels of relative humidity.

These studies have described the possible implications of the PassivHaus design strategies for IAQ and occupants' well-being. However, airtightness, ventilation rates and MVHR systems should be understood as one entity in PassivHaus dwellings, in order to provide a deeper understanding of the level of protection achieved following the rigorous criteria for certification. Different points of view have been presented above, namely, those that advocate that these design strategies may improve IAQ and those that suggest the opposite. However, they all converge at one point; if they are used appropriately, they will achieve low energy consumption.

Given the context of high levels of airtightness and reliance on a mechanical system, IAQ is of particular interest in low-energy homes, especially in PassivHaus. However, this raises the question of how good indoor air quality in naturally ventilated dwellings. For this reason, the following section will provide a broad overview of the methods and techniques used for natural ventilation in dwellings, as well as the performance of current natural ventilation practices.

3.7 Natural ventilation in dwellings and IAQ

The recent need to control the energy we consume has led to new ventilation practices, but natural ventilation is still the most attractive solution to ensure minimum energy consumption and control IAQ and thermal comfort (Larsen and Heiselberg, 2008; Yik and Lun, 2010; Yu and Kim, 2012). However, natural ventilation relies on different driving forces, such as wind and thermal buoyancy, which need to be used adequately with the ventilation provision (i.e. wind tower, double façade, chimneys, trickle vents) to be effective (Kleiven, 2003). The primary purposes of natural ventilation are to provide thermal comfort and acceptable IAQ, based on fresh air supply diluting or removing indoor pollution and acting as a mode of heat transportation (Awbi, 1991; Allard and Alvarez, 1998). The natural driving forces for natural ventilation, as explained by Kleiven (2003, pp. 37-40), are:

- Thermal buoyancy driven ventilation occurs due to density differences caused between indoor and outdoor air temperatures, which creates pressure that drives air in and out of the building through suitably placed building openings. When the indoor temperature exceeds the outdoor temperature, over-pressure is generated in the upper part of the building, and at the same time under-pressure occurs in the lower part. The neutral plane occurs at the point where indoor and outdoor pressures are equal. Above this point, where over-pressure occurs, air is pulled out, and below

– where under-pressure happens – it is pulled in through openings in the building envelope. See CIBSE (2005, pp. 11–13) for detailed information.

- Wind-driven ventilation is a result of different pressures created on the building envelope by the wind. This is a dynamic form of ventilation whereby air is driven into the building through openings in the windward side and driven out at the leeward side. However, it depends on several factors, such as the geometry of the building envelope, wind velocity and its direction relative to the building and the location of the building in relation to other buildings as well as the surrounding vegetation and topography. See CIBSE (2005, pp.13–14) for detailed information.

A thermal buoyancy/wind combination can also be convened to achieve proper ventilation through thermal buoyancy on cold days with practically no wind and wind pressures that may happen on warm and windy days. However, if this is the case, openings (inlets and outlets) in the building envelope need to be located carefully, to avoid conflict between both forces (Fisk *et al.*, 1993; CIBSE, 2005, pp. 14–15).

The ventilation principle indicates how natural driving forces are used to ventilate the building and how indoor and outdoor air is linked. This is related mostly to two architectural elements, i.e. the shape of the building and the location of the ventilation openings in the building envelope. There are different ventilation principles for natural ventilation, namely single-sided ventilation, crossflow ventilation, a double-skin façade, night ventilation (CIBSE, 2005, 2011) and passive hybrid ventilation strategies (Short, 2018), such as the passive downdraught cooling (Short *et al.*, 2009).

These ventilation principles should be enough to provide fresh air to control IAQ by reducing pollutants. However, recent literature indicates that modern practices in this regard may not suffice and that indoor pollution is usually higher indoors than outdoors, as outdoor pollution, human occupation and activities may have a negative impact on the IAQ. As suggested by Dimitroulopoulou (2012), ventilation practices are often poor, resulting in increased concentrations of pollutants.

In the UK, ventilation requirements are identified by Document Part F (HM Government, 2013) and in the Technical Handbook Section 3.14 in Scotland (Scottish Government, 2017). However, it has been suggested that these regulations may not be adequate in achieving low-energy consumption, due to over-ventilation, especially in social housing (Kinnane, Sinnott and Turner, 2016). Conversely, poor levels of IAQ have been measured in naturally ventilated homes in the UK (MEARU, 2014; R. A. Sharpe *et al.*, 2015; T. Sharpe *et al.*, 2015). A study that evaluated PM_{10} in naturally ventilated dwellings in four different cities in Wales, situated in urban, suburban and rural locations, found higher concentrations of PM_{10} indoors than ambient levels and that the composition of PM_{10} is controlled by outdoor sources and indoor anthropogenic activities (BéruBé *et al.*, 2004).

Environmental and economic circumstances in Mexico City promote the use of natural ventilation as the main source of air exchange, with ventilation rates described by the building codes in CONAVI (2010) and Gobierno del Distrito Federal (2004a, 2004b). Another study evaluated different naturally ventilated housing typologies in Mexico City and found that higher deposits of dust and fibre were common in public areas, with ultrafine particles being the most prevalent (Bernal, 2015). Another study suggests that dwellings in Mexico may have high indoor levels of carbon monoxide, especially during winter (Montoya *et al.*, 2008) while Miller et al. (2009) examined over 100 naturally ventilated US dwellings occupied by Mexicans and showed that indoor $PM_{2.5}$ and CO_2 concentrations were higher than those stated by US National guidelines. The authors suggested that indoor $PM_{2.5}$ did not correlate to ambient pollution but to occupants and their activities (Frey *et al.*, 2014).

In the US, ASHRAE 62.1-2007 describes the most accepted guidelines for residential ventilation (Sherman, 2008). Studies have shown that indoor $PM_{2.5}$ could be higher indoors than outdoors in naturally ventilated US dwellings (Escobedo *et al.*, 2014). A study that looked at 72 flats in the US found that indoor formaldehyde concentrations (36.9-38.8ppb) were higher than the recommended levels (40ppb) in at least 44% of the houses. Indoor PM_{10} (58-66$\mu g/m^3$) and $PM_{2.5}$ (53-62$\mu g/m^3$) were found to be higher indoors than outdoors.

3.8 Chapter conclusions

The findings in this chapter highlight a lack of studies addressing IAQ in PassivHaus dwellings. The PHI has demonstrated the applicability of its standard in any location, albeit the study only looked at a virtual simulation to assess the energy requirements and cost-effectiveness of the approach, assuming buildings would achieve high levels of acceptable IAQ. While particular PassivHaus design strategies (airtightness, controlled ventilation rates and mechanical ventilation with heat recovery systems) are useful for reducing energy consumption, their implication on the quality of the indoor environment have not been properly addressed. However, the problem is not only due to PassivHaus designers, as inhabitants and outdoor conditions play a fundamental role in determining the quality of their environments.

Limited literature is available, and often the evidence is contradictory, in that where some studies have measured acceptable levels of IAQ and positive occupant satisfaction levels, others have reported high exposure to indoor pollutants and CO_2 levels. Many of the studies discussed herein have examined CO_2 concentrations as a metric for IAQ. Furthermore, as studies have started linking other indoor pollutants to issues in human health, $PM_{2.5}$ and PM_{10}, individual and tVOC are now used to assess IAQ issues. Available IAQ studies often look at the indoor environment over very limited time frames, especially if IAQ assessments are carried out during investigations (one spot measurement to two weeks). Moreover, despite evidence on the impact of IAQ in terms of health, very few PassivHaus studies link occupants' well-being and IAQ perceptions to physical concentrations of indoor air pollution.

This chapter has reviewed the body of knowledge on PassivHaus and IAQ. In so doing, it identifies the need to: (1) compare IAQ between PassivHaus, other low-energy rating systems and conventional dwellings in urban locations not yet assessed in warm and temperate climates; (2) assess IAQ, by obtaining high-quality data simultaneously in different buildings over a more extended time frame; and (3) link occupants' IAQ perceptions and well-being to physical exposure to indoor pollution levels and indoor environmental parameters. Finally, the chapter identified IAQ criteria on which this research is based. The will present the research design, the methodology and the monitoring protocol, using Foobot and Netatmo as a research tool.

4 Methodology

4.1 Summary

The case study is one of the most common research designs used in the built environment. However, single case study research may suffer from identifiable limitations, in which case the use of multiple case studies is recommendable. This research design is used to investigate the “how” and “why” of a real-life event where there is no control over a set of circumstances. Case study weaknesses open up the possibility to adopt the advantages of the qualitative and quantitative research methods, thereby strengthening the research.

This research uses three case studies to investigate the suitability of low-cost monitors for IAQ research. The quality of indoor air in PassivHaus dwellings is compared to the ambient data and indoor air in control homes. The research structure, case study selection criteria, analysis and methods employed to collect qualitative and quantitative data are presented in this chapter. Pilot studies informed the development of the data collection method and helped to identify its strengths and limitations.

This study had identifiable limitations and obstacles related to time, case study recruitment, funding and the availability and accuracy of IAQ monitors among others. The research ethics followed for literature- and fieldwork-based research are presented in this chapter. This study looks at “typical” indoor environment conditions; however, despite efforts to communicate this to the participants some behaviours may still have affected the outcome.

4.2 Study design

This work examines the IAQ in certified PassivHaus dwellings looking at the level of protection against air pollution, comparing them with standard contemporary dwellings. This could be investigated using different research methods, such as experimental, case studies simulations or qualitative research. Experimental and quasi-experimental research could test different IAQ parameters in physical models in an environmental chamber. Simulation research can take a similar approach through virtual simulations.

Whilst both methods allow for a higher degree of control, they lack 'real-world' impact, such as occupant' behaviours. IAQ could be explored through occupant's perceptions, researcher's observations and focus groups in qualitative research but it would lack measured exposition to air pollutants. Finally, case studies and combined strategies, i.e. qualitative-quantitative research, could be used to investigate IAQ under 'real-world' dwelling settings gathering and analysing quantitative and qualitative IAQ data to conclude. Nonetheless, 'real-world' setting may suppose an evident loss of control for some variables (human behaviours, ambient pollution, sensors accuracy and ventilation levels).

The most common methodologies utilised to research the built environment are quantitative and case study approaches (Phelps and Horman, 2010). This work examines the suitability of low-cost IAQ monitors to quantify indoor air pollution in PassivHaus dwellings under real-life residential settings. The 'case study' methodological approach was found to be the most appropriate. Groat and Wang (2013) explain that the case study approach, either single or multiple cases, focuses on real-life contexts allowing an understanding of causal links finding multiple sources of evidence. Yin (1994, p. 13) explains:

> "*A case study is an empirical enquiry that investigates a contemporary phenomenon with its real-life context, especially when the boundaries between phenomenon and context are not clearly evident.*"

As described by Yin, a case study involves reviewing the relationship between a specific incident and the broader characteristics from which it is inseparable. Other authors, such as Gillham (2000), present similar definitions that involve understanding a phenomenon in a real-world context. In the built environment research, "*[case studies] have an important function in generating hypotheses and building a theory[…]" (Amaratunga et al., 2002; p.26).* This work tests the use of IAQ low-cost monitors to assess the IAQ in dwellings. This methodology could be used for large-scale projects to generate building theories.

An investigation of contemporary phenomena such as those addressed herein may require replication, to confirm the studies' outcomes (Groat and Wang, 2013). Therefore, the methodology collects data over extended periods in three different locations, allowing such a level of replication. A 'multiple case study' research design was selected to examine the IAQ PassivHaus and control homes with low-cost monitors. The overall study may become more robust and compelling when the evidence derives from multiple case studies (Herriott and Firestone, 1983). The different case studies facilitate the investigation of IAQ across homes in Mexico, Scotland and the US.

Outdoor climate, behavioural context and ambient pollution may vary between these cases, as do the ventilation strategies allowing 'literal replications.' Literal replications test the outcomes, principles or hypotheses of the initial case in different circumstances (Yin, 2013), allowing the researcher to corroborate the results. Various case studies with similar characteristics help to generalise the outline of the research, while the replication that a case study supposes cannot be accomplished with other methodological approaches (Gillham, 2000). When conducting investigations according to a case study design, it is critical to have at least two case studies so that the researcher can provide direct replications or contrasting situations as well as analytic conclusions and a stronger argument on the findings (Yin, 2013). This PhD work uses three case studies, with two dwellings each, to explore the use of low-cost IAQ monitors to conduct remotely IAQ assessments.

4.2.1 Case study research misunderstandings

A case study approach is appropriate for investigating the "how" or "why" of phenomena with which there is little or no control over different factors. However, there are some common concerns when using the case study approach (Yin, 2013). As explained by Yin (1994, p.9), "*[p]erhaps the greatest concern has been the lack of rigour of case study research*". The absence of universal rules, procedures or methodologies complicates case study research, although the depth, complexity and multifaceted quality of this approach may provide a robust research design in architecture (Groat and Wang, 2013).

One misconception of the case study approach is that it is biased toward verification (Flyvbjerg, 2006), as preconceived ideas or hypotheses might influence the judgment of the researcher. The level of subjective bias however, is indicated to be at most equal to other methodologies, as discussed by Flyvbjerg (2006, p.237):

> "*[...] the case study contains no greater bias toward verification of the researcher's preconceived notions than other methods of*

> *enquiry. On the contrary, experience indicates that the case study contains a greater bias toward falsification of preconceived notions than toward verification*".

Flyvbjerg (2006; p.221) discusses some other criticisms about the case study methodology *"[g]eneral, theoretical (context-independent) knowledge is more valuable than concrete, practical (context-dependent) knowledge*" and "*[o]ne cannot generalize on the basis of an individual case; therefore, the case study cannot contribute to science development".* Generalisation from case study research might be criticised, as it draws 'petite generalisations (Erickson, 1986)' or 'lower-order generalisations (Brown-Saracino, Thurk and Fine, 2008)' as the generalisation of findings are *within* their unit of analysis. However, the real concern of case study research is not generalisations, as:

> "*[the] case study is particularization [...] We take a particular case study and come to know it well, not primarily as to how it is different from others but what it is, what it does. There is emphasis on uniqueness and that implies knowledge of others that the case is different from, but the first emphasis is on understanding*" (Stake, 1995, p. 8).

In the same vein, Amaratunga et al. (2002, p.26) advocate that in the built environment research:

> "*[d]etailed case studies may be essential in comparative research, where an intimate understanding of what concepts mean to people, the meanings attached to particular behaviours and how behaviours are linked.*"

Many authors have debated the level of effort and time spent on this kind of research (Stake, 1995; Flyvbjerg, 2006; Yin, 2013). However, as Yin (1994; p.10) notes, there is "*[...] no need [for] case studies to take a long time*," which nevertheless depends on the approach and the kind of study the researcher is undertaking. In the current study, the case study monitoring periods were longer providing robust data using low-cost IAQ monitors. Case study research might be seen as 'soft' research, probably due to the lack of systematic procedures (Yin, 2013). Although following a procedure in experimental research does not guarantee high-quality research (Groat and Wang, 2013), it requires the researcher to think carefully about the framework and the research design. The use of mixed methods is frequent in the case study approach (Yin, 2013), and in a way, it becomes stronger by adopting the advantages of other research methods.

4.2.2 Integrating qualitative and quantitative research with case studies

Enquiries in the built environment fit into a broad category of disciplines, such as the natural sciences, social sciences, engineering and management (Amaratunga *et al.*, 2002), where objective and subjective perspectives are embedded in the research design. Architecture is part of an objective discipline, relying on physics, material science and building science principles. However, it is also subjective, as it relies on occupants' perceptions of the indoor environment and well-being.

The mixed methodology design integrates these principles, as the researcher enquires about aspects of both strategies with an equal degree of emphasis (Groat and Wang, 2013). The mixed methodology, as defined by Johnson and Onwuegbuzie (2004, p.17), is "*[…] the class of research where the researcher mixes or combines quantitative and qualitative research techniques, methods, approaches, concepts or languages into a single study*"*.* Therefore, it is a desirable way to approach architectural research, as both quantitative and qualitative techniques collect and analyse data that share the same research question as a case study (Yin, 2013). Furthermore, "*[t]he value of most case study research increases with the use of dissimilar, multiple research methods and the inclusion of multiple study objectives*" *(Woodside 2010, p.11).*

Rossman, G. and Wilson (1994) suggest that a mixed methodology research design allows researchers to see the same phenomena through multiple lenses. Data analysis may also be improved, as qualitative and quantitative methods inform each other reciprocally for the purposes of corroborating, elaborating, developing and initiating research findings. Rossman, G. & Wilson (1994) justify the use of mixed methods, as they enable corroboration or confirmation via triangulation, complementarity, the elaboration or development of analysis, thereby providing richer details, and the initiation of new lines of thinking. Greene et al. (1989, p.259) describe the purposes of the mixed methodology approach: triangulation, complementarity, development, initiation and expansion.

'Triangulation' is a factor that many authors have presented when discussing mixed methodologies (Greene, Caracelli and Graham, 1989; Amaratunga *et al.*, 2002; Johnson and Onwuegbuzie, 2004; Bryman, 2006; Yin, 2013). It is defined as the use of multiple methods and sources of evidence in an attempt to seek the convergence, corroboration and correspondence of results within the same line of enquiry (Johnson and Onwuegbuzie, 2004; Yin, 2013). There is indeed evidence that multiple sources of evidence converge within the same line of enquiry (Johnson and Onwuegbuzie, 2004); however, if misused, they might lead to different findings (Yin, 2013). This work achieves an in-depth understanding through the triangulation of different sources of evidence: physical measurements, building surveys and occupants' perceptions of the indoor environment.

In a mixed methodology, research 'complementarity' is used to measure overlapping and yet different conditions, enabling a greater understanding of a phenomenon (Greene, Caracelli and Graham, 1989). As explained by Amaratunga et al. (2002), the use of quantitative and qualitative approaches provides such complementarity, but moreover, it enhances the quality of the work by providing a deeper understanding of the research question. This project examines occupants' perceptions and physical measurements of IAQ to understand the impact of PassivHaus design strategies on IAQ. By implementing both qualitative and quantitative approaches for the same phenomenon simultaneously, the two counteract each other's biases and limitations, as suggested by Greene et al. (1989).

Johnson and Onwuegbuzie (2004) explain how qualitative and quantitative methods are used for 'development', to inform each other. For this purpose, housing characteristics are examined through building information and physical measurements, and then they are contrasted to occupants' perceptions of IAQ and self-reported well-being. The mixed methodology approach facilitates the discovery of fresh perspectives through the contrasting and paradoxical nature of the 'initiation' of studies (Greene, Caracelli and Graham, 1989; Rossman, G. and Wilson, 1994).

Finally, 'expansion' seeks to use different methods for diverse enquiries, in order to extend the range of enquiry (Greene, Caracelli and Graham, 1989), as the utilisation of the mixed methodology approach could develop into a transformative study (Johnson and Onwuegbuzie, 2004) and result in a sequential method. The idea of using a "*sequential methodology is not to measure the same* *phenomenon at the same time, but to use the findings of one methodology to inform […] in the subsequent evaluation*" (Moran, 1987, p. 624).

To conclude, applying a mixed methodology approach in built environment research produces "*an appropriate and, at times, desirable research*" (Amaratunga *et al.*, 2002, p. 30). The quantitative and qualitative research approaches are combined in practice (Bryman, 2006), and a clear example of their application in the built environment research is presented in Brunsgaard et al. (2012) and Cablé et al. (2016). The numerous advantages of this methodological approach may enhance the quality of this work.

4.2.3 Research structure

To effectively evaluate the potential of low-cost IAQ monitors for remote monitoring, PassivHaus and control homes' IAQ was evaluated. Long-term indoor pollutants' exposure data was compared to ambient conditions. Occupant' perceptions were collected using online surveys. Figure 4.1 shows the structure of the research.

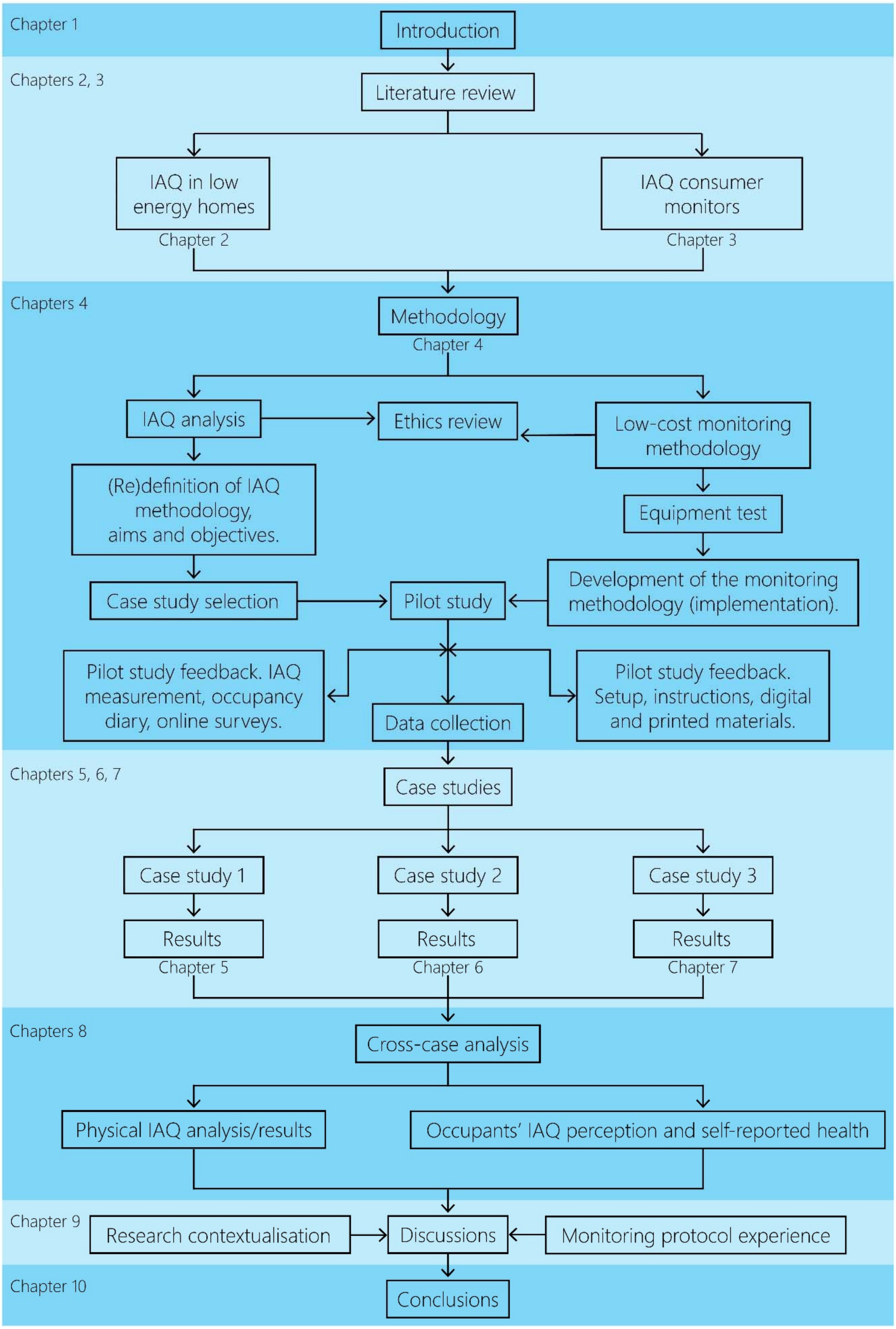


Figure 4.1 Flow chart of the research chapter structure.

4.2.4 Research design

Initially, the aim was to select case studies in temperate climates with dwelling layouts as equal as possible with different building contractions. However, due to practical and economic challenges (see Table 4.5) the section of the case studies was revaluated. The case study choices still correspond to temperate climates (classification C on the Koppen climate classification), but with different different climate conditions (Mexico City – oceanic subtropical highland (cwb), San Francisco – warm-summer mediterranean (csb) and Dunfermline – temperate oceanic (cfb)). One of the most significant difficulties was to find PassivHaus and control dwellings with the same layout. Although the Scottish case study have this characteristic, there were density differences. Long-term monitoring projects were performed to obtain a representative dataset. This provides confidence in the findings and the desired depth considering the limitations of this study (see section 4.6). The selection of the case studies (Table 4.1) was representative according to the dimensions, interests and objectives of the study. However, the case studies should also allow confirmation or confrontation (Seawright and Gerring, 2008; Groat and Wang, 2013). The buildings in each case study selected exemplify the following criteria:

i. they are residential buildings and not used for other purposes,
ii. each case study has a certified PassivHaus and a comparative dwelling built using the conventional building practices of the region of study,
iii. they are located in urban environments,
iv. each of the case studies compares the same housing typology,
v. they are single-family households,
vi. they have similar levels of occupancy and
vii. they can provide internet access for the monitoring instruments.

The specific characteristics of the case studies herein serve specific purposes within the scope of the research, and they were chosen carefully to represent different perspectives on the enquiry of interest and included the following variations:

i. The level of sustainable building approach. The Scottish case study incorporates an additional house, which represents a low-energy approach that could be considered between conventional and PassivHaus constructions.

ii. Different ventilation strategies used by PassivHaus buildings (MVHR and hybrid ventilation).

iii. Natural and MVHR ventilation strategies in non-PassivHaus projects.

iv. Construction type.

v. Building occupancy and associated behaviours.

Table 4.1 Case study characteristics.

Case study	Location	House code	Sustainable method	Building type	Construction type	Living area (m^2)	Household occupancy	Ventilation strategy	Construction date (year)
1	Mexico City	MX-PH	PassivHaus	Flat	Steel frame, timber closed panel	43.79	2 adults 1 baby	Hybrid	2011-2014
		MX-CO	Common building practices	Flat	Concrete frame and masonry	52.54	2 adults	Natural	2010
2	San Francisco	SF-PH	PassivHaus	Detached	Timber closed panel	182	2 adults 2 child	MVHR	2015
		SF-CO	Common building practices	Detached	Timber closed panel	172	2adults 2 child	Natural	2011
3	Scotland	SC-PH	PassivHaus	Semi-detached	Timber closed panel	94.00	3 adults 1 child	MVHR	2012
		SC-GD	Gold Standard	Semi-detached	Timber closed panel	96.00	2 adults	MVHR	2012
		SC-CO	Common building practices	Semi-detached	Timber closed panel	96.00	2 adults 3 child	Natural	2012

4.3 Case study analysis, data collection and analysis

The data obtained from each case study were analysed individually following a final analysis of the findings. Individual reports were then drawn upon to formulate a cross-case conclusion, as proposed by Yin (2013; p.60).

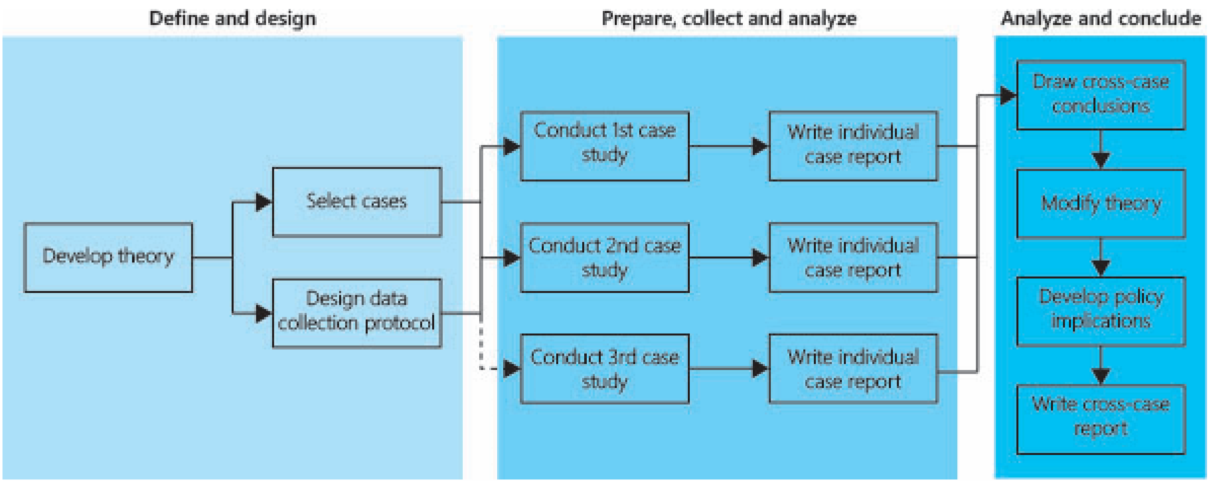


Figure 4.2 Multiple case study procedure. Source: (Yin, 2013, p. 60).

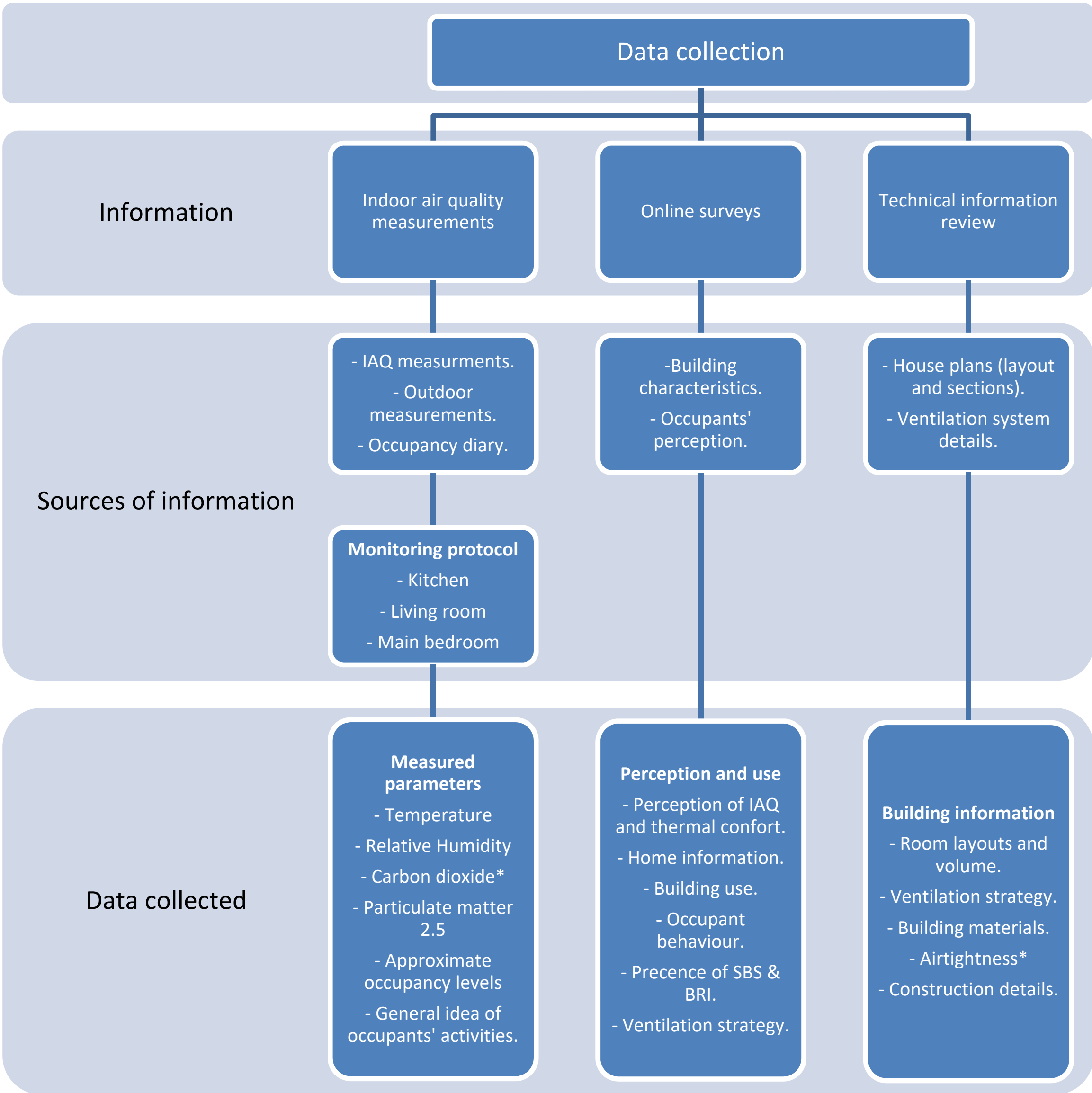


Figure 4.3 Data collection methods.

As explained in Figure 4.3 the data were collected using different methods:

i. Indoor air temperature, relative humidity, $PM_{2.5}$ and tVOC data were collected in the bedroom, kitchen and living room;

ii. Ourtdoor air temperature, relative humidity and $PM_{2.5}$ data were collected from local networks;

iii. An occupancy diary, completed by the adult that spent the most time at home, was used to collect general information about the use of the dwellings;

iv. The occupants that spent the most time at home were asked to complete the online surveys, to collect information about household, building characteristics and occupant' perceptions, and

v. Technical information, when available, was collected to gather technical data about the building and ventilation strategies. Occupants were asked directly for the information or the approval to contact the architect/designer of their homes.

The data from each Foobot were downloaded, using a program commissioned for such a purpose, and then exported manually to Microsoft Excel every 15-20 days. Excel was used for data cleaning , data quality, create single datasets of each case location, data input, and graphs and table creation. Further statistical analysis of the data was performed in SPSS, allowing complex analysis. The protocols for this are described later in the Chapter.

4.3.1 Air quality and environmental parameter measurements

Air quality and environmental parameters were quantified using the Foobot and Netatmo (only in Mexico City) devices. Measurements were conducted from 6.5 to 12 months in the case studies (Table 4.2). Data were recorded simultaneously in each room of all homes of each location at five-minute intervals, providing sufficient depth and seasonal variations to identify variations and trends in IAQ.

The interest of this research is the quality of the indoor environment, especially air quality. Therefore, stationary instruments were used instead of personal air samples for personal exposure. The parameters included were air temperature, relative humidity, $PM_{2.5}$ and tVOCs. Due to economic limitations (section 4.6) CO_2 measurements were conducted only in Mexico City making possible to track peak occupancy end evaluate ventilation control. Outdoor data were downloaded from local monitoring networks (weather stations and pollution stations) at one-hour intervals.

Table 4.2 IAQ and environmental parameter measurement dates.

Case study	Location	House code	Duration of the measurements	Dates
1	Mexico City*	MX-PH	13 months	May/2016-May2017
		MX-CO	13 months	May/2016-May2017
2	San Francisco	SF-PH	9 months	June/2017-February/2018
		SF-CO	9 months	June/2017-February/2018
3	Scotland	SC-PH	6.5 months	February/2017-August/2017
		SC-GD	6.5 months	February/2017-August/2017
		SC-CO	6.5 months	February/2017-August/2017

4.3.2 Foobot monitoring protocol

Some of the biggest barriers to performing a post-occupancy evaluation (POE) are cost, time and lack of skills (Hadjri and Crozier, 2009). Moreover, difficulties arise when trying to recruit from within the building industry, as owners and developers are reluctant to undertake a POE, as it could potentially uncover shortcomings in the performance of their building relative to equivalent constructions (Zimmerman and Martin, 2001). In addition to these challenges, POE professionals need to deal with other difficulties related to the lack of building user participation and privacy issues (Council and National Research Council, 2002). In this study, the complications in this regard were significant, and conventional approaches whereby housing associations and architects act as a “gatekeepers” were exhausting and time-consuming. Therefore, a protocol that would be versatile enough to circumvent these issues was developed for this research. It was challenging to design a protocol to collect technical data (i.e. construction methods and floor plans) from occupants and, whereas in small number of case studies, such as this study, may work, it may differ in large-scale projects.

The result was a monitoring protocol that could be used remotely, was economically affordable, required minimal occupant participation and provided reliable data and privacy to the participants. This monitoring protocol was developed using Foobot as a monitoring tool. The monitoring protocol had the following structure:

i. **Recruitment of participants.** Participants were contacted throughout the MEARU contacts network. This allowed us to introduce ourselves directly to

PassivHaus occupants. The study was explained directly to the participants via email or by phone call. PassivHaus occupants were asked to approach one of their neighbours, in order to have access to a control house. This proved to be efficient, as they had good relations with their neighbours, and a similar process was then followed to introduce the study to them. Once a participant agreed to participate, they received an email with links to access a "Participant Information and Consent Form," which contained detailed information on the study, what could they expect from the research and contact information if they had further questions.

ii. **Monitoring instrument set-up.** When the participants fully understood the study and signed the consent form, they received ten Foobots, posted directly from the maker. They were asked to keep the original packaging, so once the study was finished, they could post the instruments in the same package. Additionally, they received a separate parcel with a hand-made card thanking them for taking part, instructions on how to set up the Foobots (see Appendix 1) and three extension leads. These materials were developed following the recommendation of AirBoxLab, personal experience with the Foobot and adhering as strictly as possible to the ASTM-D7297 and ISO:16000-1:2006 international standards. These materials were developed as step-by-step guides with text and images. The topics they covered are: how to set-up a Foobot, how to dim the light, how to change the location of the Foobot, how to name a Foobot, where to place the Foobot in the bedroom, kitchen and living room, maintenance instructions and health and safety instructions. Participants also received an A4-sized paper with information on user details, to create and set-up the Foobots, so that the data could be download remotely in Glasgow.

ii.1. **Setting up the equipment.** Participants were asked to set up the instruments, as described in Appendix 1, not only trying to avoid placing them near to heat sources, open windows or inlets/extract vents, walls or any other element that may block the airflow (about 1m from them), but also to set the Foobot at head height (~1.2-1.7m above the ground). The guide also notes that the most suitable spot to a place a Foobot is in an open space. Recommendations were made to avoid placing the instruments near to any source of contamination or under direct sunlight.. Participants were asked to set up three Foobots in each room.

ii.2. **Ambient conditions.** Ambient data were collected from the nearest monitoring network for local weather and pollution. The data were accessed online from Mexico City's air quality and weather website (http://www.aire.cdmx.gob.mx/default.php), the Scottish air quality website (http://www.scottishairquality.co.uk/), the UK Met Office's (http://www.metoffice.gov.uk) and San Francisco's Bay Area Air Quality Management District (http://www.baaqmd.gov/) and National Centre for Environmental Information (https://www.ncdc.noaa.gov/) websites. Data are usually available at 1-hour intervals on any of these websites, which provides sufficient information on ambient conditions during the monitoring period.

iii. **Online surveys.** Personalised online surveys were created (see 4.4.3) based on the Royal Society of Health questionnaire for IAQ investigations (Raw, 1995), CBE (Zagreus *et al.*, 2004) and BUS methodologies (Cohen *et al.*, 2001) to collect data about occupants' IAQ perceptions, thermal comfort and self-reported health conditions.The ASTM D7297-14 (ASTM, 2014) survey was adapted to collect building information. They were created using SurveyMonkey and divided into independent sections with no connection between them. A link to the surveys was sent to the participants by email, complete with instructions on how to complete them. They were asked to provide one response to the building characteristics survey (see Appendix 2) and up to three (depending on the number of occupants) for the occupants' perceptions (see Appendix 3). The survey structure is explained later in this chapter.

iv. Remote IAQ measurement data retrieval. Whilst the Foobot devices allow for remote access; data had to be downloaded manually on a day-to-day basis, which can be considerably time-consuming. To overcome this limitation, a software was commissioned to a software engineering student. This software uses the API key provided by the maker at http://api-eu-west-1.foobot.io/apidoc/index.html for the case study based in the UK or http://api-us-east-1.foobot.io/apidoc/index.html for those in the Americas.

Data from each Foobot were downloaded on a single file separately so that a data quality test could be performed, and then the data were merged into a master file containing information on all Foobots per case study. In this file, additional information was added and the mean for each parameter of the three Foobots per space was calculated. These values were used for analysis (Data retrieval, cleaning and quality are discussed in detail in Chapter 9).

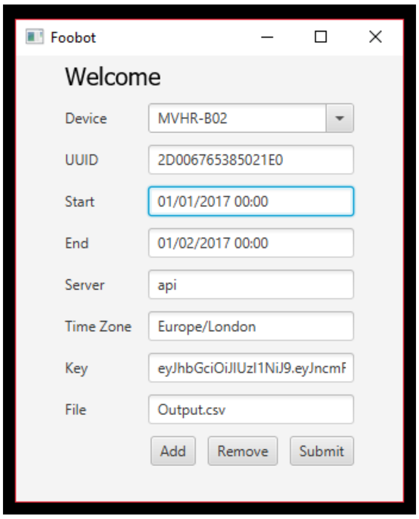


Figure 4.4 Software interface for downloading the Foobot data.

iv.1. **Data cleaning and quality.** Data cleaning and data drifting correction were performed individually for each of Foobot parameters, before applying the algorithm to calculate the mean of the IAQ monitors in each space. The data was examined looking at consistency in Excel and missing data; when one to ten entries were missing, they were added using Excel's *Fill* command. More important, the use of three Foobots in each room allowed for data corroboration by comparison (Figure 4.5). Data were also examined to detect any drifting from one Foobot to the other two in the same room (Figure 4.6 and Figure 4.7), when it happened it was corrected and then corroborated by comparison with the other Foobots (Figure 4.8).

iv.2. Mean calculation. An algorithm was developed using Excel formulas and then combining them to calculate the mean of the IAQ monitors in each space. The algorithm, applied to every monitored parameter of each Foobot, had three primary functions. The first was to identify missing data from the three Foobots, while the second was to calculate the mean of a given time, and the third mixed the output of both parts, identifying missing data and errors in the calculation of the mean (i.e. when all data were missing), thus preventing error outputs (Figure 4.9).

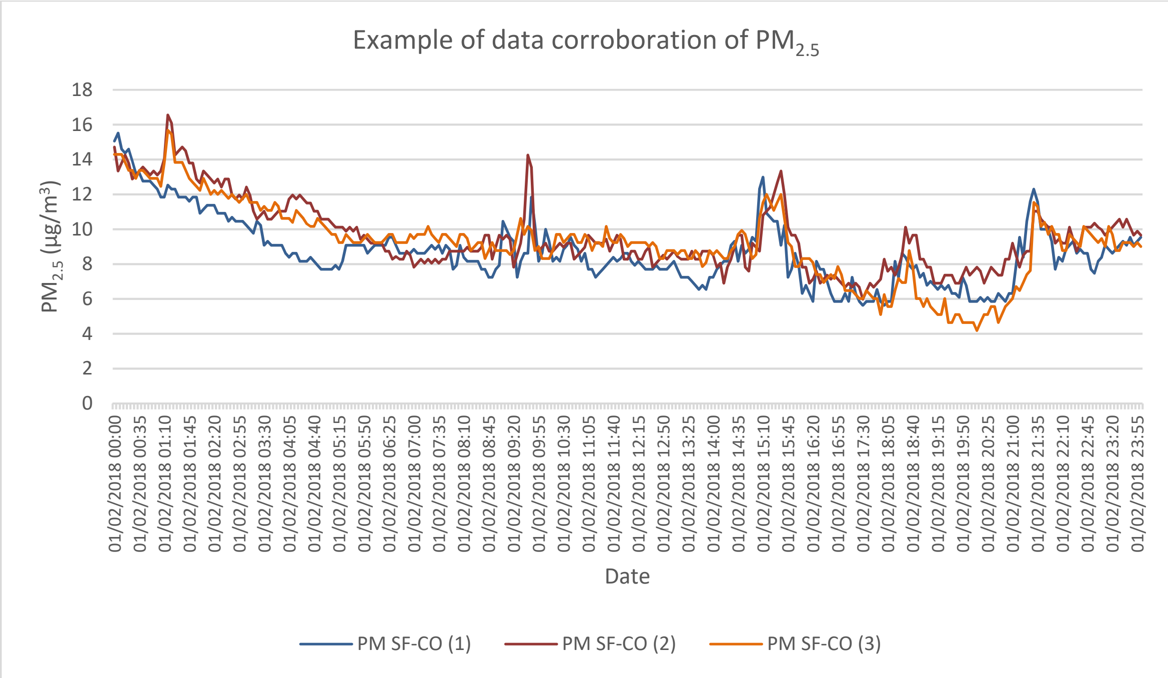


Figure 4.5 Example of data corroboration of PM2.5 data in the living room of the control house in San Francisco on 01/02/2018.

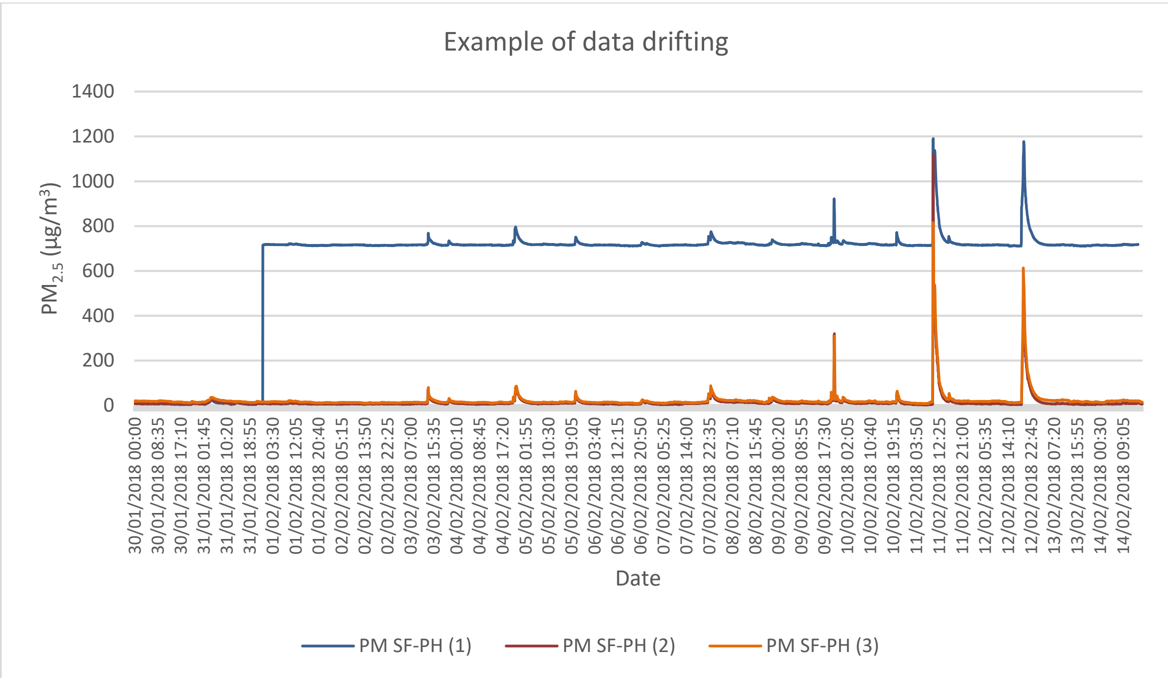


Figure 4.6 Example of data drifting as a result of the "learning process" performed by the Foobot algorithms.

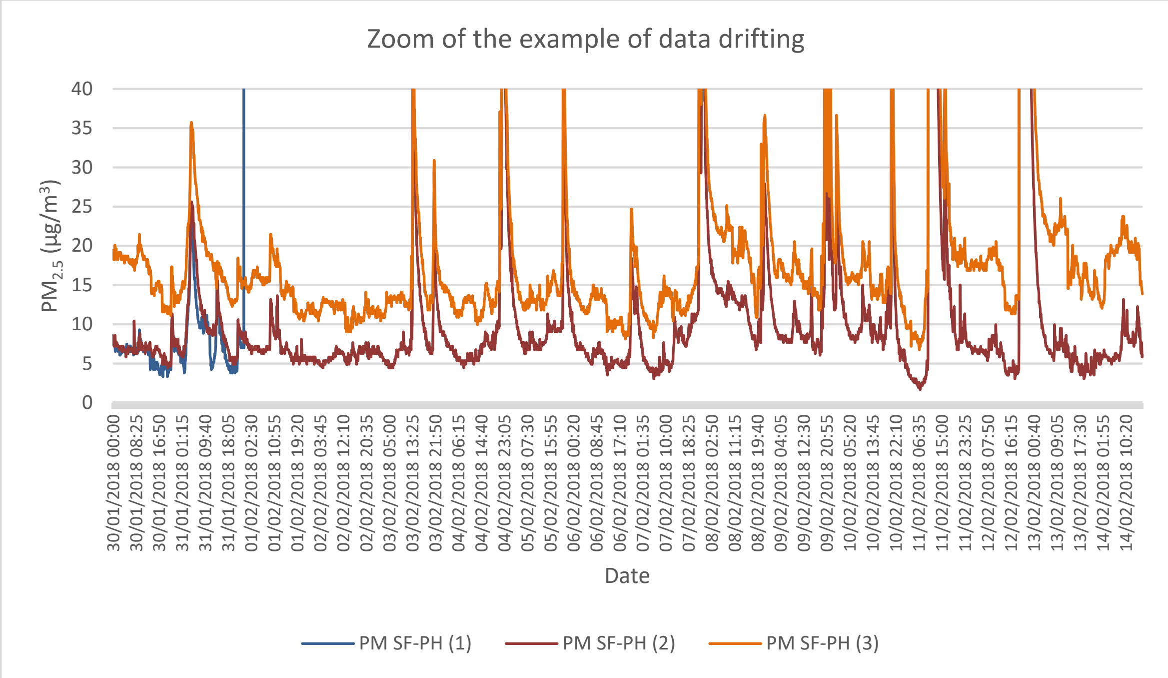


Figure 4.7 Zoom to the example of data drifting in Figure 4.6. The maximum $PM_{2.5}$ axis scale was set up to 40µg/m³.

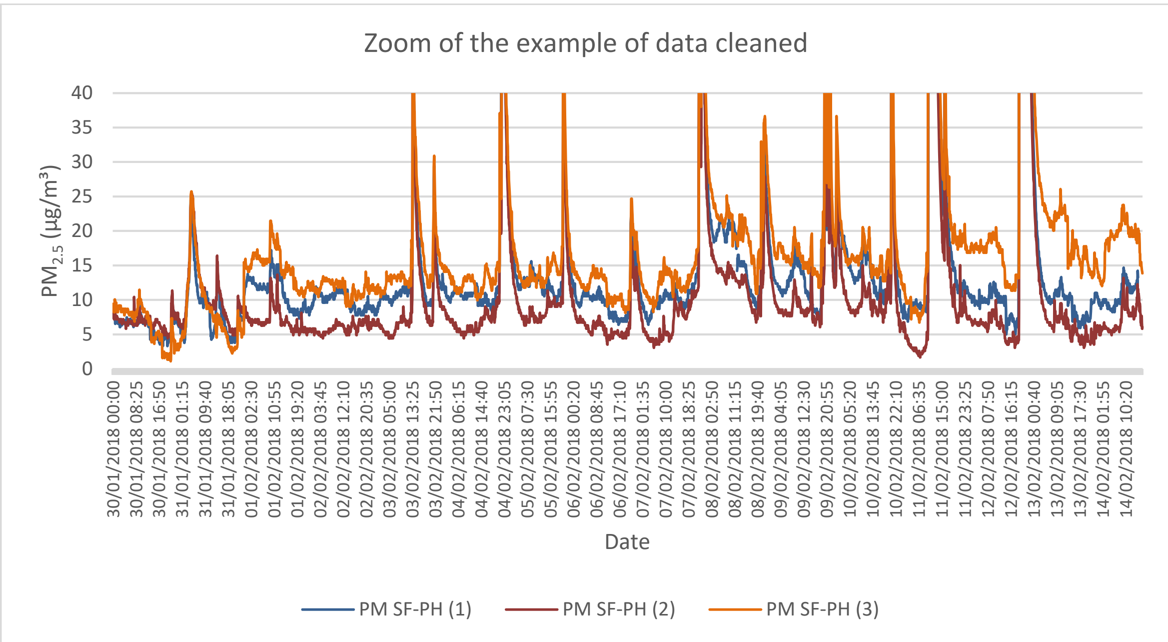


Figure 4.8 Zoom to the example of the data drifting correction and data cleaning.

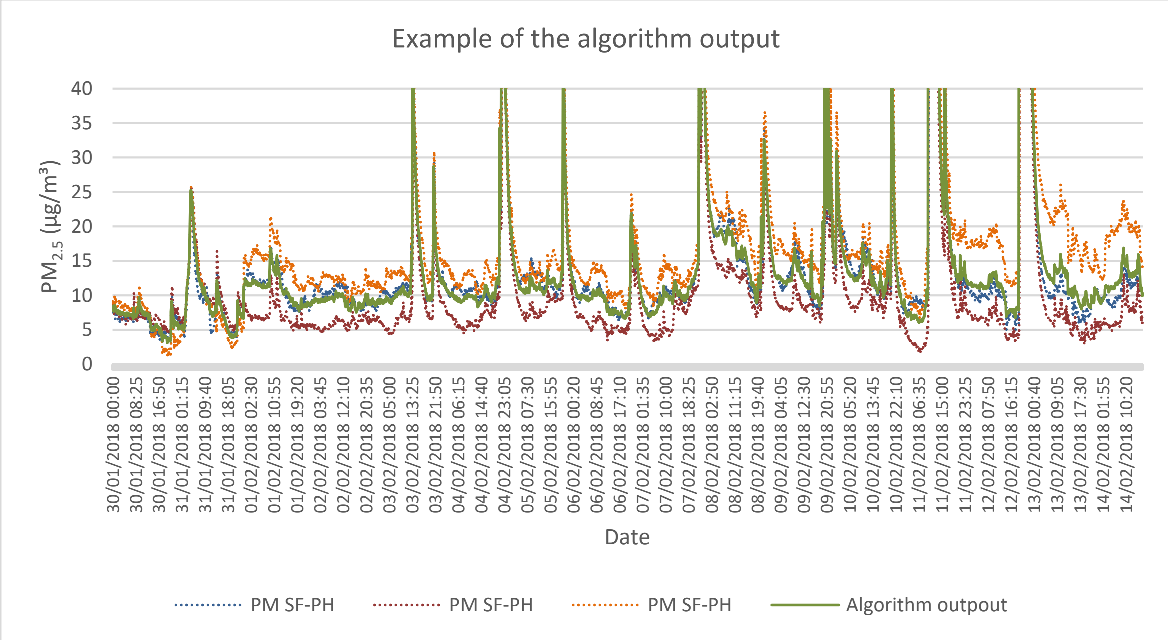


Figure 4.9 Example of the algorithm output.

vii. **Return of the instruments.** At the end of the monitoring project, the participants were asked to post the equipment in the original packing they received. They were supplied with a prepaid label for door-to-door service. The collection was arranged for a suitable time, but they also could drop the packages at their closest collection point.

viii. **Statistical analysis.** The Kolmogorov-Smirnov test was used to test the normal distribution of the data of each dataset. The results indicated that the data do not follow normal distribution, therefore, non-parametric tests were used to evaluate the data, otherwise indicated. Depending on the distribution of the differences the Wilcoxon signed-rank or the sign tests (non-parametric equivalent to the t-test) were used to test the median differences between the two data, while, the Spearman's correlation indicated the degree of association between them.

4.3.3 Online surveys

When designing a web questionnaire, it is essential to develop a respondent-friendly, self-administrated survey. Dillman et al. (1998) describe a usable web questionnaire as one that not only interfaces effectively with a variety of browsers but also makes it easy to respond to questions. There are three main criteria for a respondent-friendly web questionnaire design: (i) take into account a potential inability of respondents to receive and respond to web questionnaires with advanced programming features, due to computer, browser and/or transmission limitations; (ii) follow the logic of how computers perform and how respondents expect questionnaires to operate and (iii) take into account the likelihood of their use in mixed-mode surveys (Dillman et al., 1998: p.4-6). SurveyMonkey assures that the questionnaire technology used is adapted to a wide range of browsers and platforms, therefore avoiding the inability to respond due to advanced programming features. The logic of the structure is accomplished by providing a logical relationship between each question, giving instruction on how to answer each question and the addition of "*Next*", "*Prev*" and "*Done* (*Thanks for your participation*)" types of buttons to go on to the next question or to finish the survey. Whereas there was the intention to collect all responses by online surveys, participants were given the option, upon request, to be interviewed via Skype or telephone allowing for a mixed-mode survey. However, all participants completed the online surveys.

To guarantee the correct questionnaire design, the surveys used in this study follow the 12 principles proposed by Dillman et al. (1998, pp. 7–14) and Dillman and Bowker (2000, pp. 66–67), taking advantage of low-cost, high-speed and longer responses to open-ended questions (Denscombe, 2008). Therefore, the following principles were used to ensure consistency within the surveys:

i. A small introduction to the questionnaire on a motivational welcome screen emphasised the ease of response and instructed how to proceed to the next page.
ii. The first question was entirely visible on the first screen and easily comprehensible.
iii. Questions were presented in a conventional format, similar to how they would be on paper questionnaires.
iv. The background colours were consistently uniform, to maintain readability and measurement properties.
v. Visual differences in the appearance of each question were avoided for all platforms and browsers.
vi. The platform limited line length, and in the case of a PC or a Mac, this was limited automatically to 750 pixels in length.
vii. Specific instructions were provided on how to take action to respond to the questionnaire.

viii. Instructions on computer actions and specific response instructions (i.e. choose one answer) were provided as part of the individual question structure.

ix. There was no requirement to respond to each question before being allowed to answer any further questions, and when compulsory answers were requested, a "*Prefer not to answer*", "*I'm not sure*" or "*I don't know*" options were provided.

x. It was possible to scroll from question to question within the same section of the survey. Sections were structured to ask related information and to keep them independent from other parts, avoiding the need to look at previous answers.

xi. Double-banking was avoided in multiple-choice questions, but it was used for rating scale options.

xii. A progress bar was added at the end of each section, which contained a graphical symbol and words which conveyed a sense of where the respondent was in the completion progress, avoiding the need to scroll forward or backwards to have a sense of the questionnaire's length.

4.3.3.1 Questionnaire design and structure

The questionnaires adapted for this investigation were designed by following suggestions in the literature on IAQ surveys (Raw, 1995; Berry, Brown, *et al.*, 1996; Berry, Crump, *et al.*, 1996; Bordass *et al.*, 2001a, 2001b; Bordass, Leaman and Ruyssevelt, 2001; Cohen *et al.*, 2001; Coward *et al.*, 2001; Leaman and Bordass, 2001; Crump *et al.*, 2002; Zagreus *et al.*, 2004; SCHER, 2007; ASTM, 2014). Two sets of surveys provided information about building characteristics and occupants' perceptions of IAQ, thermal comfort and health. They were divided into different sections to increase the respondents' answers, but also due to the limitations of SurveyMonkey's free version.

The building characteristics questionnaire was divided into the following sections: general building information, ventilation, heating and cleaning habits, cooking and washing habits and pets and environmental quality (Figure 4.10). The occupants' perceptions questionnaire was divided into the following sections: background information and personal well-being, environmental conditions of IAQ and environmental conditions in terms of thermal comfort (Figure 4.11). A copy of these questionnaires is available in Appendices 2 and 3. Each of the sections in both questionnaires has ten or fewer questions in a logical sequence within each of the sections, but with no continuity between each other, so they can be taken independently.

The structure for both questionnaires was a mix between close-ended and open-ended questions; however, most of the questions were close-ended questions, and these were used at the beginning, followed by general questions when the use of open-ended could not be avoided. Rating scales were used to obtain information about the frequency of activities or the use of specific features by choosing from five options, from “never” to “constantly”, as shown in Figure 4.12. Rating scales were also used to indicate occupants’ perceptions of specific factors by choosing between seven-option unipolar (one extreme is good and the other is bad) and bipolar (neither end of the scale is ideal) rating scales, as suggested by Raw (1995) and shown in Figure 4.13. Raw recommends using the following parameters for analysis:

i. Unipolar scale:
   a. Ideal score: 1,
   b. A score higher than 3 requires further investigation,
   c. A score above 5 is cause of concern,
   d. Any score higher than the mean should be investigated further and ratings above one standard deviation above the mean should be a cause of concern.
ii. Bipolar scale:
   a. Ideal score: 4,
   b. A score outside the range 3-5 requires further investigation,
   c. A score outside the range 2-6 is cause of concern,
   d. Any figure above one standard deviation above the mean should be a cause of concern.

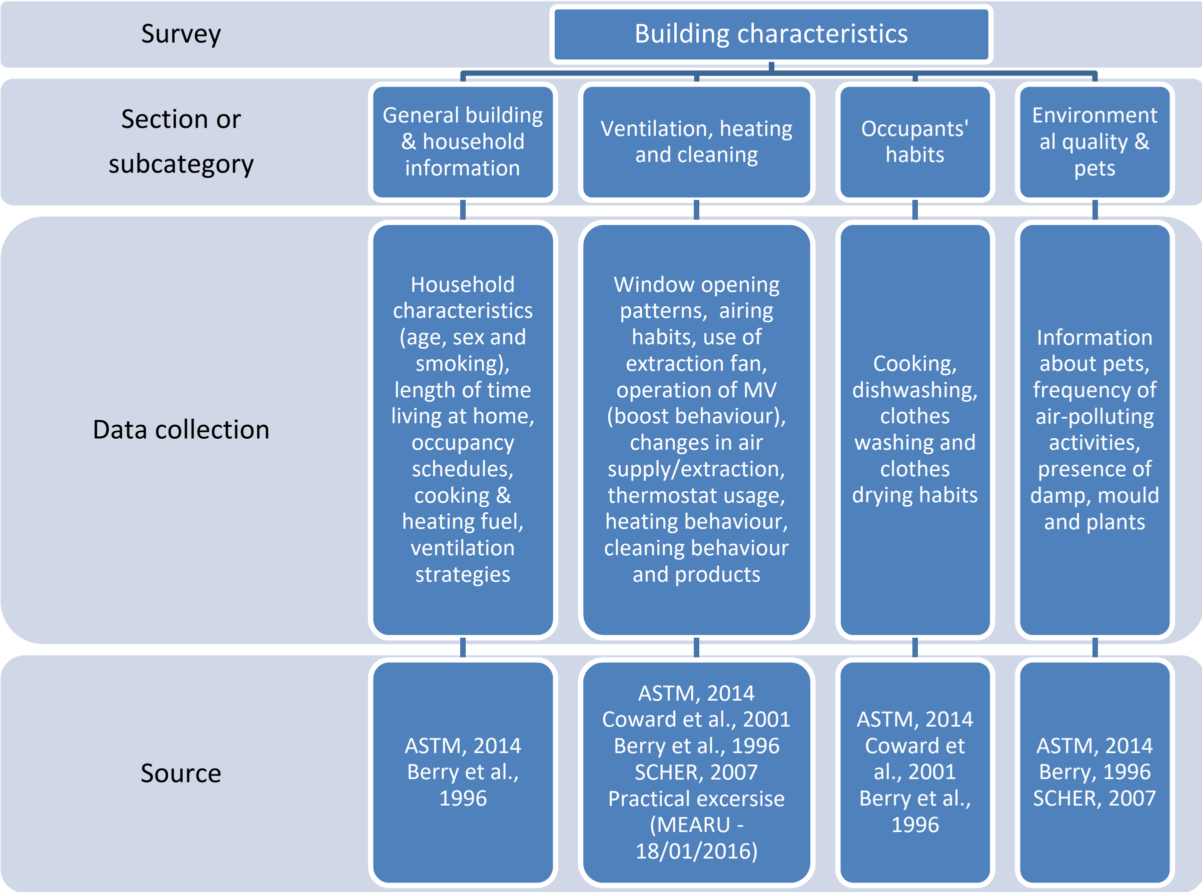


Figure 4.10 Building characteristics survey design and structure.

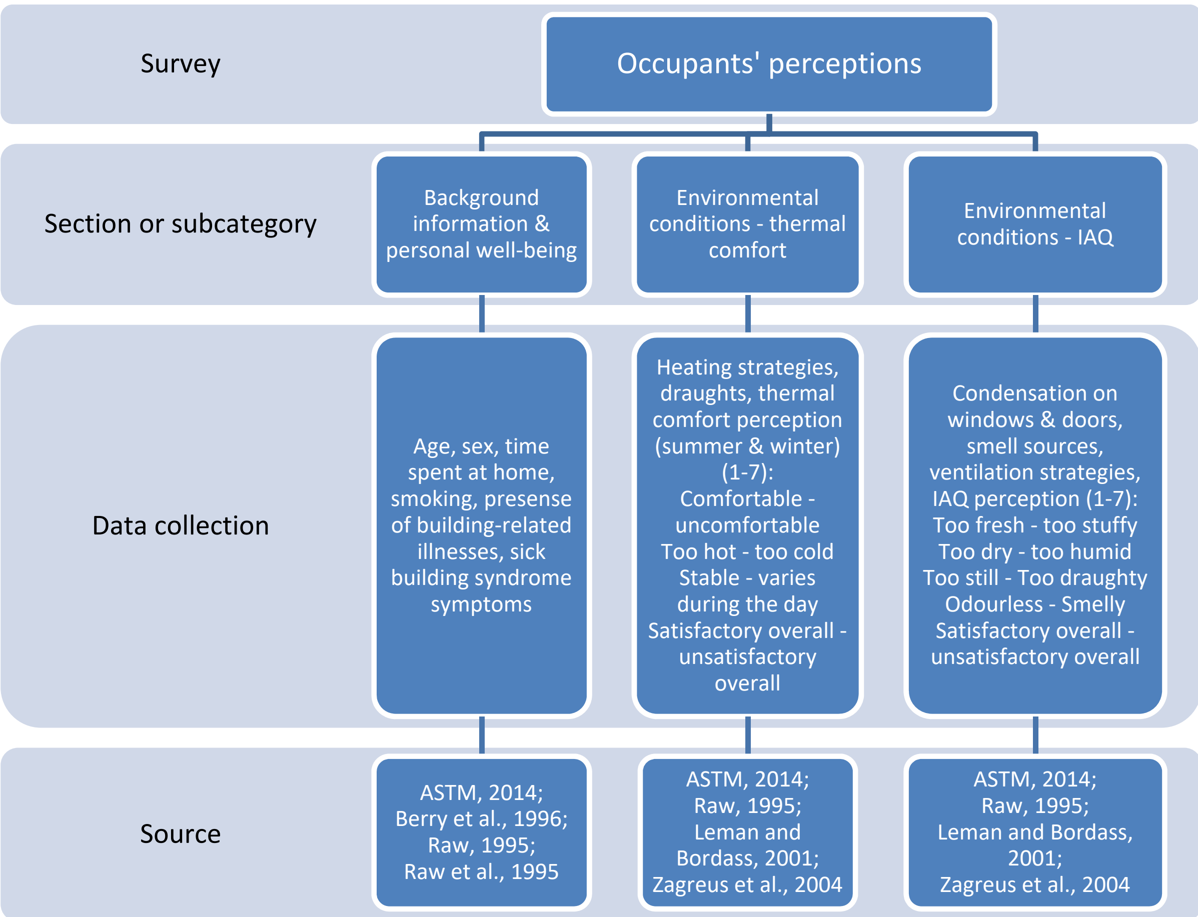


Figure 4.11 Occupants' perceptions survey design and structure.

The scale method provided data that were easy to analyse and reduce the time burden for participants, as suggested by Fellows & Liu (2015). The questionnaire on occupants' perceptions was limited to three participants per household, in line with SurveyMonkey's free version limitations. Standardised questions and scale rating systems were used to gain information about IAQ perceptions, thermal comfort, sick building syndrome (SBS) and building-related illnesses (BRI), as proposed in the literature (Andersson and Stridth, 1992; Raw, 1995; Raw *et al.*, 1995; Coward *et al.*, 2001; Hedge, 2004; EHSO EMORY University, 2012; ASTM, 2014).

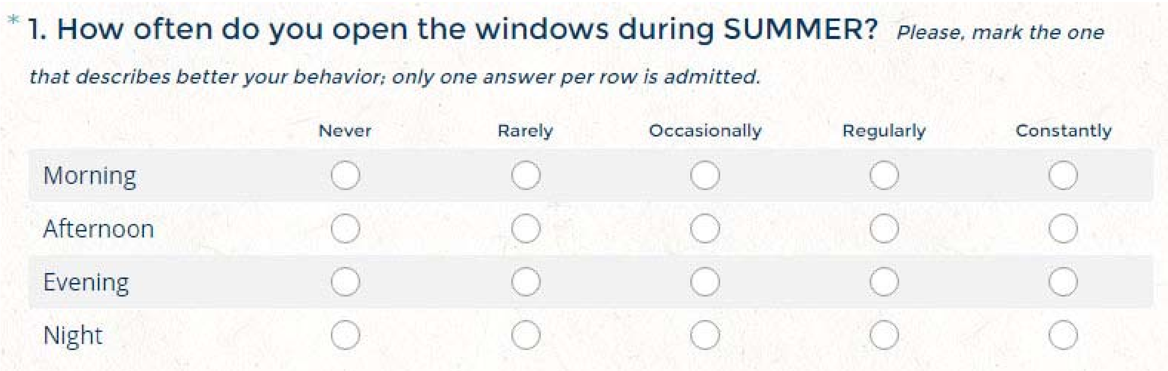


Figure 4.12 Use of the five-option rating scale. Source: author, taken from "Building characteristics" questionnaire.

Figure 4.13 Use of the seven-option rating scale. Source: author, taken from the "Occupants' perceptions" questionnaire.

SBS symptoms for each home were evaluated as proposed by Raw (1995, p. 6) and Burge (2004). The intention was not to correlate the Building Symptoms Index (BSI) to other homes but to have a better understanding of occupants' self-reported health. This study evaluated all symptoms – dry eyes, blocked or stuffy nose, dry throat, headache, tiredness or lethargy, dry, itching or irritated skin, itchy or watery eyes and runny nose –as suggested by Raw (1995).

4.3.3.2 Online surveys: building information and occupants' perceptions

Online questionnaires were designed to collect occupants' perceptions of environmental conditions. Self-administered questionnaires are used commonly for indoor environmental research, allowing participants privacy and anonymity and enabling the researcher to gather information about thermal comfort and IAQ perceptions, SBS symptoms and other building-related illnesses. Web questionnaires are to a greater extent self-applied questionnaires that are easy to administer and offer several advantages, such as checks for incomplete or implausible answers (Balter, 2005, p. 577) that can be remotely applied. The questionnaires were divided into two, the building survey split into four sections, and the occupants' perceptions survey split into three sections. In so doing, we expected to avoid questionnaire fatigue, as they could respond to each of the surveys in five-minute and then go back when they wanted, therefore providing more in-depth answers. Each of the questionnaires was divided into specific environmental factors for the interest of this research. Therefore there was no continuity between one or the other, thus avoiding confusion for the participants.

Cook et al. (1993) argues that the application of self-administrated questionnaires is more valid than those applied by the interviewer, as personal questions may be more likely to be answered honestly than face-to-face interviews. However, this kind of survey has weaknesses, in that answers cannot be corroborated, and maintaining motivation might be difficult. The questionnaires had a mix of close-ended and open-ended questions, when detailed answers were needed, as explained by Reja et al. (2003). In self-administered questionnaires, open-ended questions allow the respondent to give a point of view while avoiding the influence of the researcher, while close-ended questions limit the range of potential responses (Foddy, 1993). Reja et al. (2003) suggest that in web questionnaires open-ended questions not only need to be sufficiently accurate to avoid problems and garner the desired answers, but their use also needs to be planned carefully. When they are regularly used, respondents may skip a question.

4.3.3.3 Building data

During the pilot test, one of the biggest challenges was collecting building information, because in many cases the participants did not know where to look for specific information.. Building information was collected from straightforward questions and, where possible, we asked the occupants if it would be acceptable to contact the house designers for additional information. This proved to be a simple process, as all of the occupants from the PassivHaus were very keen to obtain information about the performance of their homes; however, for the control homes, this process was more challenging and the occupants did not always provide enough information.

At the beginning of the study, participants were asked if they could provide information about the building (or permission to contact the building designer on their behalf). However, to reduce the burden, participants were only asked for the most essential technical information, floor plans, construction methods and ventilation parameters. This proved to be difficult, as participants provided the data in different formats and timing. For instance, Mexico City participants building data was provided at the beginning, in San Francisco at the end of the monitoring phase, whereas Dunfermline data was supplied by Edinburgh Napier University (research partner for this case study). The proposed monitoring protocol was on a *do-it-yourself* basis, and so the participants supplied all of the necessary available information. This limited the capacity of the researcher to have visual confirmation of the information, and the researcher assumed that all of the information provided was correct. One of the most significant limitations of this study is related to information given by the building occupants. After completing the pilot study, it was noted that a building survey was required to identify some significant building characteristics that might influence IAQ. Thus, building information about the presence and operability of the windows in each room, aligned with general details about heating operation, ventilation, cleaning, kitchen and washing habits, was recorded on building surveys as shown in Appendix 2 in addition to the occupant diary.

4.3.3.4 Occupant diary

Information on activities that occurred over the monitoring period was recorded in an occupant diary (see Appendix 4). However, due to the length of the monitoring projects (6.5 months to a year), it was difficult to engage participants for such a long time, so each household was asked instead to provide a general weekly summary of regular activities and occupancy patterns.

In the pilot, this diary intended to ask the participants to record their behaviour for every hour, but this schedule was reduced to once a day in the main studies in order to gather sufficient information but avoiding frustration or nuisance to the participants. They were asked to record occupancy in the kitchen, living room and bedroom, indicating rough times and numbers of people, activities (i.e. window and door opening/closing, drying clothes indoors, cooking, smoking indoors, heating/cooling schedules and cleaning). Drying clothes indoors signifies a higher count of airborne mould spores (Porteous *et al.*, 2014) They also indicated the times and frequency of using air-contaminating products (i.e. candles and cleaning products). The diary was provided in a table in a Word document, which proved efficient for:

i. Remote access
ii. Providing clear data by avoiding any misinterpretation of the participants' handwriting
iii. Providing sufficient space for filling in answers.

4.3.3.5 Technical information

Participants were asked to provide technical information on their homes, architectural drawings, construction details and photographs. In some cases, they did not provide all of the data, so the researcher used whatever was available. In the Scotland case study, building envelope U-values and air blow-door tests were performed on each of the homes before setting up the sensors. These tests were in collaboration with another researcher from Edinburgh Napier University. Some public results about the energy-performance of these houses were scrutinised for building information (Jack *et al.*, 2013; Bros-Williamson, Garnier and Currie, 2016). These houses were previously monitored, the interest was concerning energy efficiency and IAQ data were not collected. The collected information and their sources in the case studies are shown in Table 4.3. This proved to be challenging on the pilot studies; however, in the case studies the participants provided all the information, or the author collected them from third parties except the layout of one home.

Table 4.3 Collected data and their sources in each case study.

Case study	Location	House code	IAQ measurements	IAQ perceptions	Thermal measurements	Thermal perceptions	Building information (online survey)	Digital Occupant diary	Construction methods/details	Floor plans	Ventilation parameters	Heating patterns	Window opening pattern
1	Mexico City	MX-PH	x	x	x	x	x	•	•*	•	•	•	•
		MX-CO	x	x	x	x	x	•	•*	•		•	•
2	San Francisco	SF-PH	x	x	x	x	x	•	•*	•	•	•	•
		SF-CO	x	x	x	x	x	•	•*			•	•
3	Scotland	SC-PH	x	x	x	x	x	•	‡	‡	‡	•	•
		SC-GD	x	x	x	x	x	•	‡	‡	‡	•	•
		SC-CO	x	x	x	x	x	•	‡	‡	‡	•	•

• Provided by participants
x Collected from physical measurements and online surveys
‡ Collected from (Jack *et al.*, 2013; Bros-Williamson, Garnier and Currie, 2016) and/or from Julio Bros-Williamson.
* Calculated U-values.

4.3.3.6 Data analysis

As mentioned previously, the participants were asked to set up three Foobots in the living room, kitchen and main bedroom. The intention of this was to introduce some redundancy and reduce bias errors for single low-cost IAQ monitors, one of the most important limitations of this approach was that it was difficult to spot one location with three plugs for the Foobots. Participants were asked if they would like 3-way sockets/adaptor plug to be posted to reduce the number of plugs required. Some of the occupants decided to locate the Foobots in different locations in the same room to avoid the use of adaptor plugs. This may suppose some differences from one instrument to another, but as they are located far from pollution sources they should have a good representation of the background levels in the room.

Data from all Foobots were then merged into a single master file in Excel. Additional data inputs – seasons, months, days, hours and occupancy patterns – and an algorithm to calculate absolute humidity as defined in Chapter 2 were then applied to the ambient and Foobot. Another algorithm was applied to calculate the mean of each parameter of each row for the three Foobots in each space. The file was used to produce the graphs and tables shown in this work. The total amount of missing data was calculated for each parameter so that the the dataset mean could replace the missing values. When doing statistical analysis, it is essential that the missing data is less than 3% of the total data as suggested by

Field (2016). Once all data was in a single file, the missing values were substituted by the means for statistical analysis in SPSS.

A Kolmogorov-Smirnov test was applied to assess the normality of each parameter. Depending on the results, Pearson's correlation test was applied when data distribution was normal, or a Spearman's rank-order correlation was applied when the test rejected the hypothesis of normal data distribution. The correlations served to assess the relationship between the indoor and outdoor environments of each home and to assess indoor conditions from one house to another, especially during occupied hours. The data then were analysed using different combinations of cases between the nominal (seasons, months, days, hours and occupancy patterns) and scale (IAQ parameters) data-type values. Thus analysis of condition sets across time was possible, for example, the hourly mean of a month, or calculating the occurrence of temperatures above 25°C during occupied hours in May.

4.4 Pilot Study

The monitoring protocol was tested during a pilot study in Glasgow focusing on the data collection and monitoring methods. Pilot studies were carried out for two weeks during March and April 2016 in Glasgow city centre. Participants received instructions by email, and printed set-up guides and the Foobots were given to them in an attempt to imitate the real study as much as possible. As the researcher tested the methodology and monitoring devices, the pilot study served to obtain objective feedback. The participants were asked to note down any problems they had during the process. This section focuses on this feedback rather than the steps taken to asses the IAQ. Feedback from the participants was vital in the development of the monitoring protocol.

This process identified some issues with the monitoring protocol, physical measurements and surveys that were adapted to the final protocol (Table 4.4). Temperature, humidity, $PM_{2.5}$ and VOCs were monitored for two weeks, and outdoor conditions were obtained from the local network as described previously.

Table 4.4 Lessons learned from the pilot study: physical IAQ measurements, occupancy diary and online surveys.

Problem	Solution
Participants found the first set of questionnaires confusing.	Open-ended questions were changed as much as possible to close-ended questions. Simple instructions to fill out the questionnaires were written clearly for each of the questions.
It was not possible to ask all the participants to fill out the same survey, as the free feature in SurveyMonkey only allows three respondents per survey.	Personalised surveys were created for each participant with the same questions. Questions intended to identify the location of the house were omitted. Personalised surveys allowed the researcher to control and identify survey respondents. Additionally, this resulted in better engagement with the participants.
Lights from the Foobot were on at all times.	Once the participants set-up the Foobots, the researcher switched off the light IAQ indicators from all Foobots. Additionally, instructions were provided to the participants so they could dim/turn off the lights, and they were advised to get in touch if they required further assistance.
Locating the devices was problematic. The ASTM (2014) suggests that the best place is in the centre of the room. In some cases, this was not possible or was inappropriate.	Instructions were adapted to ensure the placement of the monitoring devices in a convenient location where they did not disrupt day-to-day activities. Extension cords needs were individually identified when explaining the study and posted upon participants' request. Also, the maker's recommendations for placing the Foobot were advised.
Occupant diary was very detailed, but the participants became confused and consequently not enough information was collected. Occupants were asked to fill the diary on an hourly basis for two weeks; however, it was found that they filled in just one week and marked their activities for both weeks on a one-week sheet. They also forgot to do it sometimes, so the information was mixed between both weeks.	Occupancy diary was amended to be filled daily over a single week allowing the collection of general activities and behaviour. This resulted in more participation during the second pilot study. Clear and straightforward instructions were written and provided at the top of the occupancy diary. A day example was given in the first row of each week. Occupant diary collected information on the general behaviour of the occupants by season, rather than expect them to complete one during all the monitoring phases.

Printed material was found to be costly and challenging to keep, collect and post, particularly since the aims of this study is to do remote monitoring. Participants in the pilot study received hard copies of the surveys and all the material.	Participants of the second pilot study were given a hard and digital copy of the instructions, occupant diary, surveys and Foobot guides. Participants stated that filling in the digital occupant diary and online surveys were easier than doing the paper version; they preferred the Foobot guides in hard copies as they were more useful. Digital occupancy diary enables the participants to have enough space to provide answers and avoids the researcher misinterpreting handwriting.
Printed instructions for placement of the monitors were too small, making instructions difficult to read.	Each of the participants in the second pilot study was given the option to choose from among three varied font sizes. This helped identify the best compromise between paper size and font size. The medium size was found to be optimum.
Questionnaire application took more time than expected; this exceeded the time identified to participants, and they were frustrated at not finishing on time as suggested.	The first pilot study showed the need to adapt surveys to make them simpler. Therefore, the online surveys were divided into different individual sections and a completion bar was added at the end of each part. This allowed the participants to take the surveys in short time slots (less than 5 minutes) whenever they wanted. Each of the parts contained 10 or fewer questions and there was no direct continuity between any of the sections.
The stored data were accessible at 30-min (or more) intervals, depending on the duration of the study from the maker's dashboard.	A software was developed to download the information. This used the API key provided by AirBoxLab. Software development was commissioned to a third party.
Written instructions were confusing and sometimes difficult to follow.	The how-to guides (set-up, maintenance and health & safety instructions) were adapted to provide an image for each instruction. A sketch showed the best locations to place the Foobots in the bedroom, kitchen and living room. Separate guides were made for each room. ASTM, ISO and the maker's recommendations were adapted using

	the personal experience of the researcher and the pilot study participants' feedback to give more explicit instructions.

4.4.1 Lessons learned from the pilot studies

The pilot study provided invaluable insights into the practicality of this investigation. At the end of it (after two weeks), participants were asked about their experience. They reported that they took a little while to become used with the Foobot and ignote its precence; however, it was difficult to track if its presence affected their behaviour. Whilst this period varied from participant to participant, it was suggested that one week was about the average time, which matches the adjusting period indicated by the manufacturer so that the Foobot algorithms perform "environmental learning". However, during the Foobot test, data were found to be more accurate and stable after two weeks. This lesson was learned in personal experimentation with different IAQ monitors and the GrayWolf instruments from 6th February to 1st March 2016 in the researcher's flat. Therefore, this period of adaptation would also serve to reduce the Hawthorne effect (see section 4.7.1. Hawthorne effect).

The key lessons from the initial investigation and the pilot studies are presented in Table 4.4, but the following elements were identified from this previous work and tested in the pilot studies:

i. The equipment (scientific and low-cost) has a continuous backlight, which could be irritating when trying to sleep
ii. The Graywolf particulate counter produced a low but constant sound, which over a given period could cause discomfort and be irritating
iii. The space that the Graywolf equipment occupied was invasive; it was difficult not to be noticed
iv. Cables and equipment interfered with day-to-day activities.

In summary, the use of Graywolf and other common monitoring equipment has some practical drawbacks, as well be being much more expensive, and not available in such large numbers. The assessment of the low-cost device gave sufficient confidence that robust data could be collected.

4.5 Research implications

4.5.1 Research scope

This project focuses on IAQ in urban PassivHaus residential buildings and develops an IAQ monitoring protocol using low-cost monitors that can be deployed remotely. The monitoring protocol may serve for any IAQ investigation where more extensive sampling is required but funding is limited, or where researcher access is not possible. Whilst there is confidence that the monitoring regime can provide data which provides insights, it should be noted that the desired outcome is to scrutinise the IAQ trends through relative rather than absolute IAQ values. However, the research has a number of limitations:

i. Available funding was limited which restricted the number and type of sensors, laboratory analysis on airborne fungi and physical access to the homes;
ii. The availability and recruitment of the case studies was challenging; so limited numbers of case studies are selected;
iii. The accuracy of IAQ monitors has some limitations;
iv. The indoor and ambient air quality and environmental parameters were measured with different instruments and were from different datasets;
v. The collection of technical building information was challenging and not all information was obtained; and
vi. The researcher did not have the opportunity to confirm the information about the dwellings' use or the occupants' behaviour. It is assumed that what they stated in the surveys was indeed true.

IAQ monitoring work was carried out for periods that allowed to identify IAQ variations between winter, summer and a transitional season. It was important to collect data about the indoor performance during summer and winter, as during these seasons the ventilation patterns in the homes are completely different due to outdoor temperatures. In some occasions, the Foobot set-up in took place during winter or summer and recorded data until the campaign's end, nevertheless significant data of each season were secured.

4.5.2 Research ethics

Ethical approval was granted by the Glasgow School of Art Ethics Sub-committee on 19th January 2016, and changes made after the pilot study were passed to the committee to keep them updated. The following are the key issues that were addressed.

4.5.2.1 Literature review

The literature review was gathered from a wide variety of sources, including books, academic journals and magazines, conference proceedings, articles, guidelines papers, government publications, international standard practices, handbooks and building standards. These included a broad mix of databases, among them ELSEVIER, Scopus, Web of Science, Indoor Air Journal, JSTOR, Pergamon, SAGE and Science Direct. The use of Google Scholar was limited, as it is considered to have a business bias, and this may affect the quality of the search. However, a frequent practice was to look for additional literature by scrutinising the references of peer-reviewed literature and then look for specific literature in Google Scholar. Emphasis was made to look for literature on residential IAQ and PassivHaus, but when it was not possible, other IAQ studies from different low-energy approaches were used.

Furthermore, the literature was not limited to a geographical area, as the scope of this investigation is to study urban environments in different parts of the world. The literature on IAQ is limited in specific locations, and there is much to learn from other places. The review of the documents was made selectively by evaluating the state of knowledge in critical terms (Ridley, 2012), i.e. whether positive or negative focusing on a specific knowledge area (Knopf, 2006) but in an impartial, clear, consistent and systematic manner (C. Hart, 1998, pp. 79–99).

Other works were used to construct a critical argumentation and create a judgment to formulate a hypothesis. Efforts were taken to avoid plagiarism while keeping objectivity by citing others' work (Park, 2003; Shenton, 2010). Special attention was given to remaining objective in the judgment of all sources (Pears and Shields, 2005), and care was taken when using sensitive or confidential information (Kaiser, 2009), as it is the moral responsibility of the researcher to protect participants (Giordano *et al.*, 2007), particularly those related to domestic BPE (Sharpe, 2018). It is of equal importance to observe ethical guidelines for internet research, as suggested by Buchanan (2010, p.83), Berry (2004) and Markham & Buchanan (2012).

4.5.2.2 Fieldwork

Fieldwork is a "*form of inquiry in which one is immersed personally in the on-going activities […] for the purposes of research*" (Wolcott, 2005, p. 55); therefore, it involves all of the activities the researcher does, from the beginning to the completion of a study. In this research, it was important that the researcher had first-hand experience of different monitoring equipment (both low-cost and standard instruments) in order to instruct the participants on the most appropriate location to place the equipment and develop more comprehensible instructions for the equipment use. It also provided a clear insight into the time the participants would take to set up the equipment, guaranteeing that it would not be too onerous and ensuring that day-to-day activities would not be affected. Safety and maintenance instructions were provided to participants, with great emphasis placed on keeping the equipment beyond the reach of children, or away from walls or areas where the air flow could be obstructed.

Participants received a digital "Participant Information Form" and a "Participant Consent Form" (see Appendix 5), both of which needed to be completed before any involvement. The forms explained that some confidential information would be recorded; however, the researcher would anonymise all personal information. The forms also explained the participants' right to withdraw at any point, data protection and the usage of information, the names of the organisations involved, contact details as well as any advantages or disadvantages of undertaking this study.

In the same way, efforts were made to avoid any subjective comments about activities, cleanliness or other observations on the surveys. When a relevant question was asked, they had an "*I don't know/I'm not sure*" type of response to allow them not to answer a specific question, if they did not wish to do so. To reduce questionnaire fatigue, the surveys were divided into sections of no more than 5-minute questionnaires, thus allowing the participants to proceed either continuously or separately, as the questions were not related to each other. Moreover, when asking sensitive questions (i.e. health and behaviours) care was taken to make it impartially, thereby avoiding any chance of collecting any subjective information. The researcher analysed similar questionnaires to minimise the risk of breaking the ethics agreement.

Due to the remote data collection nature of the study, the collection of building information was challenging and not always possible. However, to collect the most information possible, reports, academic and web publications were scrutinised looking for additional details to those provided by the participants. Asking households to provide building information proved to be time-consuming and was most likely perceived as a burden, increasing the risk of participant withdrawal. Hence a compromise was made between the required level of detail and participants' contribution.

4.5.2.3 Participant recruitment and relationships

It was essential to maintain a good relationship with the participants, to keep their interest in the project and to reduce the risk of withdrawal. However, participants were approached with care to avoid entering a quasi-relationship rising the level of expectations from the researcher and making withdrawal difficult from participants as suggested by Sharpe (2018). The PassivHaus occupants were asked to contact one of their neighbours that might be interested in the study. This proved to be effective in recruiting the control houses, but this might be an onerous task in other research.

Participation was entirely voluntary, so there was no control over the households. Involvement in the study could be perceived as a burden, especially as there were no financial incentives to do so. This exposed a possible retention issue, but it was especially relevant for recruitment. We found that on some occasions the participants were enthusiastic about participating, due to the monitoring protocol. However, the following activities helped build a better relationship with the participants:

i. Participants were contacted by a person known to them, who introduced the researcher.
ii. Each of the participants received a handmade card of gratitude at the start of the project.
iii. Participants were reassured that participation was completely free.
iv. Parcel deliveries were arranged beforehand with each of the participants, at a time that was considered most convenient for them.
v. A small token of gratitude was made at the end of the research project. Chocolates or other little candies and a 'thank you' card were posted to the participants to thank them for their participation.

4.6 Research limitations

One of the principal limitations of this study is the size and scope, only three PassivHaus and 4 control homes. Where as the sample is small for exploration of IAQ issues, it provides valuable insights on the novel measuring system, coupled to surveys/diaries. The recruitment of the participants was more challenging than expected and we faced a lack of interest from 'gatekeepers' to gain access to a higher number of dwellings. The researcher decided to approach private dwellers, but, the recruitment of the homes in different countries took longer than anticipated so that the timescales of monitoring periods changed from one case study to another. Accordinglya commitment between the recruitment timing and the expected length of this study was made. However, avoiding the 'gatekeepers' obtaining technical building information (i.e. layouts, airtightness tests or construction details) became difficult. Therefore, the need arose to develop methods and protocols to gather this type of information; this study pilots this approach.

A number of factors limited the research, the most significant of which were time, access to people's homes (PassivHaus and control dwellings), funding and cost. However, other issues such as transport and access to equipment, a deeper understanding of low-cost and standard monitoring technologies, as well as IAQ parameters, were identified. Table 4.5 discusses the limitations and the actions taken to continue this investigation. Additionally, the experiments found obstacles that caused additional work on the monitoring study; these barriers were out of control of the researcher's hands and are presented in Table 4.6.

Table 4.5 Research limitations and actions taken.

Factor	Limitation description	Action taken
Access to building information	Verification of building information not always possible.	The information was corroborated, when possible, with published articles, reports and online information.
	The location of the case studies made it difficult to perform building surveys.	Participants were asked for the minimum amount of information needed and their permission to contact the designer of their homes, where possible. However, it was not always possible to

		collect all the information.
Access to equipment	Equipment (GrayWolf and Eltek) was subject to availability at MEARU.	Equipment was booked in advance.
	The equipment (GrayWolf and Eltek) was not available for extended periods during the consumer monitor tests.	The test was carried out in several stages.
	There was only one GrayWolf kit for monitoring, which was actively used.	A monitoring protocol using low-cost IAQ monitors was developed. The researcher purchased 30 new consumer monitor devices in addition to the 20 provided by AirBoxLab and 10 provided by MEARU.
Low-cost IAQ monitor	The accuracy of the monitors	The air quality monitors were tested before the study. Calibration equations were used to improve accuracy. Three Foobots were located in each room.
	Inter-sensor variability	A set of three devices was used in each room. A mean of the three devices was used to analyse the information.
	Sensor's capabilities	It was only to possible to collect indoor and outdoor θ_a. Other temperature metrics (θ_r, θ_{op}, θ_s, θ_{res}, θ_g) were not explored further due to the sensors limitations. Overheating assessment based on θ_a. CEH models were used to evaluate house dust mites based on θ_a and RH.
Ambient pollution measurements.	Exposing the low-cost IAQ monitors to ambient weather conditions may damage the sensors, thus	Temperature, relative humidity and $PM_{2.5}$ data were obtained from the closest local pollution

	producing misleading measurements.	monitoring network station.
Ambient pollution measurements. Access to properties	Different monitoring instruments to those used indoors are used to measure ambient IAQ information.	This may produce a small difference between the readings. Each country may use different technologies to measure outdoor pollution. These differences were accepted and compared directly to data collected by the Foobots.
	Difficulties to gain access to participants' homes. Limited access.	Recruitment throughout the MEARU contact network and PassivHaus designers. Development of the monitoring protocol on a do-it-yourself basis. Therefore, the researcher did not need to visit the properties.
Access to properties Case studies	Once the PassivHaus was recruited, there were difficulties in recruiting the control house.	The PassivHaus owners were approached to ask their neighbours and acquaintances if they might be willing to participate and have a property with similar characteristics (size, density, location).
	Case studies are in different countries.	We rely on the information provided by the participants. The monitoring protocol is appropriate for remote measurement.
Case studies Context	Information about case studies was limited.	Information was obtained online. We trust that participants provided accurate information. Building information was only possible to collect if the participants had it to hand.
	A small number of case studies.	Additional case studies were added to the original proposal.

		Measurements were from 6.5 months to a year (Table 4.2) in a few homes, in contrast to one-day monitoring in a broader number of homes.
	Participants communication/rapport	Communication with participants was through email and the option for video conference, or phone call was offered. Participants received 'thank you' cards and small tokens of gratitude at the beginning and end of the study. Participants were contacted one or two times in between as a follow-up.
	The homes were not adjacent or juxtaposed in all case studies.	Care was made to gain access to homes as close as possible to the PassivHaus homes, but due to the methodological approach, we relied on the PassivHaus owners to recruit the control home.
	This research limits to urban environments.	Some polluted environments were selected and the findings compared with the same contexts (at least two homes in the same city).
Cost	Elevated cost of equipment.	A low-cost monitoring technology was explored, limiting the measurement parameters. The researcher borrowed equipment from MEARU to test the low-cost monitoring technologies explored herein. AirBoxLab agreed to provide equipment at a

		significant discount ($99.00 US dollars).
Instrument transport	The equipment borrowed from MEARU was found to be bulky and difficult to move from place to place. Moreover, there was an extra cost of taking it overseas.	A low-cost monitor monitoring protocol was developed. The chosen monitoring device was not available in the case study countries. Therefore, the maker posted them directly to the participants.
Lack of ventilation measurements	Due to time, cost and practicality ventilation rate measurements and airtight tests were not performed.	The participants provided data about the ventilation strategy and rates (as designed), where possible. This investigation took those values as actual, even if they were not tested.
Specialised training on equipment.	Low-cost IAQ monitors training.	During the Foobot test, the researcher performed the Foobot set-up, to be able to provide instructions and guide the participants, if needed. The Foobots proved to be easy to set-up for participants and no training was required. Participants were given a visual guide on how and where to place the equipment.
Specialised training on equipment. Understanding of monitoring technologies	MEARU instruments required specialised training to set up and download information.	The researcher undertook fieldwork with other researchers from MEARU to get training on the equipment. For equipment not used for fieldwork, user manuals and instructions were provided by MEARU.
	MEARU equipment and low-cost monitoring devices use different technologies.	The researcher interviewed makers to understand the differences between them and to compare the results of the test. However, the Foobot

		maker was very cautious about providing information. The researcher discussed information processing from the Foobot with the maker to gain confidence in using such devices. Additional peer-reviewed literature was read, to gain a deeper understanding of the monitoring technologies.
Windows and door sensors	It was not possible to secure funding for window/door sensors to send to participants.	Participants were asked to describe their window opening patterns and record them in the occupancy diary, as well as interior door opening patterns.

Table 4.6 Obstacles and actions taken.

Obstacle	Actions taken
Missing monitored data in one of the rooms of the same dwelling.	Data were cleaned according to procedures learned from other MEARU projects. The mean of the dataset was used when data were missing as described earlier in the monitoring protocol. This is a common practice to produce reliable statistical analysis when data missing is less than 3% of the total (Field, 2016).
Problems with the internet connection of the monitors/missing information.	The researcher downloaded information regularly (10-15 days), checking that it was complete. When missing, it could be related to disconnection of the equipment, and so participants were contacted promptly to reconnect the instruments; support was provided on request.
Sampling data lost due to interruption of internet connection, electricity cuts or accidental unplugging.	Data were usually missing for a few minutes; when this was the case, data manually inputted as described in the monitoring protocol.
Technical problems with monitoring devices.	User manuals and FAQs were consulted for advice. In some cases, the maker was contacted directly for further advice.

	Participants were asked to consult the researcher for troubleshooting, and when needed they were referred promptly to the maker.
Just one of the case studies was recruited according to the original timescale	The timescale for the research was restructured, resulting in an additional year of study.

4.7 Research quality

4.7.1 Hawthorne effect

This research intended to look at “typical” real-life contexts; thereofre, the researcher did not suggest any interventions in occupants’ houses and avoided site visits. However, occupants’ behaviour might change from the moment they agree to participate, which is known as the Hawthorne effect (Landsberger, 1958). Some of the elements in the methodology tried to avoid this as much as possible, such as turning off the lights from the monitoring instruments and choosing a silent and small monitor. However, there may be specific behaviours that might have changed, i.e. the use of air fresheners, scent candles or window opening/closing behaviour might be influenced, as the participants know that the subject of the test is the quality of air. Therefore, the researcher explained to the participants that the intention was to gather information about “typical” conditions.

The chosen device was small in the hope that the participants would easily overlook it, thereby reducing the influence of the monitoring equipment in the Hawthorne effect. All visual notifications from the instrument itself, or on the participants’ smartphones, were deactivated, and participants were asked not to use at the app during the study period. Nevertheless they could access the app if they desired. As explained before, a two-week period is necessary for the devices to undertake self-calibration, but this also allowed the participants to become familiar with the devices. Consequently, data from the first two weeks were not used for analysis.

4.7.2 Replicability

The nature of the case study strategy is to research a phenomenon embedded in its context (Groat and Wang, 2013), and so it is not possible to extrapolate results. Environmental contexts, such as weather and ambient pollution, can never be replicated. Similarly, activities, behaviours and density patterns are events that are beyond the control of the researcher. Each IAQ measurement is therefore dependent on those factors that are impossible to recreate. Due to the nature of this kind of research, replicability can never be entirely achieved. However, 'literal replications', as explained by Yin (2013, p. 56), are possible despite the differences in contexts; they will not give equal results from one case study to another, but they may serve to formulate similar generalisations.

4.8 Chapter conclusions

The 'multiple case study' design study was used to investigate the IAQ in PassivHaus dwellings. It involved the collection of physical measurements of the indoor environment and the outdoor environment (quantitative data), as well as self-reported health and occupants' perceptions of the indoor environment (qualitative data). The analysis of each 'case study' was performed independently, and then a 'cross-analysis' of the case studies was performed. The case studies, located in Mexico City, San Francisco and Dunfermline, identified a PassivHaus and a control dwelling in an urban environment. Particular attention was given to ensuring that they were as similar as possible in each case study. However, each case study was unique, as they had different parameters, namely location, weather, building type, floor area and construction. Variations between each of the case studies allowed for testing different ventilation strategies, construction types and sustainable approach levels, among other variations. The real-life settings and weather conditions implied that controlling some aspects of the research would be unfeasible.

A novel data collection protocol, using low-cost IAQ monitors (Foobot) and remote data retrieval, was developed for this research. This data collection protocol takes advantage of the new technologies to collect building data, providing additional levels of privacy to participants. It is simple to use and install, and remote qualitative and quantitative data retrieval is also possible. Physical IAQ measurements were collected using the Foobot device as a monitoring tool, and the monitoring protocol was developed following international standards – ASTM-D7297 and ISO:16000-1:2006 – and the researcher's personal experience using the Foobot. Some adaptations were made according to the feedback from the pilot study.

Additionally, some strategies were used to assure the quality of the data during collection and analysis, thus reducing the bias that the use of low-cost IAQ monitors could represent. IAQ parameters collected with the Foobot were temperature, humidity, $PM_{2.5}$ and tVOCs, which were collected in the three case studies; however, additional Netatmo devices were allocated to the Mexico City case study to collect CO_2. Online surveys in self-administrated questionnaires were employed using a mix of open-ended and close-ended questions, based on The Royal Society of Health Questionnaire to Investigate Sick Building Syndrome allowing data collection of occupants' IAQ perceptions and self-reported health conditions. Due to the limitations of the conventional approach to collecting IAQ data, this IAQ monitoring protocol was considered a correct and innovative initiative.

This study has several limitations, with time, funding and absolute monitor accuracy being the most significant. However, different actions were taken to mitigate these. The following chapters present the results of the IAQ assessment and the analyses of Mexico City (Chapter 5), San Francisco (Chapter 6) and Dunfermline (Chapter 7). A cross-analysis of the findings is presented in Chapter 8. Chapter 9 discusses the implications of this study and the experience of using this monitoring protocol.

Chapter 5 Mexico City Case Study

5.1 Summary

This chapter presents the results of the case study in Mexico City, a oceanic subtropical highland climate in a polluted environment. This case study is of substantial significance as it presents the first indoor environment evaluation of the first certified PassivHaus residential building in Latin America. More importantly, Mexico City was chosen as it is well known for being one of the most polluted cities. The first part of this chapter describes the household and building characteristics of the PassivHaus and control flats in Mexico City. The second part presents and compares the measured indoor temperature, relative humidity, $PM_{2.5}$ and tVOC levels. Due to the significance of this case study, additional resources were assigned to measure indoor concentrations of CO_2.

The indoor parameters were measured in the main bedroom, kitchen and living room of both homes, as described in Chapter 4, and then compared between both flats. Furthermore, ambient temperature, relative humidity and $PM_{2.5}$ levels were compared to indoor levels, the latter of which were assessed following the guidelines discussed in Chapter 2 and this chapter presents the results of these. Finally, the chapter examines and evaluates occupant perceptions of IAQ and thermal comfort.

5.2 Background

The project to construct the first PassivHaus in Mexico was initiated in 2007. It was envisioned to be a flat, built against a tight budget and with prefabricated materials while saving energy and improving typical thermal performance. In 2011, INHAB Arquitectura Sustentable decided to use PassivHaus design strategies to achieve these goals. INHAB is an architecture office located in Mexico City; its director participated in an internship in Germany, during which time he worked on several PassivHaus projects. On his return to Mexico, he decided to work on promoting PassivHaus practices in Mexico. Taller de Arquitectura PassivHaus (TAPHA), as the owner named the project, was the first attempt to reproduce the PassivHaus design in the Mexican context. It was awarded PassivHaus certification in 2014. However, to date, no other building performance or post-occupancy evaluation has been undertaken on the dwelling except the monitoring reported in this thesis.

Many buildings in Mexico City were damaged following an earthquake in 1987, and many were rebuilt to new standards set to prevent damage after such an event. This building was a part of a housing development mixing historical buildings with recently built development. The control flat sat in the new extension, completed in 2010. The flats were located within 285m of each other and within a kilometre of the local pollution monitoring and weather station.

Mexico City, like many large cities located in valleys, has severe air pollution problems. Industries and transport affect ozone and ultrafine particles levels. Mexico City's geographical and weather conditions aggravate this condition (Edgerton *et al.*, 2000), especially during winter.

Mexico City's local building code established that all dwellings should have a window area above 17.5% (5% openable area) of the façade area. Windows should provide 0.35ach of the space where they are located. If a mechanical ventilation system provides ventilation for the whole dwelling, this should provide at least 0.40m^3/min (6.66 l/s) per occupant (CONAVI, 2010). The bathrooms and toilets should have a window area of at least 0.12m^2, and half of it should be openable unless 0.5m^3 of fresh air is provided continuously by a mechanical system or 1.4m^3 by intermittent mechanical ventilation. (Gobierno del Distrito Federal 2004b).

The control flat in this case study was built under these regulations, but it did not use mechanical ventilation. The window area to the rear façade was substantially larger than the 17.5% required, thereby meeting ventilation requirements allowing for cross ventilation (living room to kitchen) and stack ventilation (living room to bedroom). The PassivHaus flat met both requirements, namely window and opening criteria, and additionally, it provided 0.69m^3/min (11.6l/s) using extraction only ventilation system to allow for air movement when the windows were closed from the living area to the toilet at the other end of the house.

Due to the mild climate, an MVHR system is not essential to achieve PassivHaus certification (from an energy perspective) and in this case, ventilation requirements were met with an extraction fan at one end (bathroom) of the house and a vent on the other end (living room, Figure 5.7 to Figure 5.9). Whereas the use of MVHR systems is still recommended by the Passive House Institute, it is not compulsory, as long as the ventilation rates are achieved, and the thermal comfort is not compromised (Wassouf, 2014). Evidence suggests that, in fact, MVHR systems can be omitted in climates with mild winters and cool summers without compromising the comfort levels and energy savings required for PassivHaus certification (Zangheri, Pagliano and Carlucci, 2009; Sassi, 2013).

The control and PassivHaus dwellings have notable differences in the construction methods, ventilation strategies and size, however, they have clear similitudes: such as they are located at similar distances (±10m) from the main road, they are flats, and they are located very close to each other.

5.3 Methods

Monitoring of the buildings was performed from 1st May 2016 to 6th July 2017. A site visit to both flats was arranged in April 2016; this was the only visit to any of the case studies to install IAQ monitors. Air temperature, relative humidity $PM_{2.5}$ and tVOC were monitored simultaneously in the living room, bedroom and kitchen of both dwellings at five-minute intervals. Figure 5.5 shows the location of the sensors. The MX-PH devices lost internet connection between July 22nd to September 7th, December 24th to January 13th and January 20th to 25th, thus losing data between these periods. Indoor levels of $PM_{2.5}$ and tVOC were assessed as described in Chapter 2.

CO_2 levels were measured using Netatmo NWS01-EU monitors. CO_2 levels were used to evaluate the effectiveness of the ventilation techniques in the dwellings, rather than as a metric of IAQ. Ambient levels of $PM_{2.5}$, air temperature and relative humidity were collected directly from the official website of the local atmospheric monitoring programme in Mexico City.

5.4 Household characteristics

The flats are located in the North-East in the 'Roma Norte' district west of Mexico City's historic centre (Figure 5.1). 'Roma Norte' encompasses a diverse building use: residential, restaurants, bars, clubs, shops, churches and galleries. The borders of the neighbourhood are three principal avenues which have dense and constant traffic, this in combination with the winds in the city which bring the surrounding pollution of the industrial zones to the central neighbourhoods.

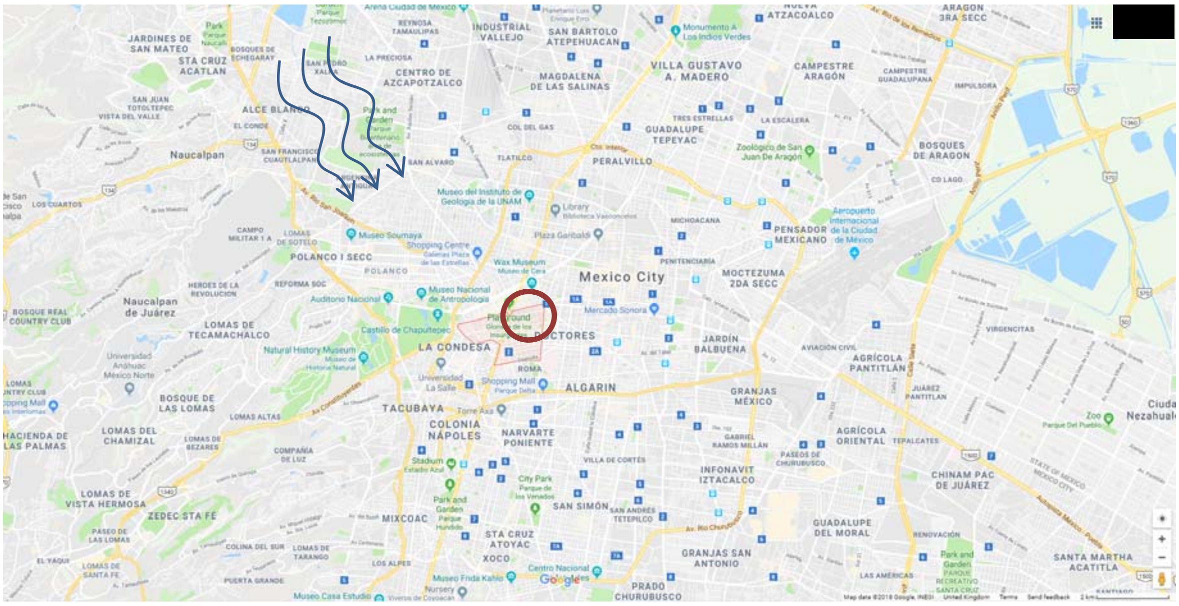


Figure 5.1 Location of 'Roma Norte' district. The red circle indicates the boundaries where the control and PassivHaus flats are located and the triangle the location of the nearest monitoring station.

The homes are located close to each other (Figure 5.2) in a central location where high outdoor pollution would be expected. Both of the flats are oriented north-south, facing the predominant north and north-west winds, thus outdoor sources are critical to the indoor environment. The flats do not have direct access to a garage (Figure 5.3). Both of the apartments had a similar layout, with a multipurpose room (living room, dining room and kitchen) connected to a hall, and from this to the bedroom(s) and the toilet. The bedroom and toilet of the control house were located on the first floor, whereas the rooms of the PassivHaus dwelling were located on one level (see floor plans, Figure 5.5). The MX-CO (control flat) had single glazing windows and patio doors, while MX-PH (PassivHaus flat) was double glazed with dark solar blinds. The living areas of both flats opened up with sliding doors onto an external private patio (Figure 5.4), where the occupants stated they smoked. Both of the courtyards had solar protection for the windows to avoid solar gains: while the MX-CO was fixed, MX-PH was an adjustable shutter. Nonetheless, MX-PH shutter was never adjusted during this study allowing for continuous shading. Table 5.1**Error! Reference source not found.** shows the building characteristics of both dwellings.

The MX-CO flat, on a second floor, is part of a non-insulated heavy construction building. It is built to the common building methods in Mexico: concrete structure (300 mm) and external and internal brick structural-walls (120 mm) plastered (10 mm) to the inside and outside, the floor slabs are a concrete slab (150 mm), base coat (4 mm) and ceramic tiles (15 mm) therefore the thermal mass is an important factor to consider in this building. The windows are single-glazing (3mm) with non-insulated steel frame (50 mm), it is a common practice to fit the glass over the frame with an aluminium frame from the inside resulting in leaky windows.

Table 5.1 Building characteristics of MX-PH and MX-CO.

Building characteristic	MX-PH	MX-CO
Airtightness (n_{50})	0.59 h^{-1}	No tested
Floor area	42 m^2	57 m^2
Main door	PVC (PassivHaus certified)	Wood (standard)
U_g-value (window)	1.64 W/(m^2K)	5.78 W/(m^2K)
U-value (floor slab)	0.33 W/(m^2K)	13.66 W/(m^2K)
U-value (roof)	0.36 W/(m^2K)	13.66 W/(m^2K)
U-value (wall)	0.37 W/(m^2K)	1.18 W/(m^2K)
Ventilation	Mechanical & cross natural Due to the mild climate, no MVHR was needed, however, an extraction fan (11.6 l/s) was used to achieve the ventilation. No kitchen hood.	Natural (cross and stack). Calculated ventilation (24.9 l/s) depending on the outdoor conditions Kitchen hood fans with no extract.
Window type	Double-glazing 6 mm/ 12 mm air, 4 mm low-e-clear-claro (PassivHaus certified)	Single-glazing 3mm (standard)
Building Standard	PassivHaus (certified)	Mexico City's Standard Building Regulation

Figure 5.2 Location of the MX-CO and MX-PH in Mexico City. Source: Google Maps (accessed November 2018)

The MX-PH is a light-weight construction built in the top (3rd floor). The external walls consist of 70 mm of insulation depth structural frame with a finish thorolastic coat to the outside (1 mm), base coat (4 mm), neopor insulation (75 mm) and an OSB board (19 mm) to the inside. The floor slab has a 3x OSB panel (30 mm) to the inside, air cavity (150 mm), air cavity with installations (80mm), nepor insulation (75 mm) over the existing roof (500 mm) in the building; finally, the roof has a pine plywood (15 mm) to the inside, a concrete slab (100 mm), waterproof bitumen (2 mm), neopor insulation (75 mm), base coat (4mm), and the waterproofing seal (2mm). Windows and doors are PVC (five chamber weather seal with insulation) PassivHaus certified components. External conditions made it possible for the MX-PH to rely only on internal and external heat gains to provide thermal comfort without MVHR ventilation, achieving ventilation rates (11.6 l/s) and the primary energy requirement (113 kWh/m^{2}a).

Figure 5.3 Front façade of the MX-PH (left) and MX-CO (right).

Figure 5.4 Rear façade and patio MX-PH (left) and patio of the MX-CO (right).

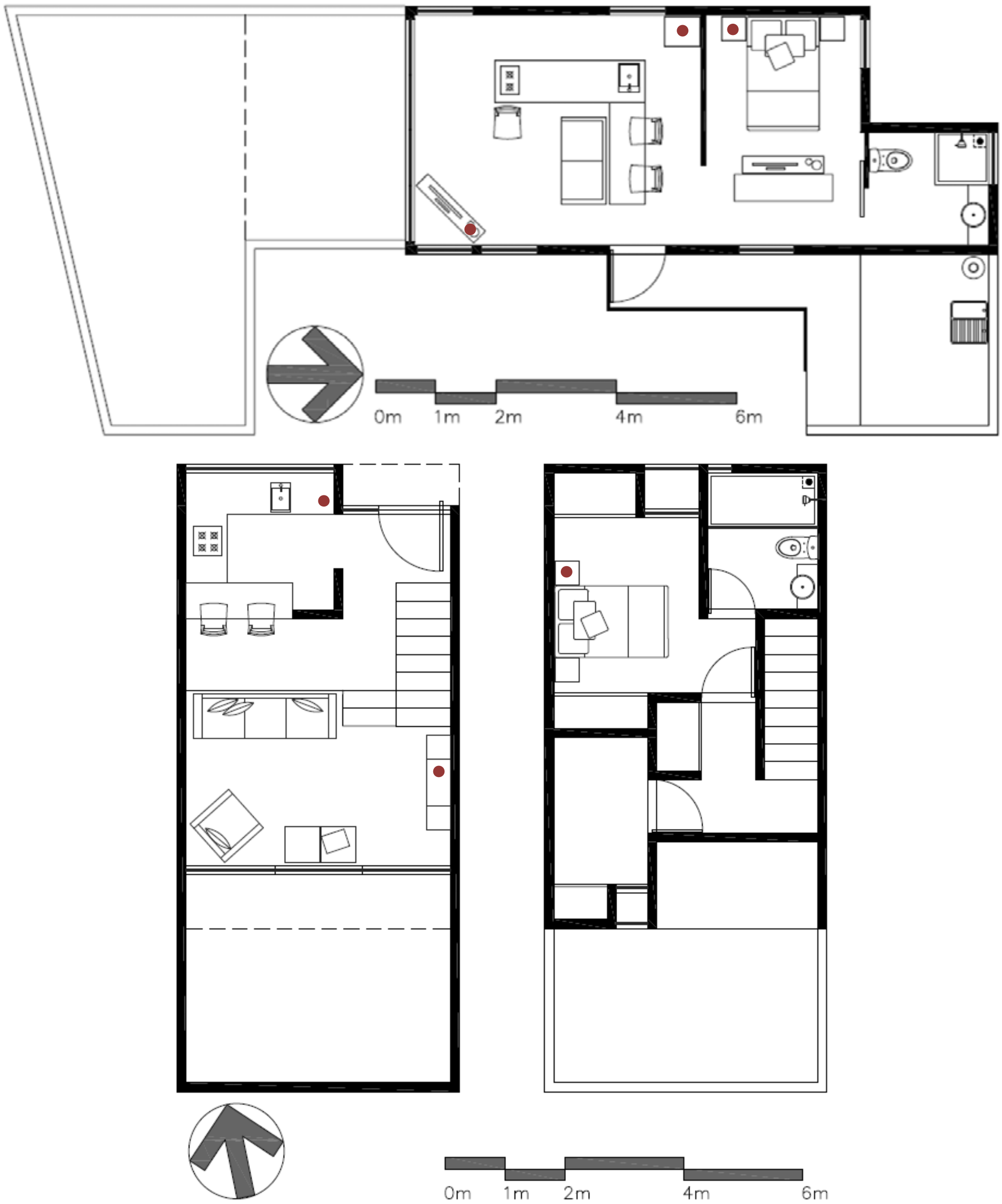


Figure 5.5 Floor plans for MX-PH and MX-CO. Floor plan for MX-PH (top), ground floor MX-CO (bottom left) and first-floor MX-CO (bottom right). The red dots indicate the sensors' location.

The MX-PH hybrid ventilation system has on one side of the house (the living room) three openings (0.05 m^2) with an F7 filter from which fresh air flows inside of the flat and on the other end (toilet) the extraction fan, with a system imbalance of 1%, as shown in Figure 5.7. In April 2016, the extract fans and supply openings were recommissioned to comply with the PHPP air flows (42 m^3/h, 11.6 l/s). The owner decided to remove the F7 filter from the ventilation system at this point. These filters are difficult to find in Mexico, and the owner was not prepared to perform the necessary periodic maintenance. The extraction fan was located in the toilet and had a higher capacity (95 m^3/h, 26.39 l/s), even after being installed (74.30 m^3/h, 20.64 l/s) than those required by the PHPP. To compensate for those differences, a timer regulated the fan to work for 34 minutes per hour, with the option of being manually activated/deactivated.

MX-CO relied entirely on opening windows and doors to control air flows in dry and wet rooms with no mechanical extract or background ventilation; therefore, the house could only be ventilated while occupied, due to security concerns. MX-CO achieved stack ventilation by opening the window/door to the patio and the door to the terrace in the main bedroom. When both windows are open, the house should achieve an airflow higher than those required for the local regulation (89.64 m^3/h, 24.9 l/s for 4 occupants as the house was designed). The door in the patio has the potential to allow for a higher airflow due to its size (3.27 m^2), however, the total air flow is restricted for the smaller size of the opening in the bedroom (1.89 m^2) and the internal doors which make it difficult to calculate an exact air flow. The house has a kitchen hood that recirculates the filtered air.

The houses were occupied by couples most of the time, with household occupancy ranging from two to three persons. In August 2016, the PassivHaus' owners moved and the flat was used for holiday lettings. Its occupancy was mostly couples, but on some limited occasions, single occupancy was reported it was not possible to collect occupancy patterns about this, however, the CO_2 levels indicate a similar pattern. During the letting occupancy 3-4 days a month the flat remained empty. Smoking indoors was not allowed in the PassivHaus, but there was a designated outdoor area. One of the occupants of the control flat stated to smoke, though stated that they did not smoke indoors. On average, the control flat was occupied 2 hours more than the PassivHaus flat, as indicated by the occupant surveys (Table 5.2). Occupancy patterns had clear differences as guests at the MX-PH usually spent more time at home during the morning (~1 hr), while the MX-CO occupants spent on average 3 hours during the afternoon/evening in the flat.

Table 5.2 Households profiles.Note: The occupants in the PH varied after August 2016 throughout the period of short lets

Household profile	MX-PH	MX-CO
No. occupants	1-2 Adults	2 Adults, 1 Baby
Cooking fuel	Electric	Gas
Heating fuel	None	Electric (only January and February)
No. smokers indoors	0	0
No. smokers outdoors	1	1
Average of occupied hours during weekdays	15	18
Average of occupied hours during weekend days	13	16

5.5 Results

5.5.1 Ventilation and heating

Both households completed the online surveys about the ventilation techniques they used and their behaviour in terms of proper ventilation, the owner of the MX-PH filled the surveys corresponding to their time in the flat, and for the time as Airbnb letting it was only possible to collect three survey responses. An information sheet with QR codes to the surveys, in English and Spanish, were hang next to the door so that the guests could upon their choice participate in the study. Comments from the PassivHaus household suggest that they relied on mechanical ventilation most of the time.

The window to the patio was occasionally open during midday, especially during summer. Interestingly, the occupants stated that they opened the window in the bedroom and the patio when it was not raining and while doing cleaning tasks (Figure 5.7-9).

Comprehension of the ventilation system was also an issue at MX-PH. For example, the owner stated they used the cooker hood during and after cooking. There was, however, no cooker hood installed in the kitchen. The owner also reported that when he lived at the property, they regularly used the boost function for the ventilation system, during and after cooking and showering. After an examination of the fan and its use with the timer, no boost function was located, but the timer could be turned to ‘continuous mode’.

The occupants reported issues with the ventilation system, in particular with the fans (such as noise, draughts and thermal comfort). MX-PH guests stated that the extraction fan was "*noisy, especially during nights*" and that sometimes they had problems sleeping due to the noise; in such instances, they said, it would be turned off. MX-CO occupants stated that the draughts caused by natural ventilation were uncomfortable from time to time, triggering discomfort that may result in closing the windows. This behaviour was more pronounced during winter. The MX-CO occupants claimed to use the cooker hood occasionally during cooking, but not thereafter.

Figure 5.6 shows the frequency of opening windows during summer and winter . The households show different patterns in this regard: whereas MX-PH owners reported that the windows were opened more frequently as the day progressed (during mornings rarely and frequently throughout the night), MX-CO reported the opposite. This coincides with the comments of the occupants that the house tended to feel cooler as the afternoon progressed into the night. Finally, only the MX-CO occupants attested to using heating (during winter), as it was "*too cold to be comfortable*".

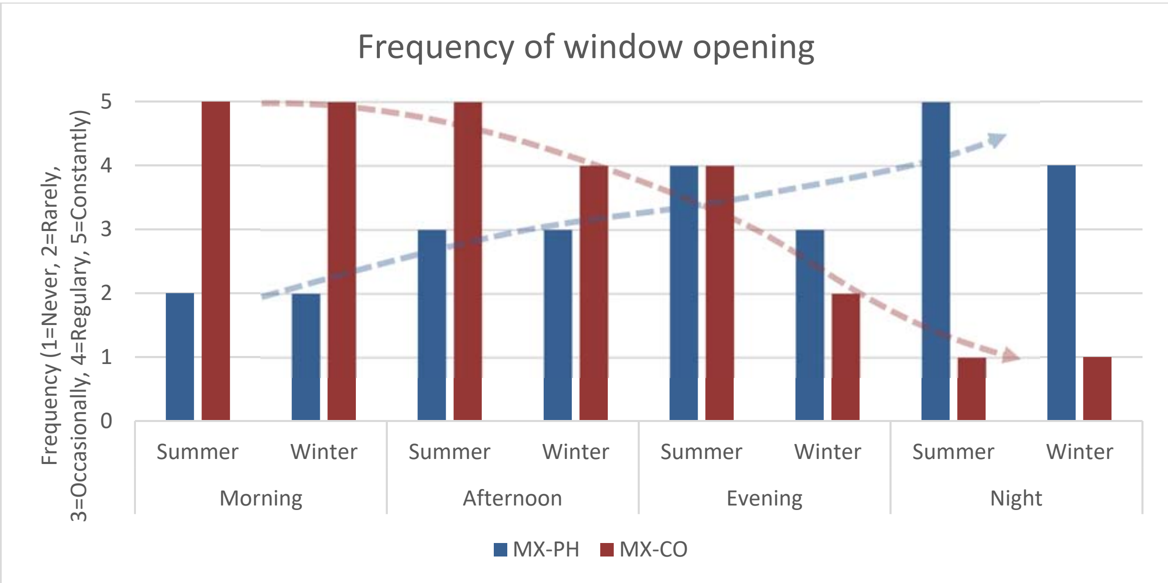


Figure 5.6 Reported frequency of window opening during summer and winter.

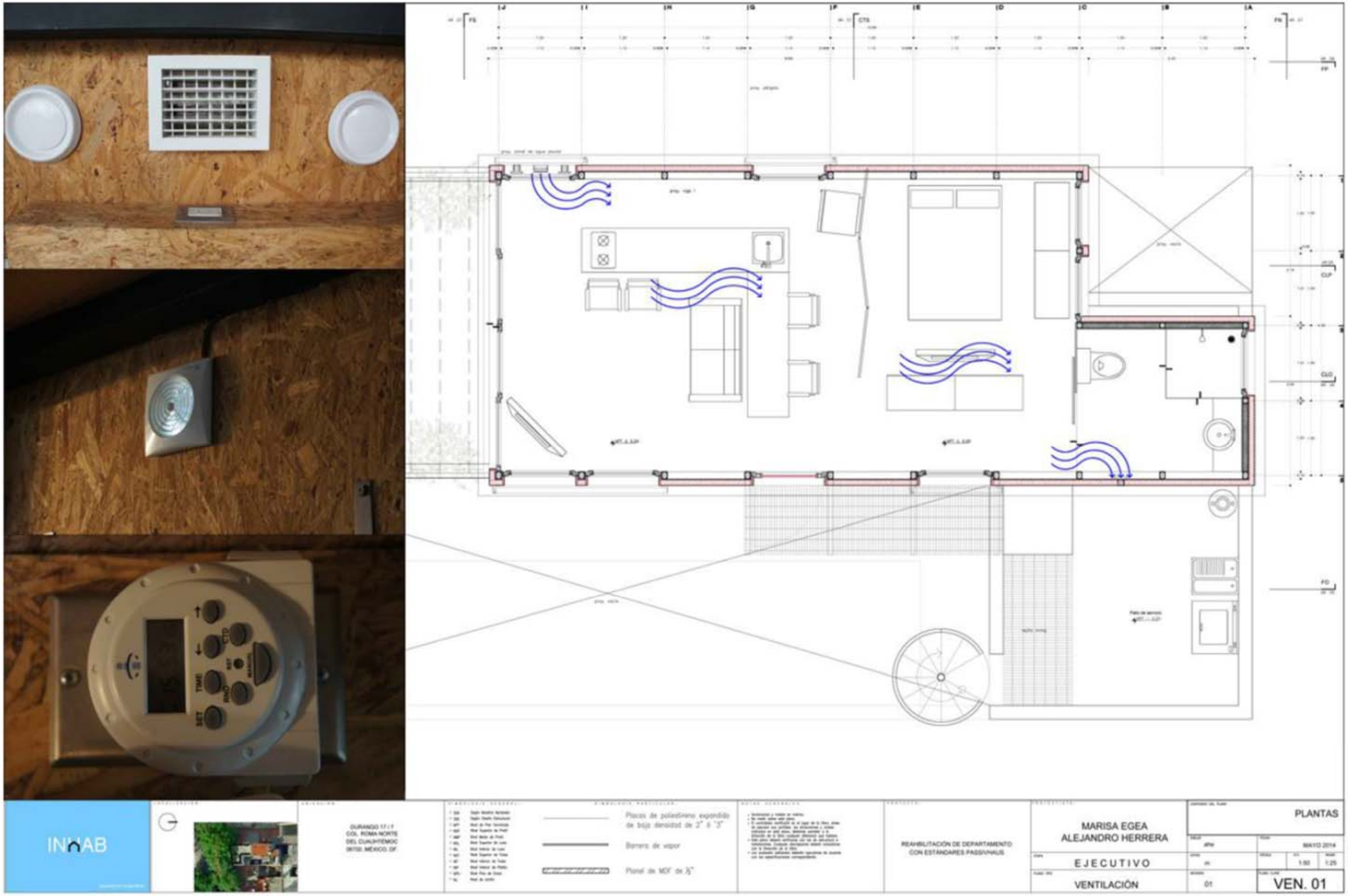


Figure 5.7 Floor layout of the ventilation strategy for MX-PH. The images represent the inlets (top), extraction fan (middle) and timer (bottom).

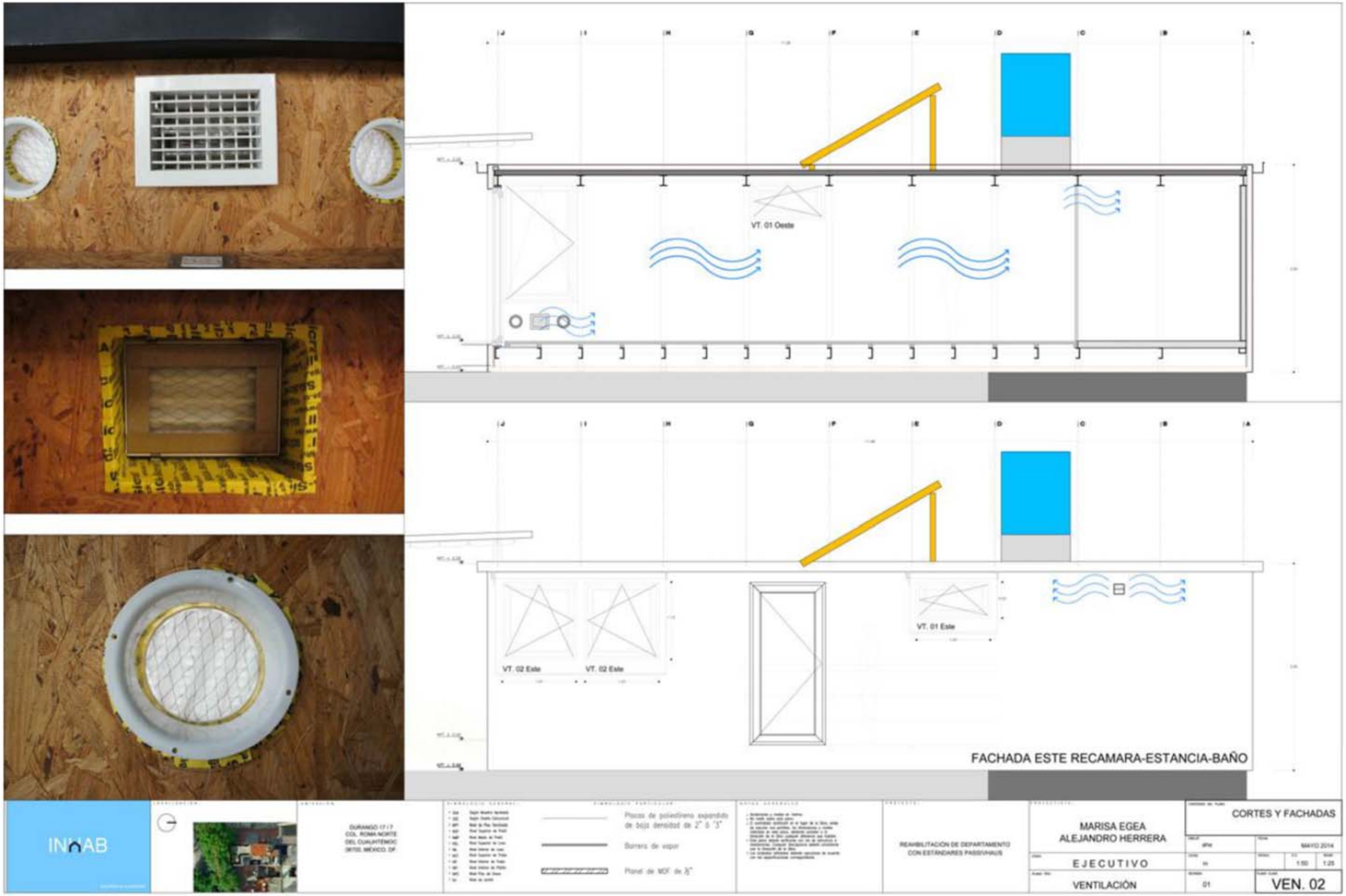


Figure 5.8 Section looking at west wall (top) and east elevation (bottom) of the ventilation strategy for MX-PH. Images show the ventilation inlets.

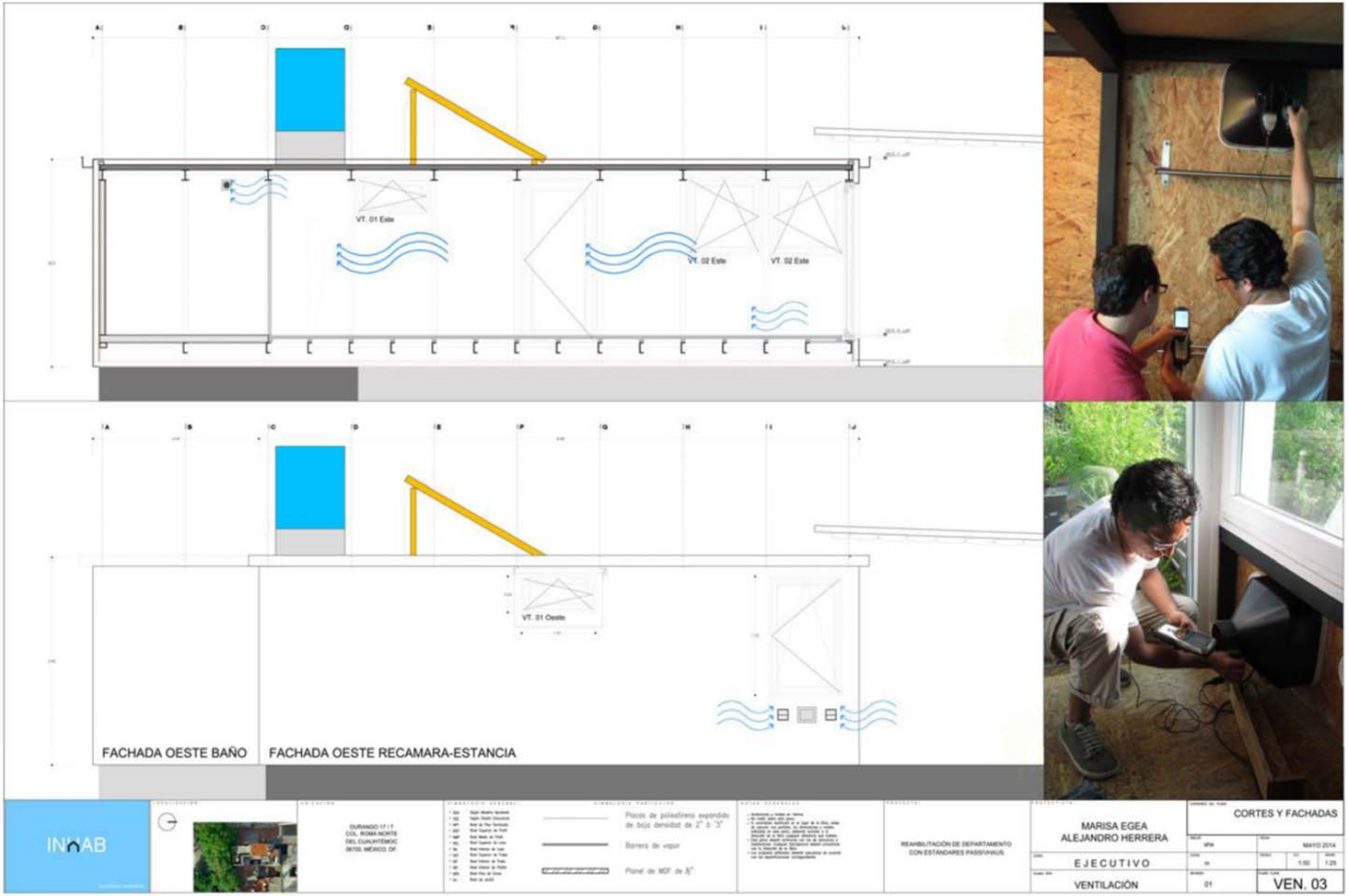


Figure 5.9 Section looking at the east wall (top) and western elevation (bottom) of the ventilation strategy for MX-PH.

5.5.2 Carbon dioxide levels

CO_2 was measured not as a pollutant but as a ventilation proxy as described in Chapter 2. The 1,000 ppm (Porteous, 2011; CIBSE *et al.*, 2015) threshold was used as ambient levels were not available. Figure 5.10 illustrates the annual profile in both flats. In the following pages.

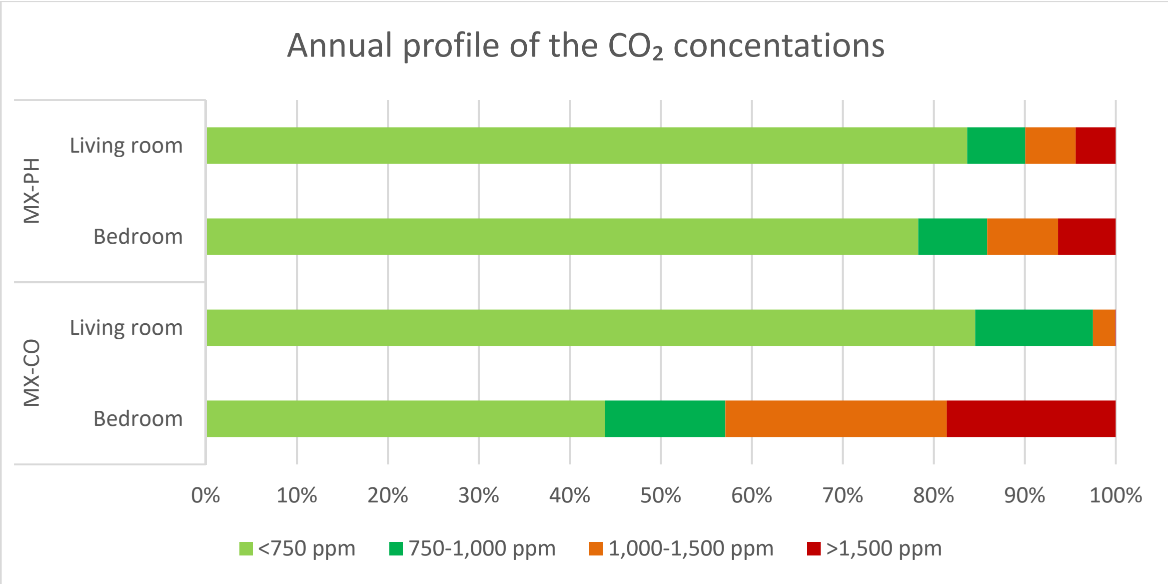


Figure 5.10 Annual profile of CO_2 concentrations in MX-CO and MX-PH living rooms and bedrooms.

CO_2 levels in the living rooms of both homes regularly exceeded the 1,000ppm throughout the year (Figure 5.12 and Table 5.3). The highest peaks occurred during spring in both flats and the highest mean levels during spring for MX-PH and in winter for MX-CO. Spring CO_2 levels peaked as high as 4,498 ppm (26/03/2017) in MX-PH and 1,971 ppm (19/03/2016) for MX-CO (Figure 5.11). Summer CO_2 levels peaked to 3,502.0 ppm (29/08/2016) in MX-PH (Figure 5.13) and 1,915.0 ppm (03/07/2016) in MX-CO (Figure 5.15). Relative living room CO_2 levels were observed to be slightly higher in MX-PH (annual mean 599.25ppm) than in MX-CO (annual mean 593.85ppm) and peak levels observed at MX-PH were usually greater than those at MX-CO. The Kolmogorov-Smirnov test indicates that the CO_2 in the MX-CO living-room, D(105,120)=0.139, $p<0.001$, and MX-PH, D(105,120)=0.238, $p<0.001$, do not follow a normal distribution. There was a significant median difference between both living rooms of 25ppm, between the MX-CO (539ppm) and MX-PH (519.98ppm), $z=-29.07$, $p<.001$. Statistical analysis indicates that CO_2 levels at MX-CO were more stable, whereas those for MX-PH demonstrated greater variations throughout the day.

As illustrated in Figure 5.11, CO_2 levels in the living rooms of both homes did not correspond to the reported occupation periods, especially in MX-PH flat, since occupants provided a ‘general use/occupation’. Therefore, CO_2 levels are more likely to give an accurate picture of the occupation. It is important to remember that MX-PH has an open plan. There was reported deactivation of the ventilation system at night, due to noise issues.

The biggest difference between the PassivHaus and Mexican ventilation standards is that the Mexican standard accounted for ventilation in individual rooms, whereas PassivHaus accounts for a total volume. A possible cause for the MX-CO’s high CO_2 at nights is that bedroom doors were usually left open, but the windows remained closed, due to security reasons (Figure 5.15). However, the occupants of MX-CO stated that they opened windows during the morning, to purge ventilate and to dissipate indoor CO_2 concentrations. This purge effect was also observed frequently in MX-PH. Nevertheless the occupants’ surveys indicated that they rarely opened the windows during the mornings.

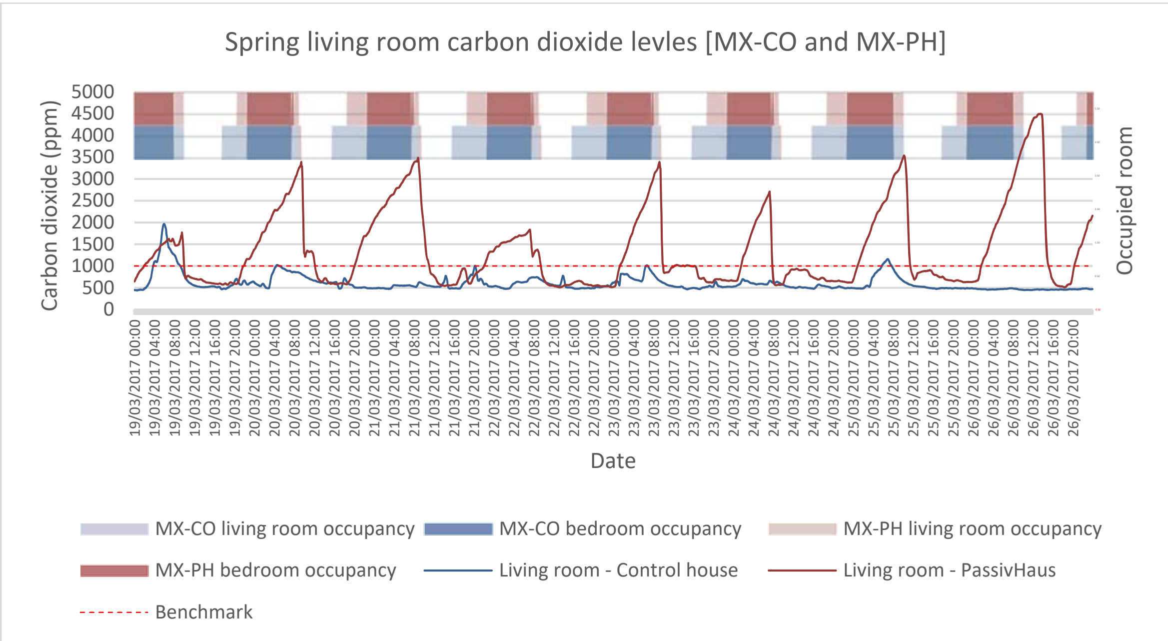


Figure 5.11 Spring CO_2 levels for the living rooms (week example). Carbon dioxide levels from 19/03/2017 to the 26/03/2017 in the living rooms and occupied periods at MX-CO and MX-PH.

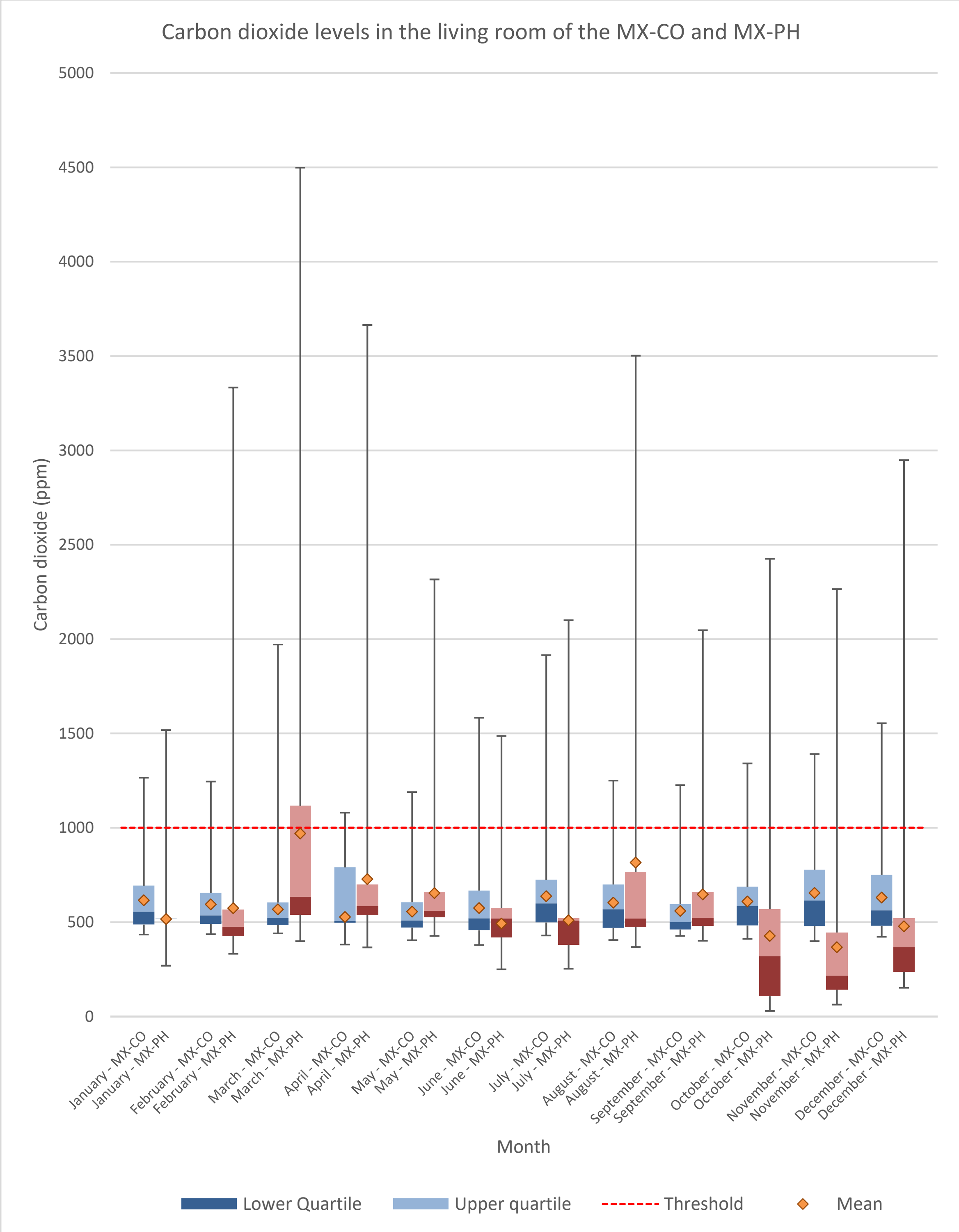


Figure 5.12 Monthly carbon dioxide levels in the living rooms of both flats. Blue refers to MX-CO and red to MX-PH (05/2016-04/2017).

Table 5.3 Percentage of time with CO_2 levels above 1,000 ppm at MX-CO and MX-PH (05/2016-04/2017).

	MX-CO		MX-PH	
Season	Living room	Bedroom	Living room	Bedroom
Winter	3.01%	48.03%	5.46%	12.22%
Spring	1.05%	38.01%	15.53%	18.24%
Summer	2.17%	44.70%	8.88%	8.50%
Autumn	3.76%	40.93%	17.17%	10.12%
Year	2.49%	42.90%	14.12%	9.93%

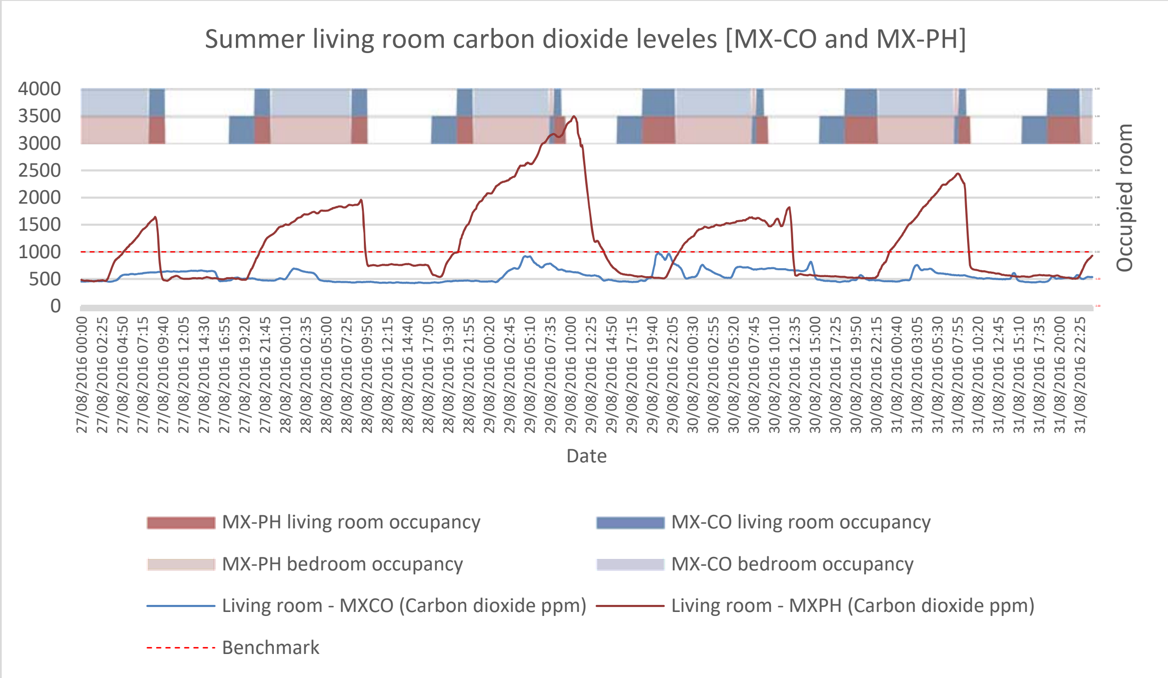


Figure 5.13 Summer CO_2 levels from the living rooms (week example). Carbon dioxide levels from 27/08/2016 to the 31/08/2016 in the living rooms and occupied periods at MX-CO and MX-PH.

Usually, CO_2 levels in the PassivHaus living room were low during the daytime and increased during night time, but unusual patterns such as those between the 19th and 30th March (Figure 5.11were observed. The daily pattern varied from 500ppm, close to those expected outdoors, during daytime hours and increased gradually to 3,500ppm during the night. The4,498ppm measured during this period were generally higher than usual. As similar measurements were observed in the bedroom, a fault in the sensors is unlikely to have happened. Due to the unusual readings since March 19th, the owner was advised to check the ventilation system on March 30th, and it was found off, so they turned on again. Differences in the CO_2 levels between Figure 5.13 and Figure 5.15 could be related to the period corresponding to some of the first Airbnb guests (Figure 5.13) and when the owner was living there (Figure 5.15). Occupancy was generally two guests for most of this time, but during this period the fan was turned off. There was no indication of when this occurred (although one of the guests complained of noise from the fan during the night at the beginning of August) and it was not until 8th September that the fan was turned on again (Figure 5.14).

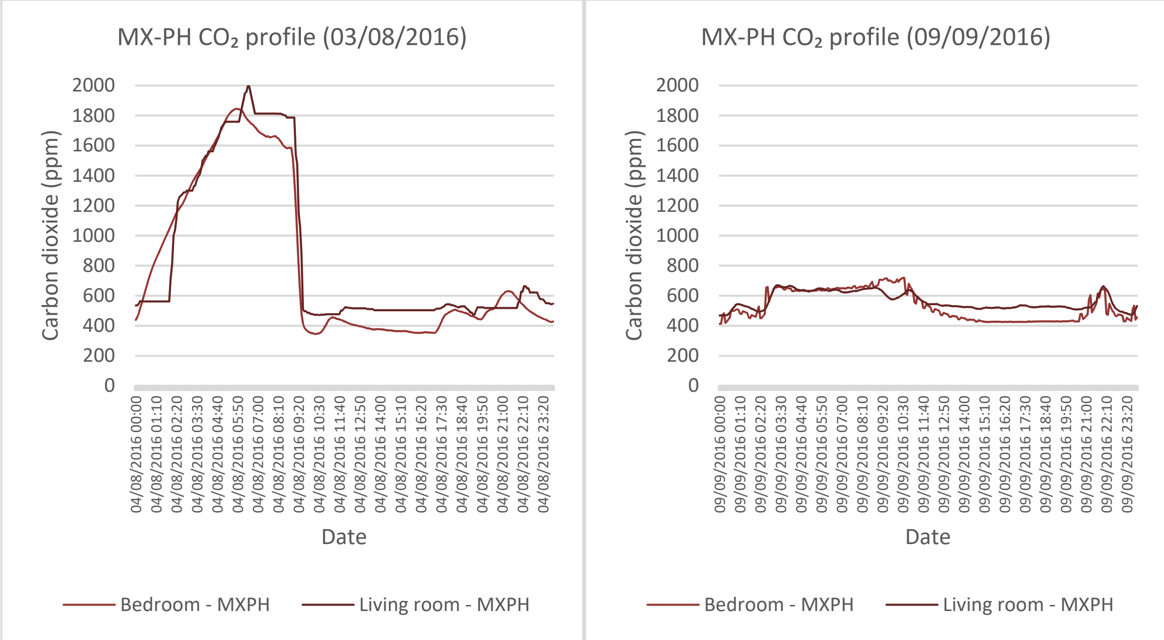


Figure 5.14 Example of the difference in the CO_2 levels with the ventilation off (left) and on (right) (03/08/2016 and 09/09/2016).

Mean levels of CO_2 at MX-CO bedroom were close to the 1,000ppm threshold and exceeded this level during winter. CO_2 levels remained close to 600ppm at MX-PH. The Kolmogorov-Smirnov test indicates that the CO_2 in the MX-CO bedroom, D(105,120)=0.135, $p<.001$, and MX-PH, D(105,120)=0.268, $p<.001$, do not follow a normal distribution. There was a significant median difference between both bedrooms of 213ppm, between the MX-CO (873ppm) and MX-PH (583ppm), z=-125.80, p<.001. However, the occurrence of levels above 1,000ppm were significantly lower in the bedrooms of MX-PH than those in MX-CO (Figure 5.10, Figure 5.16 and Table 5.3).

Levels in the MX-CO bedroom were significantly higher throughout the night, suggesting inadequate ventilation. Moreover, it was also observed that CO_2 levels usually remained high until a drop at lunchtime (~14:00), most likely as a result of the purge ventilation when opening the window to the patio and the bedroom, causing stack ventilation. This trend was observed over the whole year at MX-CO. Ventilation behaviour in the MX-PH dwelling, though, was different, in that CO_2 levels rose during the evening or early night and continued to rise, dropping considerably at around 09:30 in the morning as a result of opening a window.

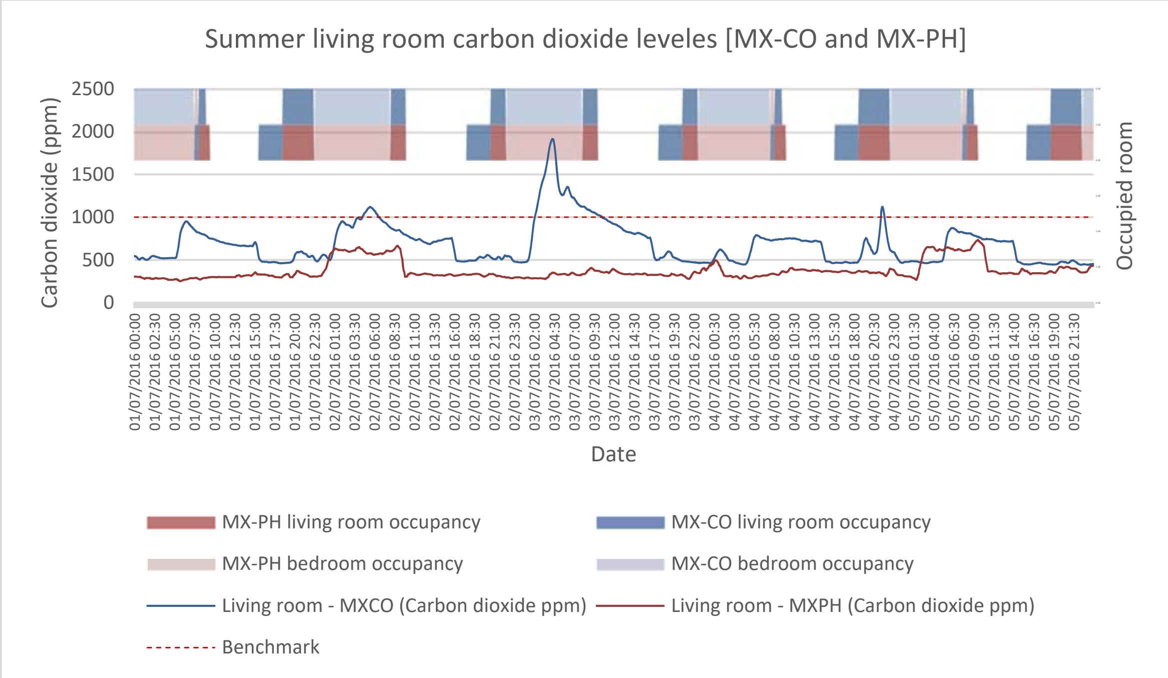


Figure 5.15 Summer CO_2 levels for the living rooms (week example). Carbon dioxide levels from 01/07/2016 to 05/07/2016 in the living rooms and occupied periods at MX-CO and MX-PH.

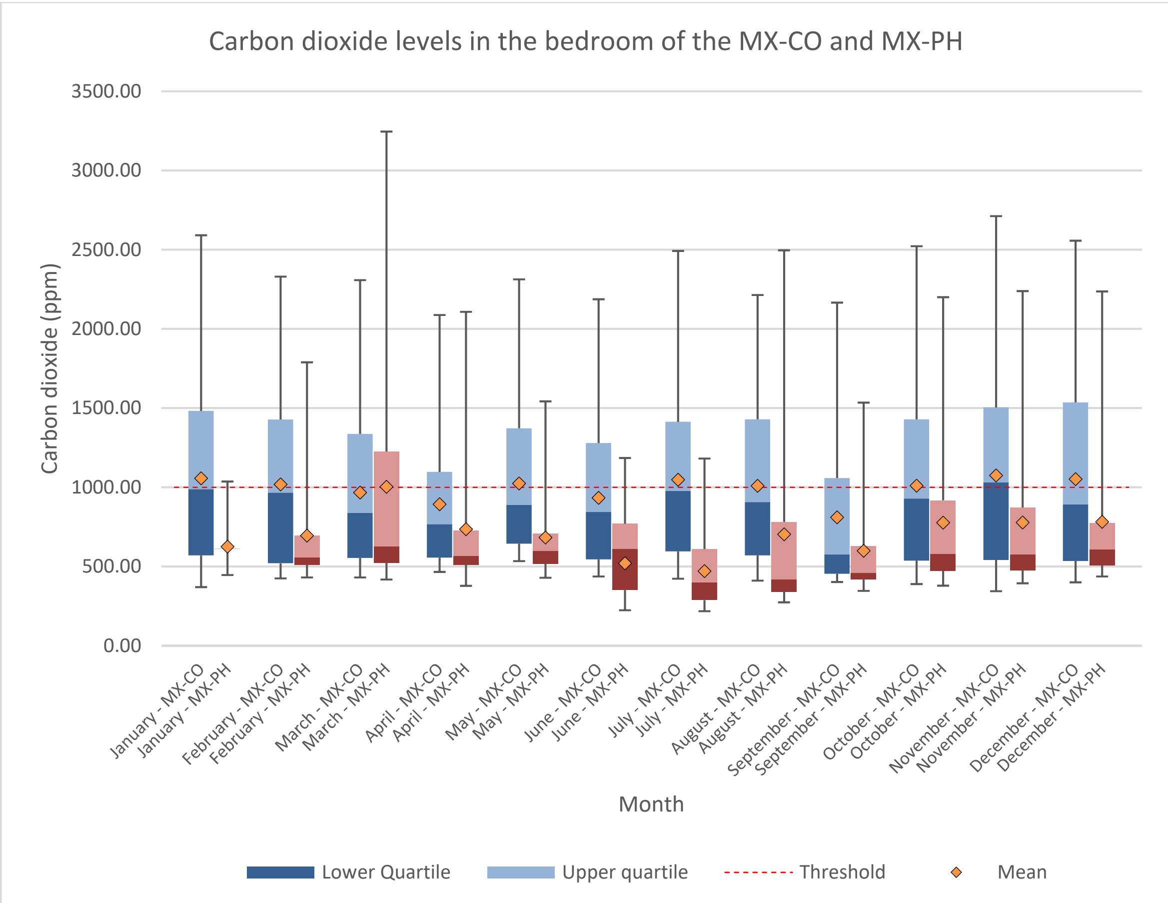


Figure 5.16 Monthly carbon dioxide levels in the bedrooms of both flats.

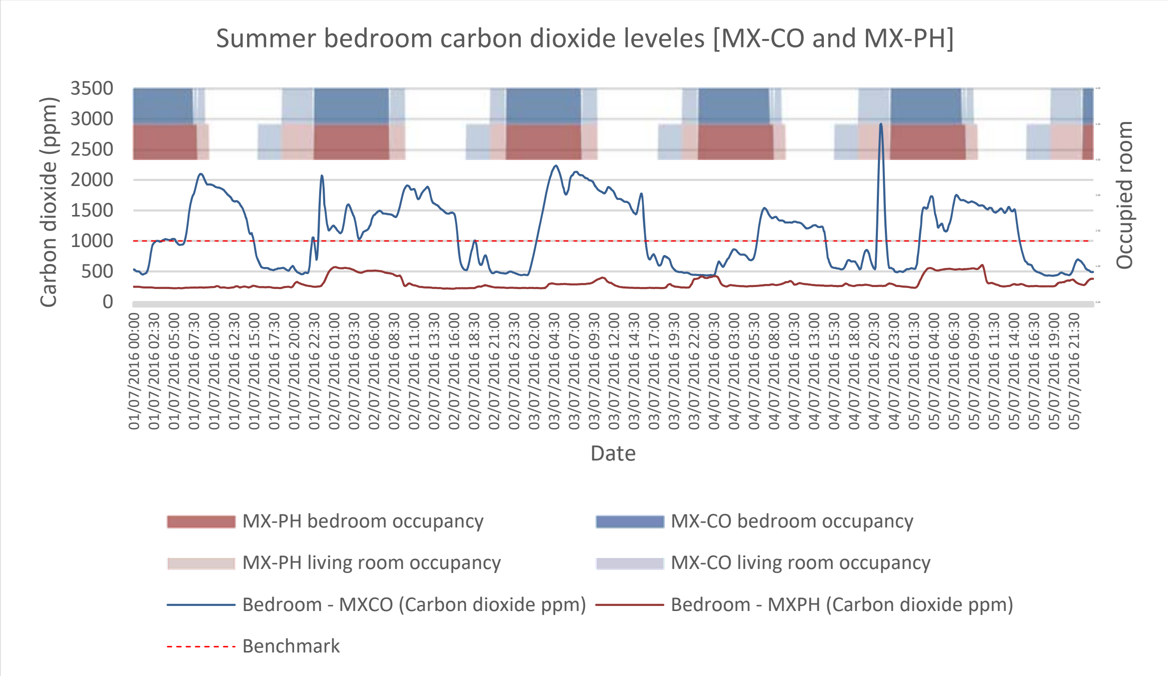


Figure 5.17 Summer CO_2 levels in the bedrooms (week example). CO_2 levels and occupancy periods in bedrooms from 01/07/2016 to 05/07/2016 at MX-CO and MX-PH.

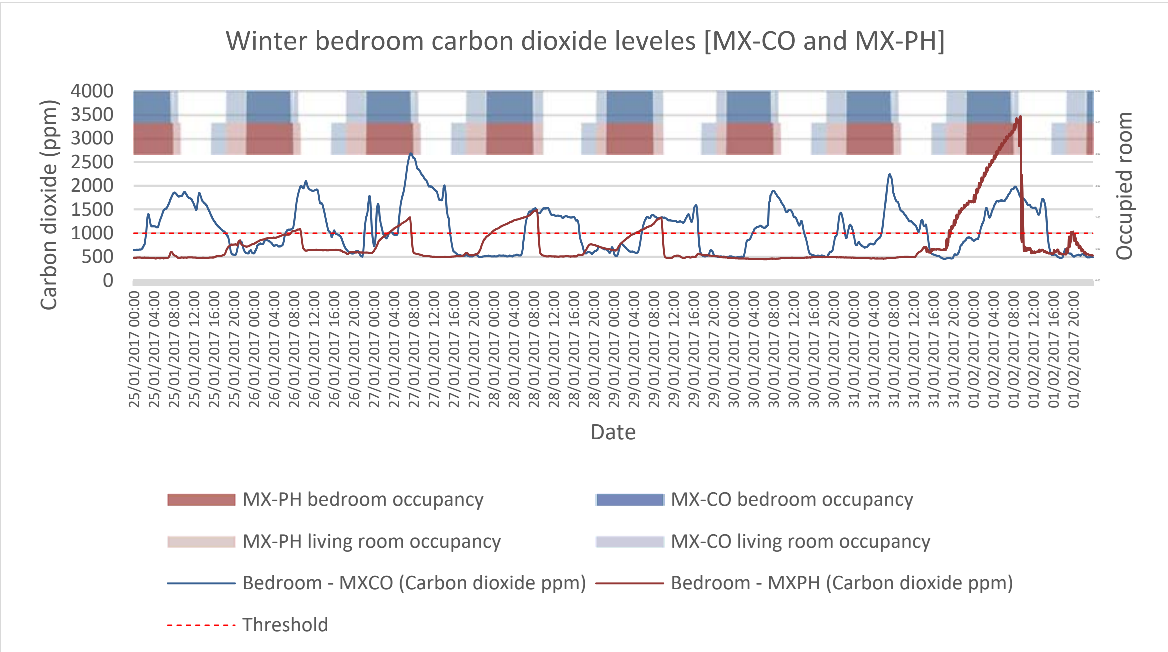


Figure 5.18 Winter CO_2 levels in the bedrooms (week example). CO_2 levels and occupancy periods in bedrooms from 25/01/2017 to 01/02/2017 at MX-CO and MX-PH.

5.5.2.1 Ventilation analysis of the PassivHaus

Specifications for MX-PH's extraction fan state that the fan should be capable of extracting 95.00m^3/h, but the airflow test indicated a flow of 73.40m^3/h. As mentioned above, to account for the difference between 73.40m^3/h and 42m^3/h (PHPP calculation), the fan was only in operation 34 minutes. This may have reduced fresh air flowing into the flat and therefore the possibility of diluting and removing indoor pollution. The on/off fan could also generate a noise nuisance, especially during the night. To test the efficiency of the fan, CO_2 concentrations in the room were modelled using the following equation (Engineering ToolBox, 2004):

$$c = (q \div nV)[1 - (e^{nt})] + (c_0 - c_i)(1 \div e^{nt}) + c_i$$

where

c = carbon dioxide concentration in the room (m³/m³)

q = carbon dioxide supplied to the room (m³/h)

V = volume of the room (m³)

e = the constant 2.718

n = number of air shifts per hour (1/h)

t = time (hour, h)

c_i = carbon dioxide concentration in the inlet ventilation air (m³/m³)

c_0 = carbon dioxide concentration in the room at start, t = 0 (m³/m³)

Figure 5.19 shows the measured CO_2 levels (blue line) for when the fan was on and off on the PassivHaus flat. The calibration model (generated CO_2 (calibration), orange dotted line) was produced by using real parameters[3] to estimate CO_2 concentrations. Another model was tested on which the same parameters were used, but the ventilation flow was set constant at PHPP rates[4] (generated CO_2 (42m³/h continuous) – red dotted line). Finally, in a third model, the fan was set to a continuous mode[5] (generated CO_2 (74.3m³/h continuous) – green dotted line). The mean difference between the calibration model and the PHPP calculation was 240ppm (8.86% below the calibration model).

[3] Density: two persons; activity: sleeping; time interval: 5 min; CO_2 emissions per person: 0.015m³/h; ventilation rates (calibration model): each hour from 0:00-0:15 at 0.001ach, 0:15-0:30 at 0.9789ach (74.3m³/h), 0:30-0:40 at 0.001ach, and 0:45-1:00 at 0.9789ach (74.3m³/h); room volume: 75.9m³; and ambient CO_2: 500ppm.

[4] Density: two persons; activity: sleeping; time interval: 5 min; CO_2 emissions per person: 0.015m³/h; ventilation rates (continuous flow): 42m³/h; room volume: 75.9m³; and ambient CO_2: 500ppm.

[5] Density: two persons; activity: sleeping; time interval: 5 min; CO_2 emissions per person: 0.015m³/h; ventilation rates (continuous flow): 74.3m³/h; room volume: 75.9m³; and ambient CO_2: 500ppm.

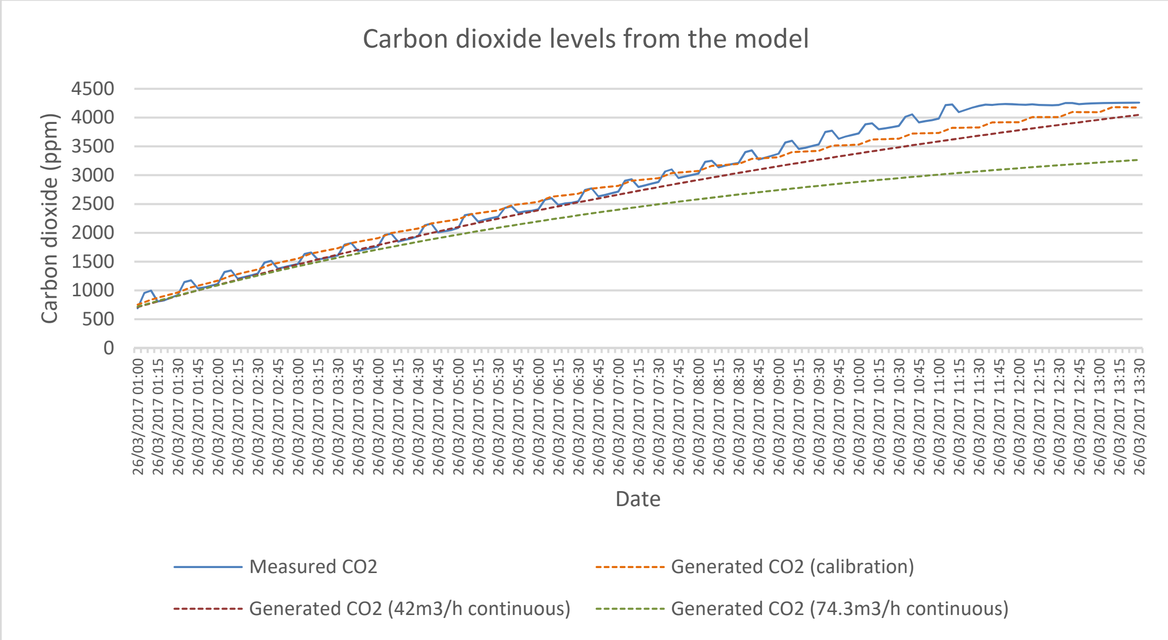


Figure 5.19 Overnight carbon dioxide levels for the MX-CO flat on 26/03/2017.The red line (generated CO_2 (42m^3/h continuous)) is the model based on the ventilation, as stated by the PHPP (42m^3/h) calculations, whereas the (generated CO_2 (74.3m^3/h continuous)) is the model based on the continuous supply of the current extraction fan.

'Controlled ventilation' rates required for the PassivHaus certification might cause inadequate ventilation and poor IAQ at higher occupancy conditions than those employed for PHPP calculations. This was observed during Airbnb occupancy, whereby on some dates there is an assumption of higher occupancy, thereby producing higher CO_2 levels (Figure 5.18). The PassivHaus ventilation concept considers the internal volume as a whole, instead of dividing it into zones. The open plan layout of MX-PH may have exhibited this, as measured CO_2 night levels in the bedroom were usually parallel to those in the living room (Figure 5.20). The ventilation behaviour in the MX-CO was different, as the layout and ventilation technique caused significantly higher CO_2 in the bedroom (Figure 5.21).

5.5.3 Hygrothermal conditions

Temperature and relative humidity (RH) levels play an essential part in the way we perceive the indoor environmental quality of a space, IAQ tends to be more acceptable at low temperatures and RH (Fang, Clausen and Fanger, 1998) reducing emissions of VOCs from building materials. The following sections present the analysis of hygrothermal conditions in the environmental monitoring. The results are shown in Table 5.5.

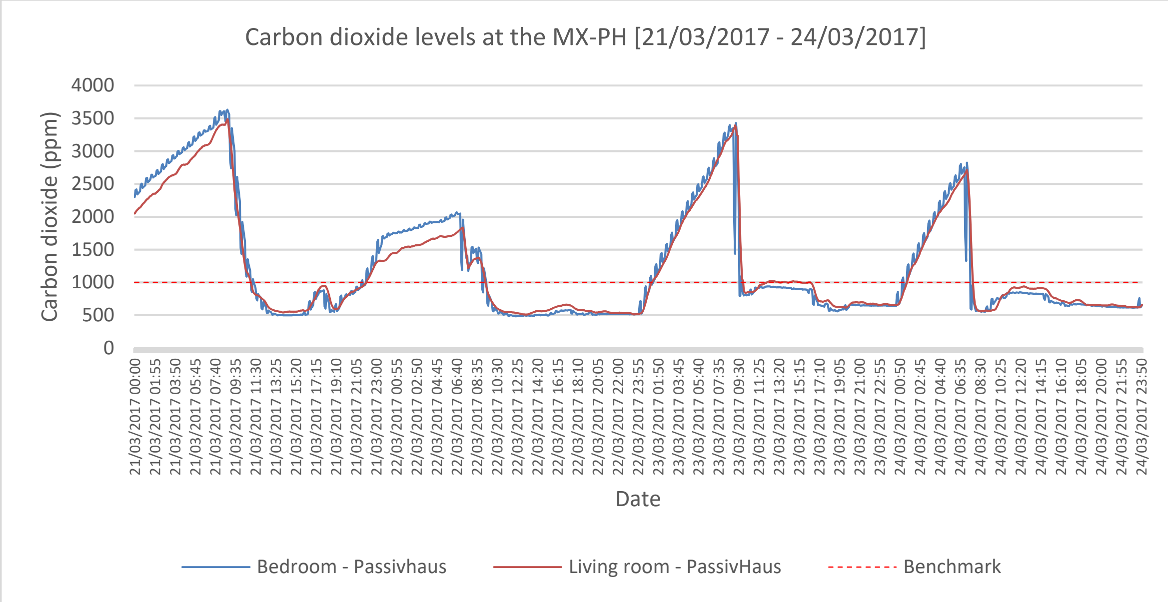


Figure 5.20 Carbon dioxide levels for MX-PH from 21/03/2017 to 24/03/2017.

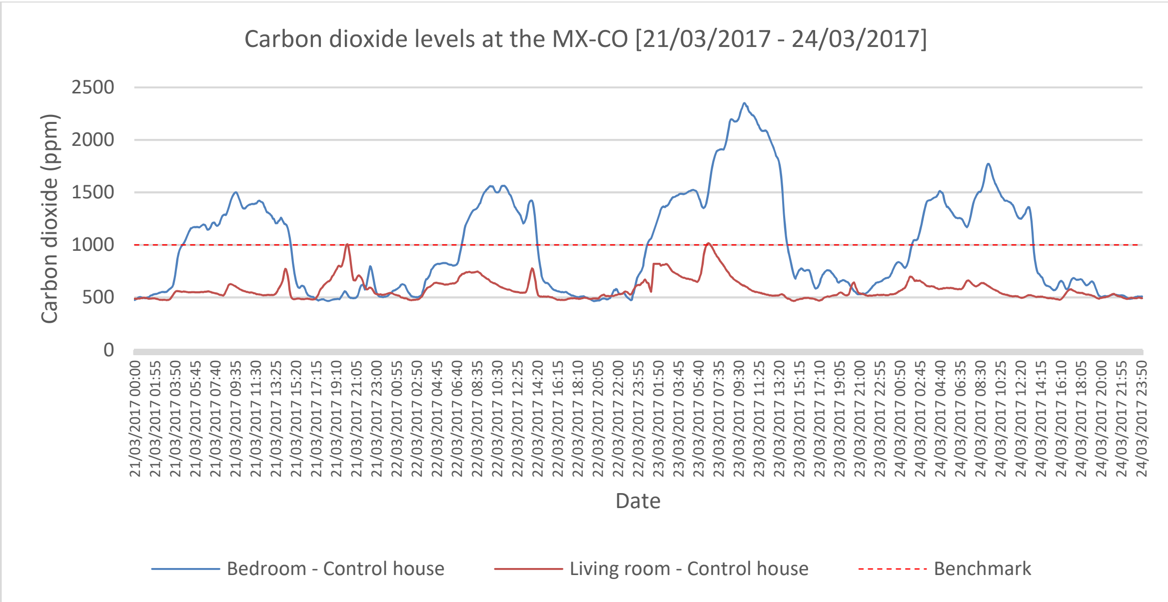


Figure 5.21 Carbon dioxide levels for MX-CO from 21/03/2017 to 24/03/2017.

5.5.3.1 Overheating and cold temperatures

Mexico's National Housing Commission (CONAVI) suggests that the ideal operative temperature should range between 20-25°C, with an extended range of 18-28°C (NOM-020-ENER-2011). Mexico's Federal Mortgage (SFH) suggests that the boundaries of thermal comfort should be 20-25°C. The Passive House Institute used these values and the extended comfort range (18-28°C) in a study to develop the PassivHaus approach in Mexico (Feist, 2012). A study that looked at operative temperatures and the thermal sensation as defined by the ISO 10551 found that the ideal comfort range is 18.6-24°C, with extended ranges from 16-26.7°C

(Figueroa-Villamar, Figueroa-Castrejon and Bojorquez-Morales, 2014). For this reason, using the CIBSE and PassivHaus static criteria was found appropriate. Average indoor air temperatures remained between the upper and lower limits for thermal comfort, calculated from the TM52b (see Chapter 2). As observed in Table 5.4, overheating was not identified through the adaptive approach, but the PassivHaus and CIBSE static criteria showed overheating in the bedrooms and the kitchens in both flats. Temperatures observed from March to August suggest that this period, especially March and April, had the potential to be perceived as overly hot.

The use of heaters or radiators is not a common practice in Mexico City, but the MX-CO occupants did report using electric radiators occasionally when needed. Temperatures below 18°C and between 18 and 20°C were observed in both flats. The occurrence of temperatures below 18°C was more frequent in the MX-PH flat, as were temperatures above 28°C (Figure 5.22). These variations suggest that MX-CO may be better at providing stable temperatures . A possible explanation is that the MX-CO temperatures may be regulated by thermal mass, while in the MX-PH the light-weight construction, lack of heating, internal volume and ventilation characteristics make it more vulnerable to outdoor conditions.

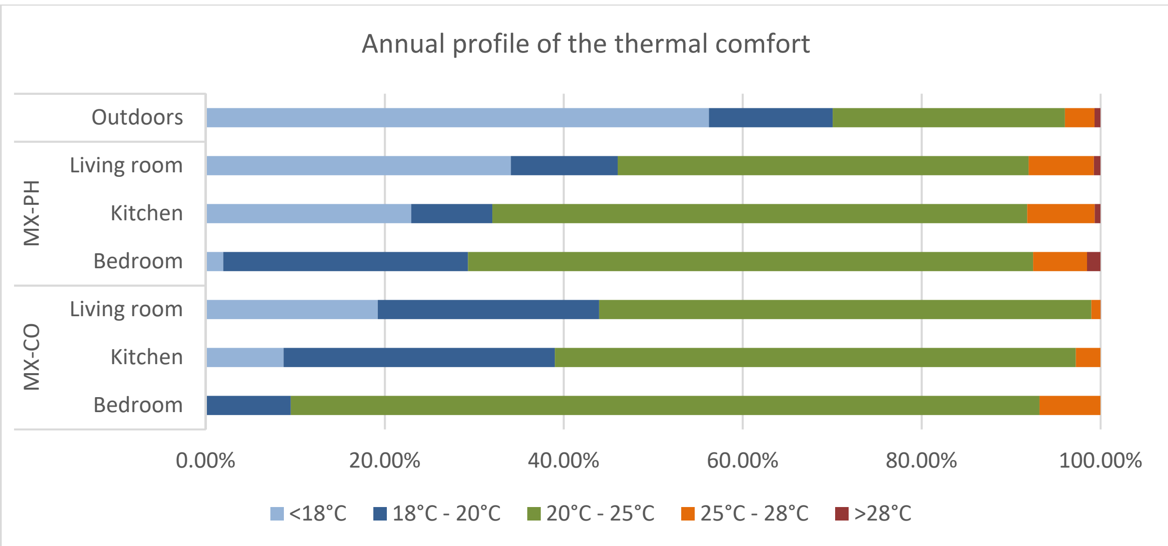


Figure 5.22 Annual thermal levels by range.

Statistical analysis demonstrated that MX-PH's indoor and ambient temperatures were correlated (r=.468 to .520, p<0.0005), suggesting that they follow the ambient temperature pattern, whereas at MX-CO this correlation was poor (r=.274 to .357, p<0.0005). Seasonal and daily temperature variations were calculated.

Figure 5.23 shows the seasonal temperature variation analysis, with temperatures at MX-PH demonstrating greater variation.

Table 5.4 Overheating and underheating temperatures analysis.

Room	Criterion	MX-CO					MX-PH				
		Winter	Spring	Summer	Autumn	Year	Winter	Spring	Summer	Autumn	Year
Bedroom	PassivHaus		•					•			
	CIBSE A		•	•		●		•		•	●
	CIBSE B		•			●		•			●
	Adaptive approach Criterion 1	N/A			N/A		N/A			N/A	
	Adaptive approach Criterion 2							•			
	Adaptive approach Criterion 3										
	18°C to 20°C <10%	×			×		×			×	×
	<18°C <10%										
Kitchen	PassivHaus		•					•			
	CIBSE A		•					•			●
	CIBSE B							•			
	Adaptive approach Criterion 1	N/A			N/A		N/A			N/A	
	Adaptive approach Criterion 2										
	Adaptive approach Criterion 3										
	18°C to 20°C <10%	×	×		×	×	×			×	×
	<18°C <10%	×			×						×
Living room	PassivHaus										
	CIBSE A										
	CIBSE B										
	Adaptive approach Criterion 1	N/A			N/A		N/A			N/A	
	Adaptive approach Criterion 2										
	Adaptive approach Criterion 3										
	18°C to 20°C <10%	×			×	×	×			×	
	<18°C <10%						×			×	×

The annual means of the daily temperature variations in MX-CO were between 1.15°C and 1.79°C, whereas at MX-PH they ranged from 3.00°C to 6.00°C. Daily temperature variations were calculated for each day, and this analysis shows that winter (the cold season) and spring (the warm season) were particularly affected by daily variations. In fact, MX-PH daily variations during winter reached 14.38°C and 10.82°C during spring, whereas in MX-CO they were 4.25°C and 4.85°C, respectively (Table 5.6). Both houses had different temperature patterns (Figure 5.24-27). However, their temperature trend was very similar from season to season, with the most pronounced changes related to daily variations.

Table 5.5 Statistical analysis of temperature, relative humidity and absolute humidity.

Room	Parameter	Statistical analysis	MX-CO					MX-PH				
			Winter	Spring	Summer	Autumn	Year	Winter	Spring	Summer	Autumn	Year
Bedroom	Air temperature	Maximum	23.3	27.8	26.0	24.7	27.8	26.1	32.5	25.2	25.4	32.5
		Minimum	18.5	19.4	20.7	17.8	17.8	16.6	16.2	20.6	16.4	16.2
		Mean	21.1	23.8	23.1	21.7	22.4	21.4	23.8	22.4	21.3	21.5
		Standard Dev.	1.1	1.8	0.6	1.5	1.7	1.3	2.5	0.7	1.8	2.5
	Relative Humidity	Maximum	63.9	54.8	76.0	69.9	76.0	60.0	60.0	69.4	76.3	76.3
		Minimum	23.4	22.6	38.4	33.7	22.6	24.5	20.1	37.1	31.8	20.1
		Mean	46.3	41.8	55.3	55.5	49.7	43.7	40.8	52.0	54.9	46.4
		Standard Dev.	6.2	5.8	4.8	5.2	8.1	6.6	7.1	5.1	6.3	9.2
	Absolute Humidity	Maximum	11.9	13.9	16.7	15.0	16.7	11.6	14.6	14.1	15.4	15.4
		Minimum	4.2	4.9	8.2	6.4	4.2	4.1	4.5	8.0	5.8	4.1
		Mean	8.6	9.0	11.5	10.6	9.9	8.2	8.8	10.3	10.2	8.8
		Standard Dev.	1.2	1.5	1.0	1.4	1.8	1.4	1.5	1.0	1.3	2.0
Kitchen	Air temperature	Maximum	22.6	26.9	25.4	24.1	26.9	26.2	29.6	26.5	27.2	29.6
		Minimum	15.9	17.5	20.2	15.7	15.7	15.3	15.1	19.8	15.1	15.1
		Mean	19.2	22.5	21.6	20.3	20.8	21.6	23.6	22.6	21.3	21.4
		Standard Dev.	1.2	2.0	0.7	1.8	2.0	1.5	2.3	0.9	2.1	2.7
	Relative Humidity	Maximum	66.9	71.7	81.1	74.4	81.1	62.3	62.2	71.3	75.3	75.3
		Minimum	23.0	21.8	38.9	36.4	21.8	19.7	17.8	34.7	28.8	17.8
		Mean	46.4	42.4	55.4	56.6	50.0	43.1	41.3	50.8	54.4	45.6
		Standard Dev.	7.2	7.7	5.6	5.5	8.9	7.3	7.9	5.0	7.3	9.6
	Absolute Humidity	Maximum	12.0	16.8	16.9	13.8	16.9	11.6	14.8	13.4	15.2	15.2
		Minimum	4.2	4.5	8.2	6.3	4.2	3.9	4.3	7.8	5.7	3.9
		Mean	7.6	8.5	10.5	10.0	9.0	8.2	8.7	10.2	10.1	8.6
		Standard Dev.	1.2	1.6	1.1	1.2	1.8	1.4	1.6	0.9	1.3	2.1
Living room	Air temperature	Maximum	22.5	25.8	23.9	29.5	29.5	29.3	29.9	27.0	29.4	29.9
		Minimum	14.9	17.0	18.5	16.4	14.9	13.1	13.8	18.1	14.0	13.1
		Mean	19.2	21.7	21.8	20.7	20.4	21.0	23.0	21.9	21.2	15.8
		Standard Dev.	1.1	1.6	0.7	1.7	2.0	2.1	2.7	1.0	2.4	3.5
	Relative Humidity	Maximum	70.9	67.3	74.4	75.4	75.4	66.1	67.0	75.8	79.9	79.9
		Minimum	22.8	30.4	38.7	33.2	22.8	19.9	18.0	32.9	29.0	18.0
		Mean	45.3	48.9	56.5	55.1	50.5	43.8	42.5	50.0	54.1	44.1
		Standard Dev.	7.6	4.5	5.4	5.7	7.9	7.9	8.8	5.3	7.7	10.6
	Absolute Humidity	Maximum	11.6	14.6	13.5	13.8	14.6	11.6	14.6	13.3	16.4	16.4
		Minimum	3.7	4.9	7.9	6.0	3.7	3.9	4.5	7.8	5.9	3.9
		Mean	7.5	9.3	10.8	10.0	9.0	8.0	8.6	9.7	10.0	7.8
		Standard Dev.	1.3	1.0	0.9	1.2	1.9	1.3	1.5	0.8	1.4	2.5

Table 5.6 Seasonal daily temperature variations in MX-CO, MX-PH and ambient. Blue background is data from MX-CO, red from MX-PH and green from ambient.

			Seasonal daily mean variation (°C)	Extreme daily variations	
				Min (°C)	Max (°C)
Summer	MX-CO	Bedroom	1.20	0.27	2.64
		Kitchen	1.74	0.87	3.23
		Living room	1.74	0.62	3.51
	MX-PH	Bedroom	2.01	0.90	4.73
		Kitchen	3.10	1.35	5.93
		Living room	5.04	3.00	7.36
	Ambient		9.05	5.40	12.20
Autumn	MX-CO	Bedroom	1.21	0.13	3.23
		Kitchen	1.67	0.60	3.16
		Living room	1.80	0.47	7.34
	MX-PH	Bedroom	2.43	1.09	6.22
		Kitchen	4.07	1.09	7.55
		Living room	5.02	1.84	10.26
	Ambient		8.83	2.90	13.20
Winter	MX-CO	Bedroom	1.08	0.28	2.82
		Kitchen	1.84	0.84	3.42
		Living room	1.70	0.29	4.25
	MX-PH	Bedroom	3.28	1.07	6.58
		Kitchen	4.67	2.08	8.67
		Living room	7.23	3.27	14.38
	Ambient		11.69	6.30	15.10
Spring	MX-CO	Bedroom	1.10	0.22	2.44
		Kitchen	1.90	0.91	3.07
		Living room	1.89	0.67	4.85
	MX-PH	Bedroom	3.95	1.01	9.80
		Kitchen	4.43	1.68	10.82
		Living room	6.29	3.35	9.64
	Ambient		11.17	7.00	14.80

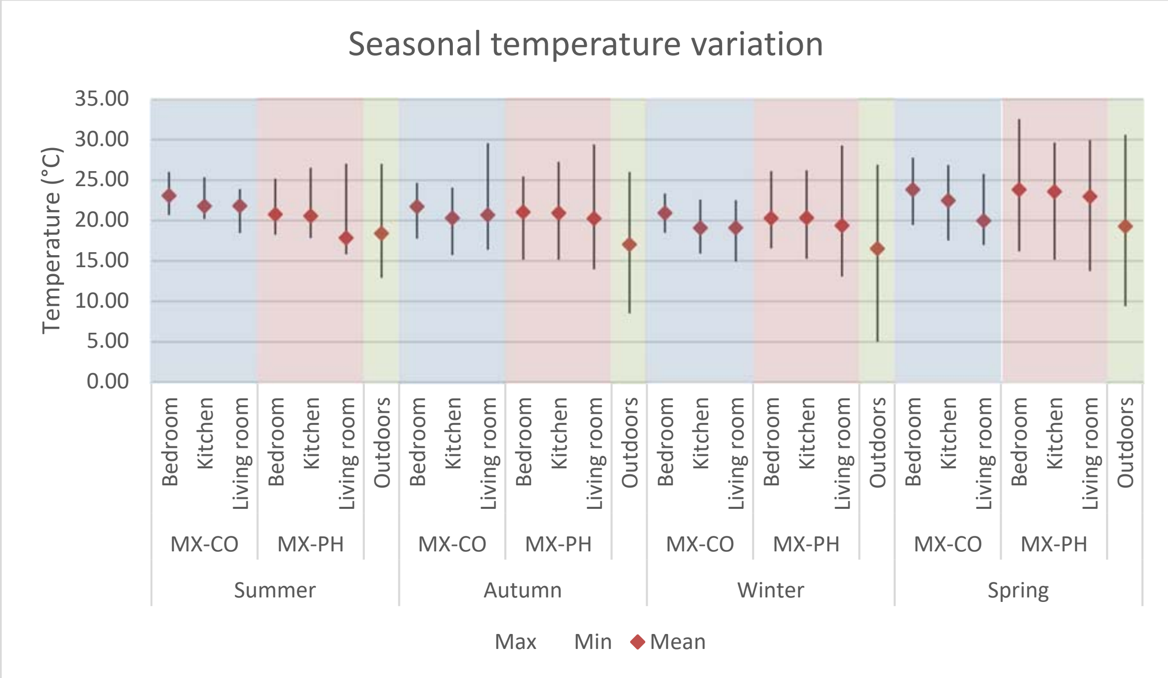


Figure 5.23 Seasonal temperature variation in MX-CO, MX-PH and ambient. Blue background is data from MX-CO, red from MX-PH and green from ambient.

The figures show the trends in the bedrooms (,) and living rooms (,) during the cold and warm seasons respectively. These figures also show the temperature variations in different seasons. The observed trends are very similar in both seasons coldest measurements, in that the temperatures dissipate very quickly when opening the windows, and the thermal mass stabilises the temperature. It is also evident the impact of closed windows closed as temperatures hardly varied. The temperature trends for MX-CO indicate that the daily temperature peak occurred around midnight (~01:00) and remained at this level until early morning (~07:00), when the temperature dropped until early afternoon (~13:00), possibly due to window opening, before rising to its daily peak level during the night. This trend differs from MX-PH, where the temperature peak occurred around early evening (19:00) and continued dropping until the morning (~09:00), before rising again. No apparent differences in this trend were observed between seasons. These trends however, seem to be related to occupant behaviour rather than the buildings themselves.

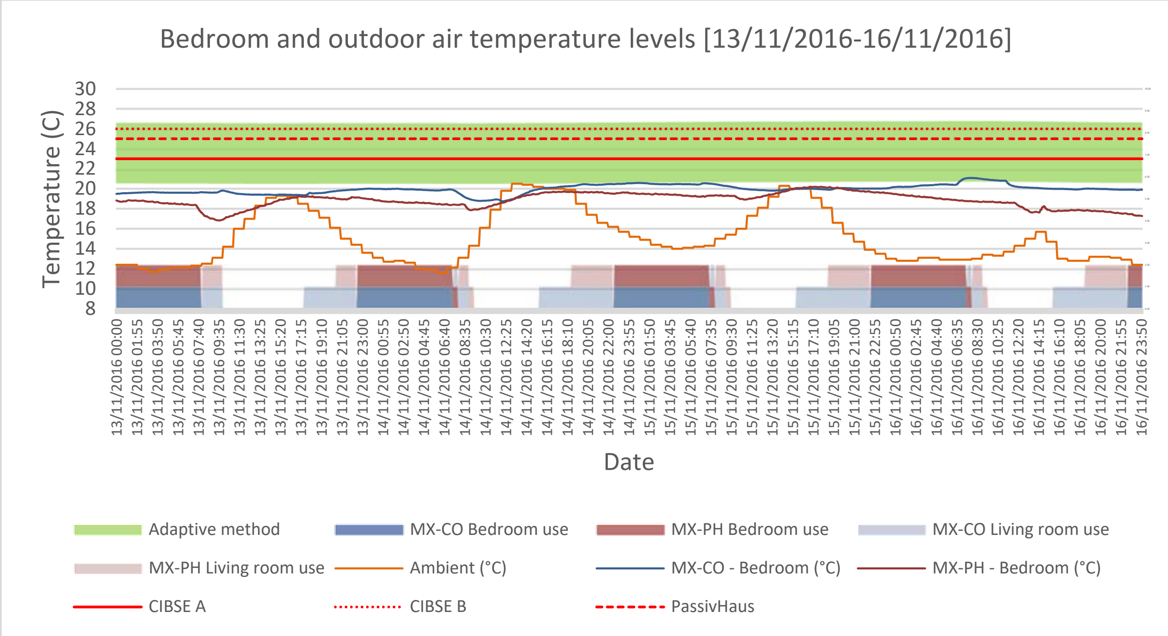


Figure 5.24 Bedroom and ambient air temperature level comparisons (coldest points). The rectangles in red (MX-CO) and yellow (MX-PH) show human interaction with the building. In most of the cases, this could be related to opening the patio door. Adaptive method thresholds were calculated using the mean ambient temperature and the Category II limits as described in the TM52b.

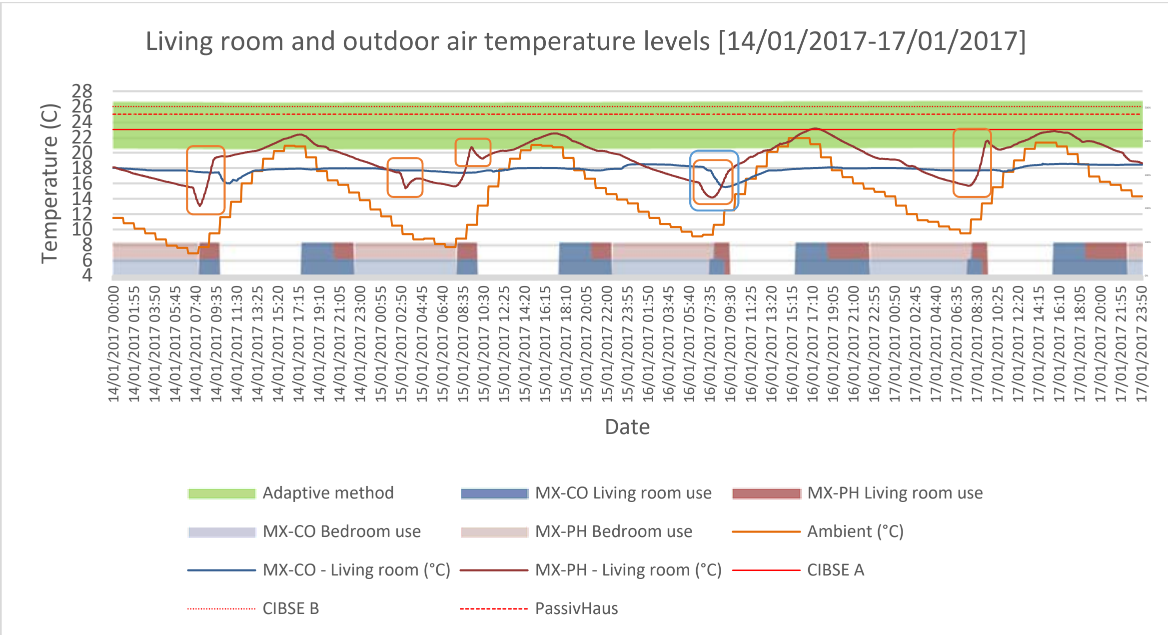


Figure 5.25 Living room and ambient air temperature level comparisons (coldest points). The rectangles in red (MX-CO) and yellow (MX-PH) show human interaction with the building. In most of the cases, this could be related to opening the patio door. Adaptive method thresholds were calculated using the mean ambient temperature and the Category II limits as described in the TM52b.

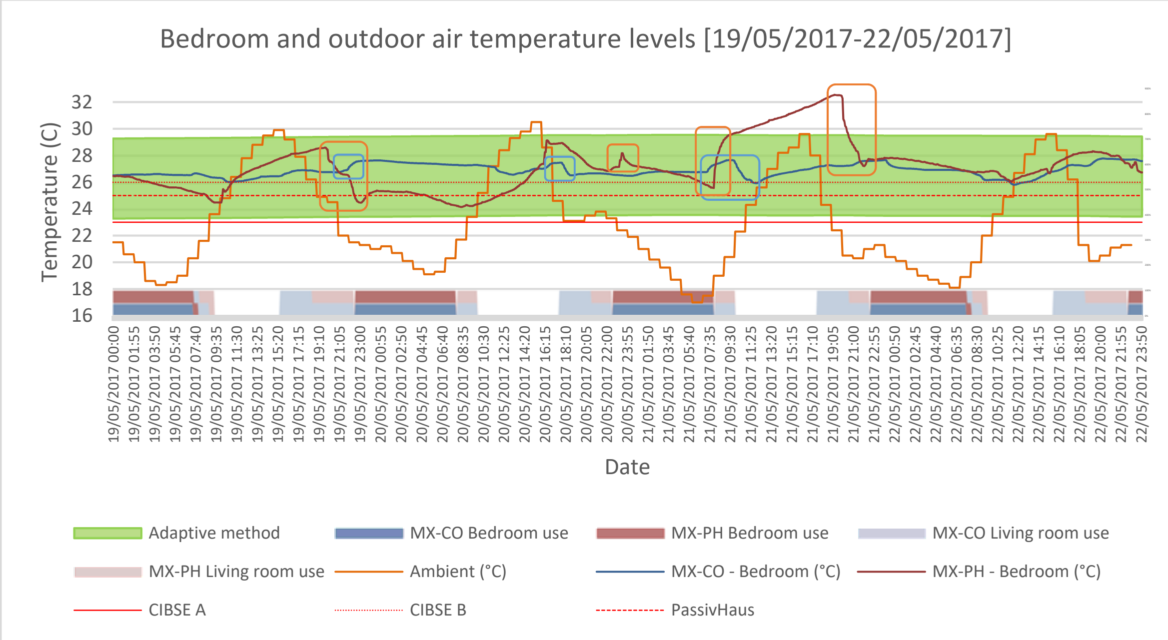


Figure 5.26 Bedroom and ambient air temperature level comparisons (warmest points). The rectangles in red (MX-CO) and yellow (MX-PH) show human interaction with the building. In most of the cases, this could be related to opening the patio door. Adaptive method thresholds were calculated using the mean ambient temperature and the Category II limits as described in the TM52b.

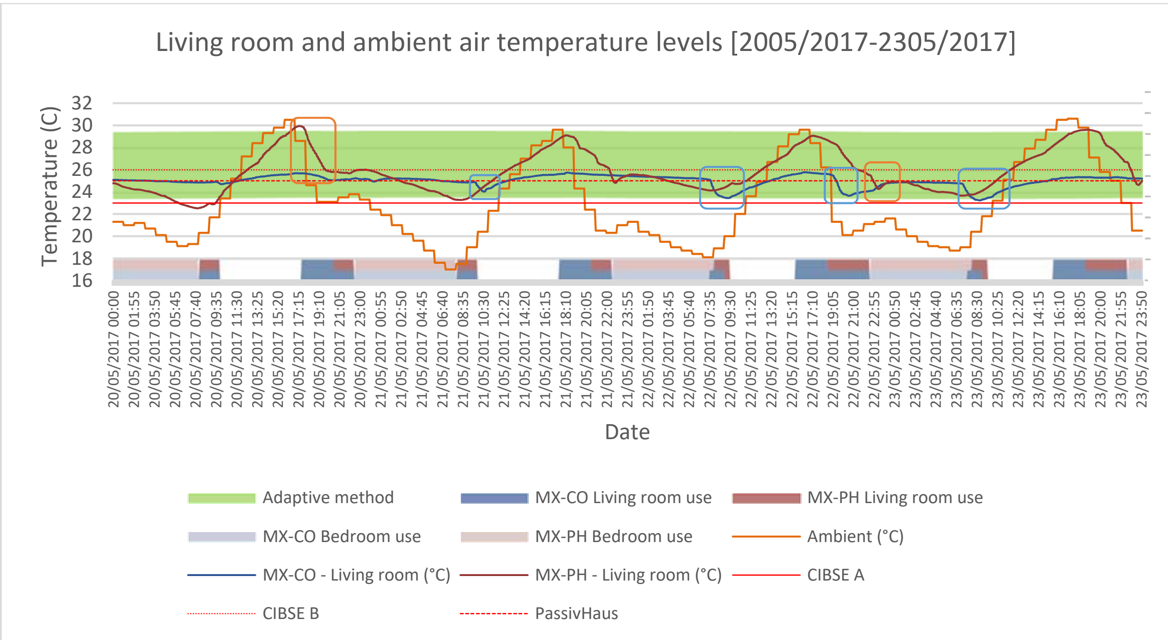


Figure 5.27 Living room and ambient air temperature levels comparison (warmest points). The rectangles in red (MX-CO) and yellow (MX-PH) show human interaction with the building. In most of the case it could be related to opening the patio door. Adaptive method thresholds were calculated using the mean ambient temperature and the Category II limits as described in the TM52b.

The occurrence of ambient temperatures below 20˚C was high (70.05% of the year), compared to temperatures above 25˚C (3.97%). It was evident that MX-CO bedroom temperatures were consistently between the ideal comfort ranges.

It is observed that MX-PH temperatures varied significantly during the day, between 2 and 4°C. The insulation may not be efficient to maintain stable temperatures in Mexico City when ventilated liberally and/or without MVHR systems. A possible explanation could be occupant behaviour, window/door opening, and architectural design. The MX-CO thermal mass maintained the temperature stable; nevertheless the impact of occupant behaviour and ventilation were also observed. The lack of night ventilation could lead to overheating problems during the warmer seasons as the thermal mass may not cool enotgh.

5.5.3.2 Humidity

Relative humidity (RH) thresholds (40%RH to 60%RH, CIBSE et al. 2006; EPA 2012) were assessed and related to air temperature using psychrometric charts (CIBSE, 2012) as described in Chapter 2. RH above the recommended 60%RH were measured in both flats, between 9% to 13% of the time in the three MX-CO rooms and 7% to 8% in the MX-PH. Similarly, levels below 40%RH were 35% to 44% of the time in the MX-PH and in less than 15% in the MX-CO (Figure 5.28). The psychrometric evaluation showed that spring levels were the most critical as they have the higher occurrence of warm and dry conditions (Figure 5.29), whereas summer were the most comfortable (Figure 5.30). Actual moisture levels could be masked to a degree by higher indoor temperatures at MX-PH, and so analyses of vapour pressure were also carried out.

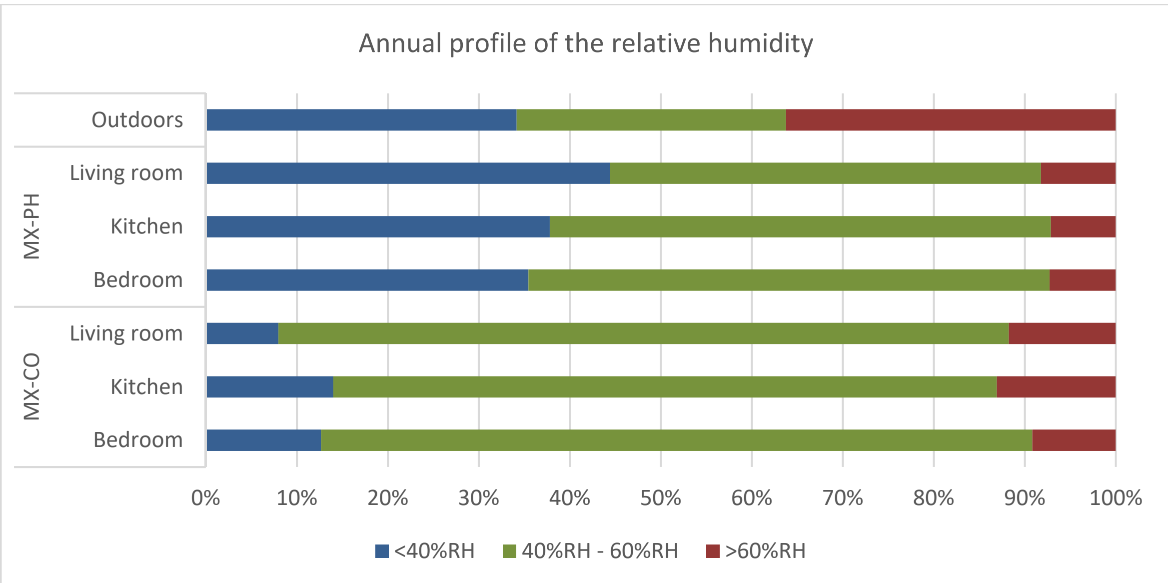


Figure 5.28 Annual relative humidity levels by range.

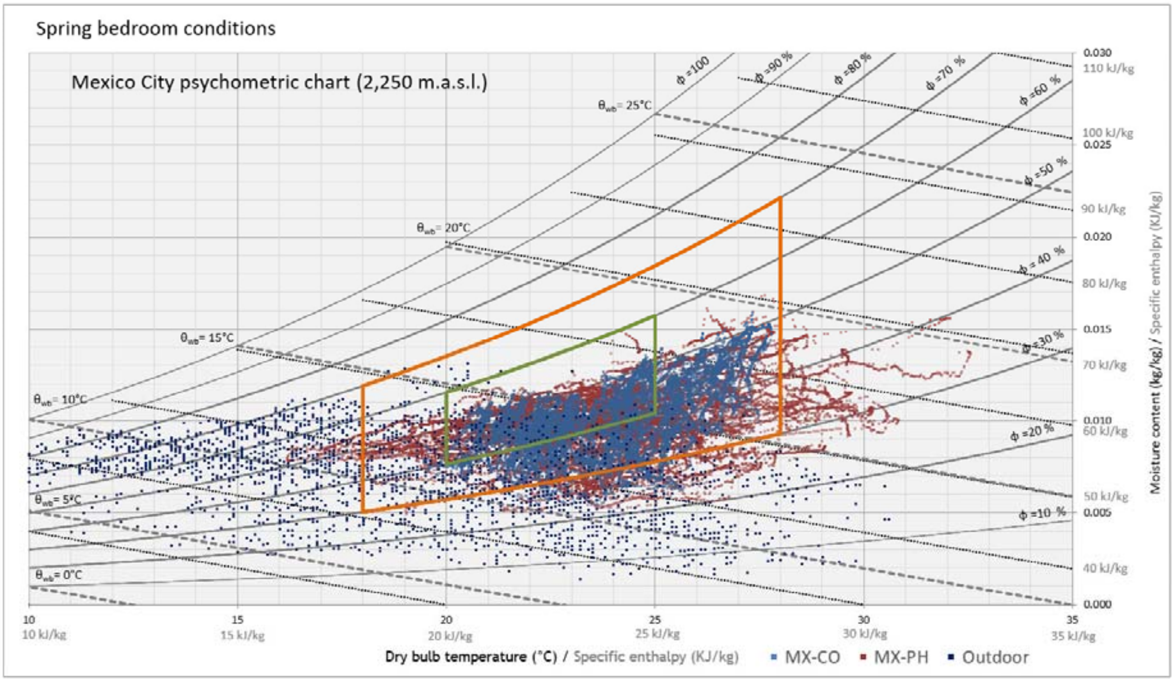


Figure 5.29 Spring psychrometric evaluation of the conditions indoors. The green rectangle delimitates the ideal range and the orange the extended range.

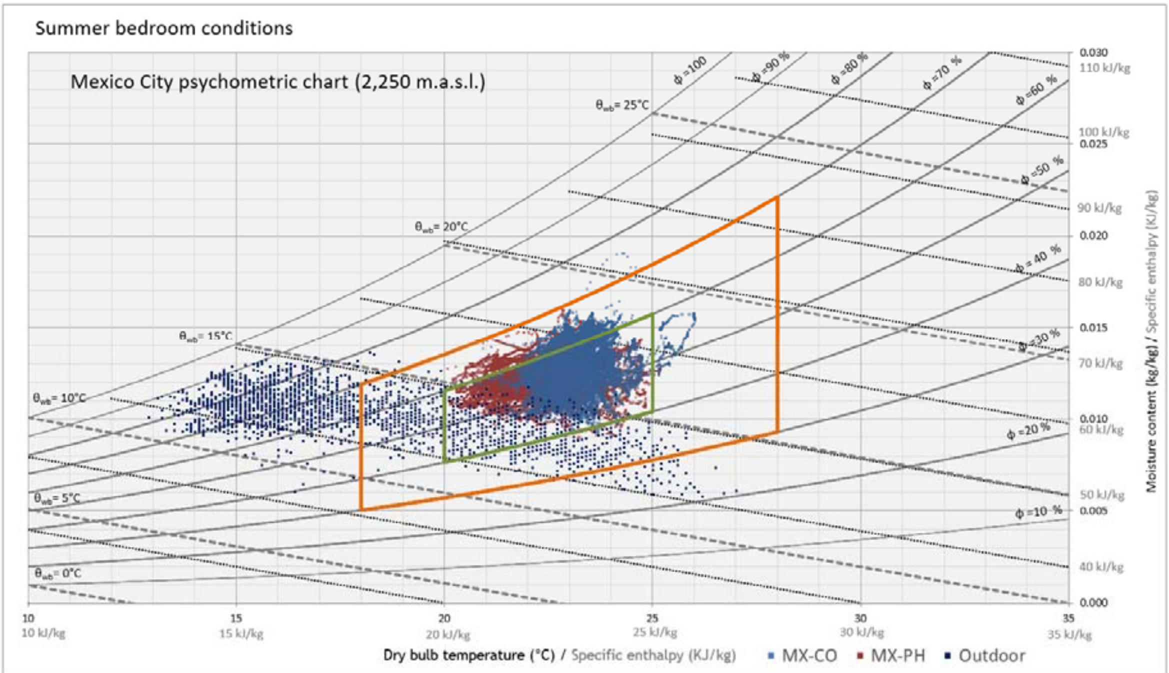


Figure 5.30 Summer psychrometric evaluation of the conditions indoors. The green rectangle delimitates the ideal range and the orange the extended range.

The threshold set by the PassivHaus standard, 12g/kg for 20% of occupied time, was exceeded only in the MX-CO bedroom (21.53% of the occupied time), whereas the rest of the rooms exceeded during 2.56% (kitchen) and 2.49% (living-room), and in the MX-PH 4.34% (bedroom), 3.56% (kitchen) and 3.65% (living-room). Vapour excess (difference between indoor and outdoor) was calculated for each room, as illustrated in Table 5.7. The low frequency of relative humidity levels above 60%RH was masked to a degree by higher indoor temperatures in both flats, especially at MX-PH, where vapour pressure above 7g/kg was more significant. Further analysis of vapour pressure identified levels of concern regarding the threshold levels for dust mite control (7g/kg). Levels above 7 g/kg were measured in both flats: MX-CO exceeded 7 g/kg 75.27% of the time (living-room), 86.82% (kitchen) and 95.57% (bedroom), whereas in MX-PH this was exceeded during 62.93% of the time (living room), 71.03% (kitchen) and 74.03% (bedroom). As explained by Korsgaard (1983) and Korsgaard & Hallas (1979), mite proliferation is likely to occur at absolute humidity levels above 7g/kg (or 1.13kPa). Dust mite levels of 100mites/g of dust are commonly observed at 7g/kg (B. J. Hart, 1998). However, these data should be viewed with caution, as this result was commonly observed in a temperature ranges from 20-22°C (Arlian, 1992), temperatures usually found in dwellings.

Table 5.7 Vapour excess from both homes during the complete period. A positive vapour excess means that the indoor concentration is higher than the ambient, whereas the negative value indicates that it is lower than the ambient.

		Summer Vapour excess (%)		Autumn Vapour excess (%)		Winter Vapour excess (%)		Spring Vapour excess (%)		Annual Vapour excess (%)	
		>7 g/kg	>12 g/kg	>7 g/kg	>12 g/kg	>7 g/kg	>12 g/kg	>7 g/kg	>12 g/kg	>7 g/kg	>12 g/kg
MX-CO	Bedroom	1.6	31.8	21.1	16.5	54.5	0.0	49.6	3.7	15.7	0.0
	Kitchen	5.8	7.1	20.8	2.6	50.1	0.0	39.6	1.5	-0.6	0.0
	Living room	5.8	7.8	18.4	3.3	41.6	0.0	4.5	1.1	0.7	0.0
MX-PH	Bedroom	-33.2	4.7	15.4	7.9	35.0	0.0	47.8	2.8	-2.7	0.0
	Kitchen	-38.0	3.0	12.3	9.0	34.4	0.0	45.5	2.9	2.4	-0.1
	Living room	-60.8	1.0	5.2	9.0	30.7	0.0	45.8	2.3	-12.0	0.0

In Mexico, house dust mite populations can be very complex. Cavazos Galvan et al. (2008), for instance, identified eight different dust mite populations in Mexico, with the most common species in central cities being *Dermartophagoides pteronyssinus* (*Dp*) and *Dermartophagoides farinae* (*Df*), while along the coast and to the south of the country, *Euroglyphus Maynei* (*Em*) *and Blomia Tropicalis* (*Bt*) proliferate. In Mexico City, two important studies have been conducted to identify house dust mite populations. Prieto Ursula et al. (1995) studied house dust mite populations in 100 dwellings with asthmatic children, finding that *Dp* was positive in 96 cases, *Df* in 80, *Em* in 41 and *Bt* in 17. A more recent study looked at a broader human population (334), 56.6% of which had allergic reactions to the house dust mite populations studied (*Dp*, *Df*, *Dermartophagoides siboney* (*Ds*) *and Bt*). In this study, *Bt* was found in 12.1% of the cases and 28.0% when *Bt* was identified in association with *Dp, Df and Ds* (Martinez Jimenez, Aguilar Angeles and Rojas Ramos, 2010).

The study of mite proliferation in indoor spaces was assessed using the critical equilibrium humidity (CEH) measure for house dust mite populations (de Boer and Kuller, 1997). The CEH for *Df* was evaluated as suggested by Cunningham (1996), Arlian (1981) and Arlian (1992), and for *Dp* as suggested by de Boer & Kuller (1997) and Ucci et al. (2011). The population equilibrium humidity (PEH) was also used to evaluate the *Dp* population (Crowther *et al.*, 2006). The PEH and CEH were plotted for all seasons. Figure 5.31 is the Spring graph, the season with the best results, and Figure 5.32 the Autumn graph, with higher problems.

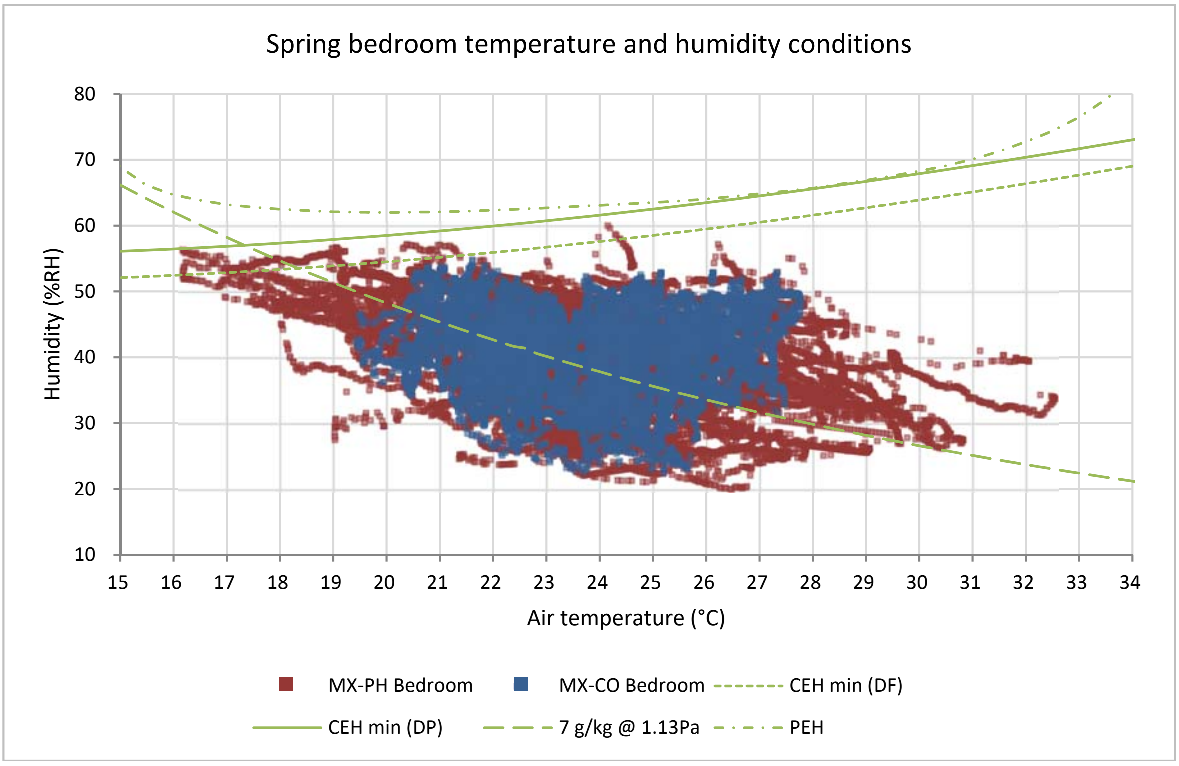


Figure 5.31 Spring bedroom temperature and humidity conditions. The figure shows analysis of the dust mite population threshold conditions according to the PEH and CEH for *Df* and *Dp*.

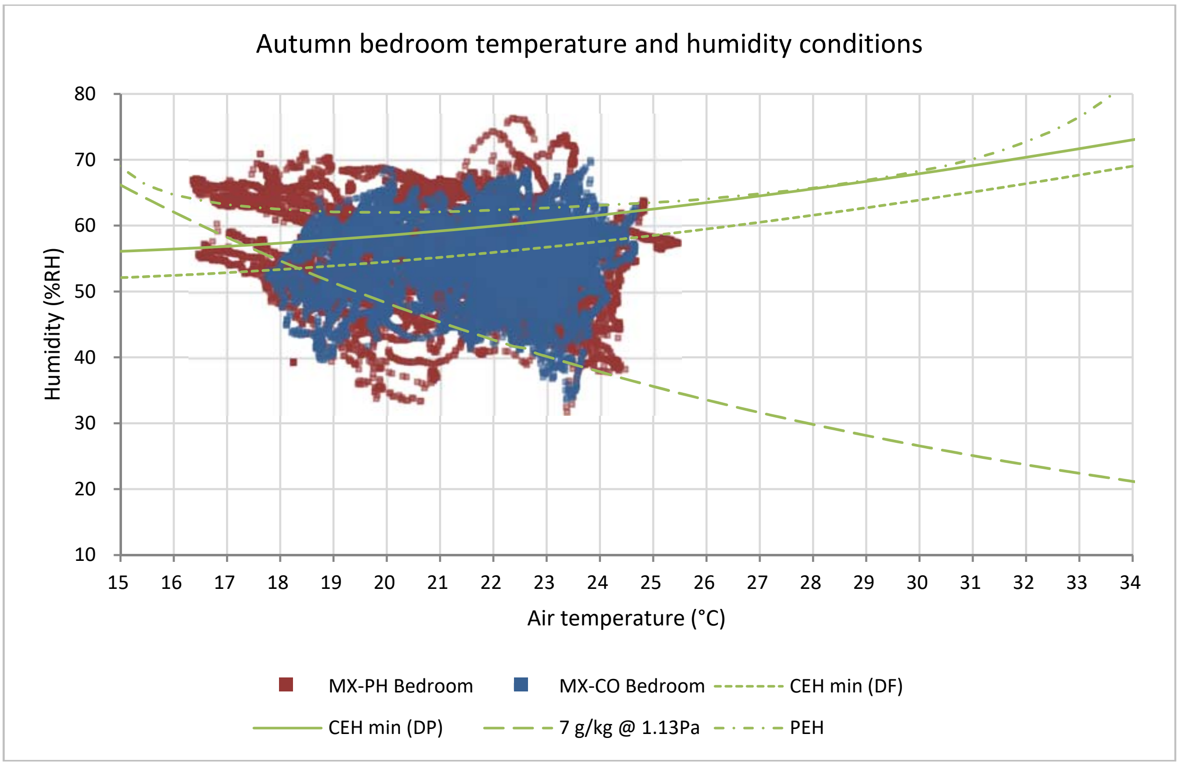


Figure 5.32 Autumn bedroom temperature and humidity conditions. The figure shows analysis of the dust mite population threshold conditions according to the PEH and CEH for *Df* and *Dp.*

5.5.4 Particulate matter 2.5µm

The WHO thresholds for annual mean $PM_{2.5}$ concentrations of 10µg/m^3 and daily mean of 25µg/m^3 (WHO, 2000), were exceeded in both flats and outdoors during the monitoring period. As mentioned earlier, neither of the houses had air filtration, and both had smokers. Mean annual outdoor concentration was 22.39µg/m^3; higher annual indoor means were measured at MX-CO (26.05µg/m^3 (kitchen), 27.82µg/m^3 (living-room) and 29.44µg/m^3 (bedroom)) than those at MX-PH (15.84µg/m^3 (bedroom), 16.91µg/m^3 (living-room) to 17.17µg/m^3 (kitchen)).

The recommended 25µg/m^3 daily mean was exceeded in both flats, but apparent differences were observed between MX-CO and MX-PH (Table 5.8 and Figure 5.33). In comparison, a study that evaluated indoor exposure to $PM_{2.5}$ in schools in Mexico City found that children were exposed to levels ranging from 4.24µg/m^3 to 102.8µg/m^3, with an annual mean of 28.9µg/m^3 (Barraza-Villarreal *et al.*, 2008). These levels are similar to indoor concentrations at the MX-CO flat and 12.26µg/m^3 above those in MX-PH. However, higher exposures to indoor $PM_{2.5}$ (35.1µg/m^3) were measured in nursing homes in Mexico City (Holguín *et al.*, 2003).

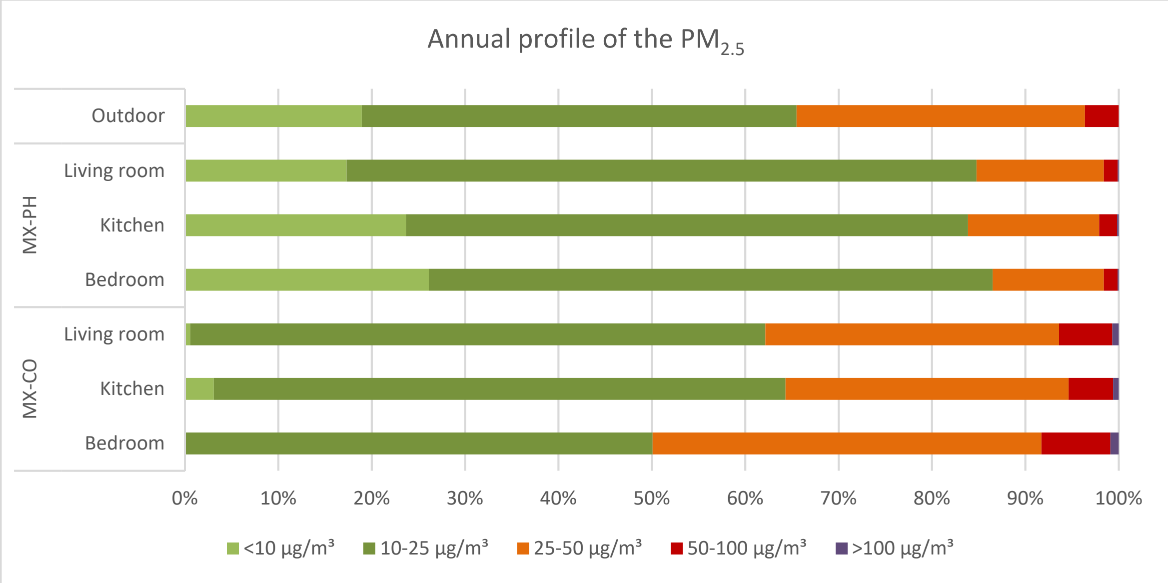


Figure 5.33 Annual $PM_{2.5}$ concentrations by exposure range during the monitored time.

The normal distribution of the data was rejected by the Kolmogorov-Smirnov test (Figure 5.34). There was a statistically significant median difference between both bedrooms (10.68µg/m^3), between the MX-CO (24.79µg/m^3) and MX-PH (13.45µg/m^3), z=279.95, p <.001. Similarly, the median differences in the living-rooms were statistically significant between both living-rooms (8.84µg/m^3), between the MX-CO (24.34µg/m^3) and MX-PH (13.29µg/m^3), z=-249.83, p<.001. Finally, the mean differences on the kitchen were also statistically significant (10.68µg/m^3), between the MX-CO (24.79µg/m^3) and MX-PH (13.45µg/m^3), z=-214.84, p<.001.

One-Sample Kolmogorov-Smirnov Test

		CO-B-PM2.5 (ugm3)	CO-K-PM2.5 (ugm3)	CO-L-PM2.5 (ugm3)	PH-B-PM2.5 (ugm3)	PH-K-PM2.5 (ugm3)	PH-L-PM2.5 (ugm3)
N		105120	105120	105120	105120	105120	105120
Normal Parameters[a,b]	Mean	29.4412	26.0482	27.8153	15.8431	17.1697	16.9129
	Std. Deviation	18.83815	16.90437	17.10698	10.84548	11.94558	10.84085
Most Extreme Differences	Absolute	.183	.180	.197	.186	.192	.189
	Positive	.171	.180	.197	.186	.192	.189
	Negative	-.183	-.145	-.161	-.107	-.118	-.095
Test Statistic		.183	.180	.197	.186	.192	.189
Asymp. Sig. (2-tailed)		.000[c]	.000[c]	.000[c]	.000[c]	.000[c]	.000[c]

a. Test distribution is Normal.
b. Calculated from data.
c. Lilliefors Significance Correction.

Figure 5.34 $PM_{2.5}$ Kolmogorov-Smirnov test.

In general, $PM_{2.5}$ concentrations did not vary significantly between rooms. However, in the MX-CO bedroom (29.44µg/m^3) they were higher compared to the kitchen (26.04µg/m^3) and living room (27.81µg/m^3). Fine particles might travel to the bedroom, located on the upper floor due to ventilation. Moreover, the windows remained open during the day and ambient $PM_{2.5}$ may have influenced the results. If the patio door remained closed but the window in the bedroom remained open, this would eliminate the effect of stack ventilation increasing the impact from outdoor pollution. Furthermore, concentrations in MX-CO were usually higher than the local ambient conditions, which suggests that pollution from indoor sources (i.e. cooking or cleaning) was not adequately removed. This suggests that occupant behaviour is a critical factor.

Table 5.8 Analysis of annual $PM_{2.5}$ concentrations.

		Annual mean (μg/m³)	Standard Deviation	% of time above 10μg/m³	No. days above 25μg/m³ as a daily mean	% of the year of days above 25 μg/m³
MX-CO	Bedroom	29.44	18.84	100.00%	241	66.03
	Kitchen	26.05	16.90	96.91%	173	47.40
	Living room	27.82	17.11	99.42%	192	52.60
MXX-PH	Bedroom	15.84	10.85	73.88%	40	10.96
	Kitchen	17.17	11.95	76.33%	50	13.70
	Living room	16.91	10.84	82.68%	44	12.05
	Ambient	22.39	13.33	81.06%	129	35.34

During summer, MX-CO occupants often opened the windows in the living room and the bedroom to control indoor temperature through stack and cross ventilation, which introduced external $PM_{2.5}$.Measured indoor $PM_{2.5}$ levels are, indeed, very similar concentrations to those outdoors and the impact of human activities (Figure 5.35). The impact of ventilation can also be observed as well as the effects of cooking fumes travelling around the homes, producing higher peak levels of $PM_{2.5}$ as pollution continues accumulating (being slowly dissipated/driven to the outdoors). For instance, Figure 5.36 shows the cooking pollution behaviour with open and closed windows. With open windows, pollution in the living room remains low as air is driven to the upper floor. $PM_{2.5}$ levels start rising in the kitchen during cooking. However, the particles travelled to the bedroom where $PM_{2.5}$ levels start rising minutes after. As cooking continues, levels of $PM_{2.5}$ rise.

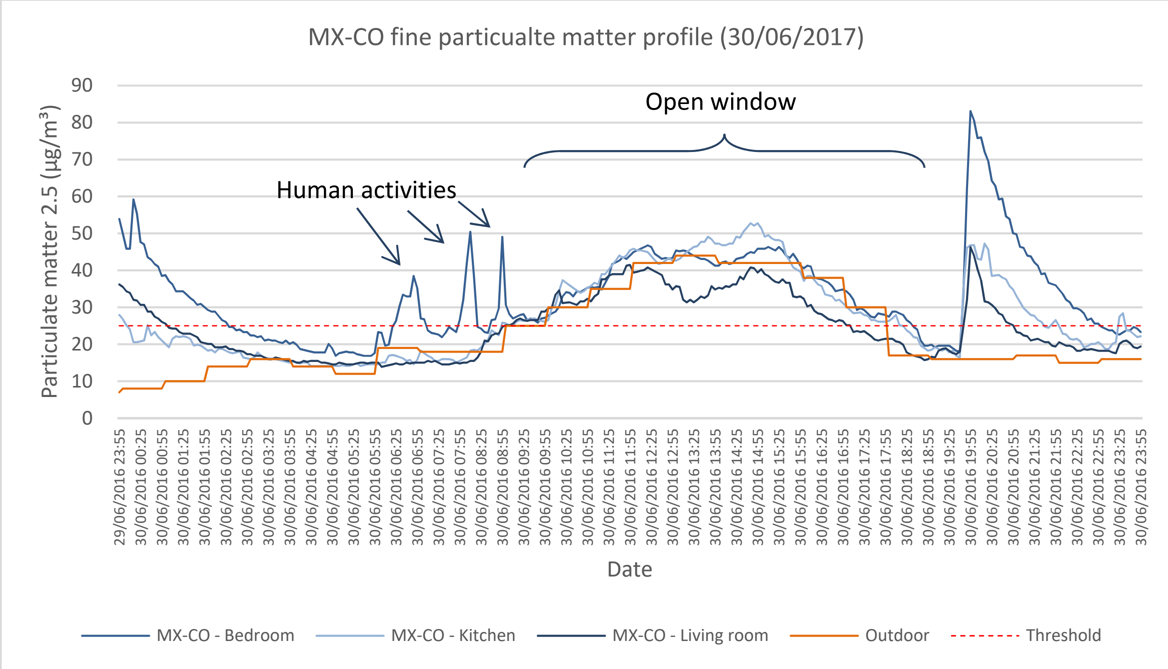


Figure 5.35 Example of the impact of outdoor $PM_{2.5}$ with open windows in the MX-CO (30/06/2016).

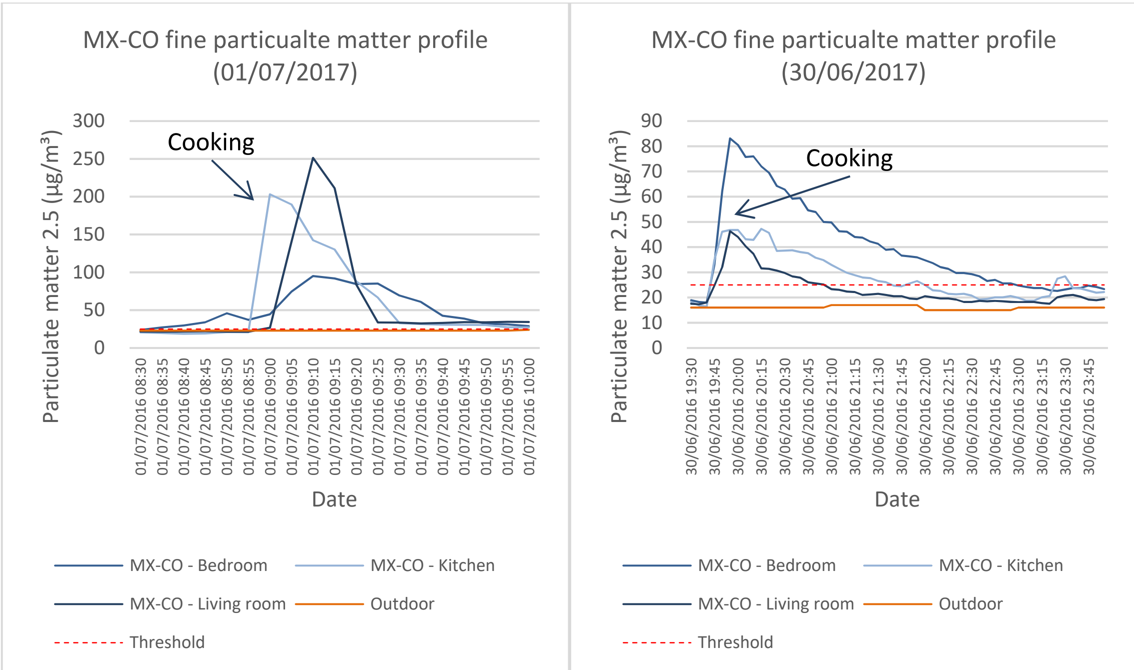


Figure 5.36 Examples of the cooking impact in MX-CO. Left, closed windows (01/07/2017), right, open windows (30/06/2016).

In MX-PH, when the windows were closed, the mechanical ventilation helped to dissipate faster indoor pollution from indoor sources (Figure 5.37). The impact of cooking was also observed and had less influence compared to MX-CO, especially in the bedroom. The effects of the window opening in the bedroom making indoor $PM_{2.5}$ levels follow outdoor concentrations, and when closed, the effect of human activities had a greater impact on peak levels (Figure 5.38). Outdoor $PM_{2.5}$ levels did not always influence indoor concentrations of $PM_{2.5}$, and higher indoor levels were observed at low outdoor concentrations in both homes (Figure 5.39).

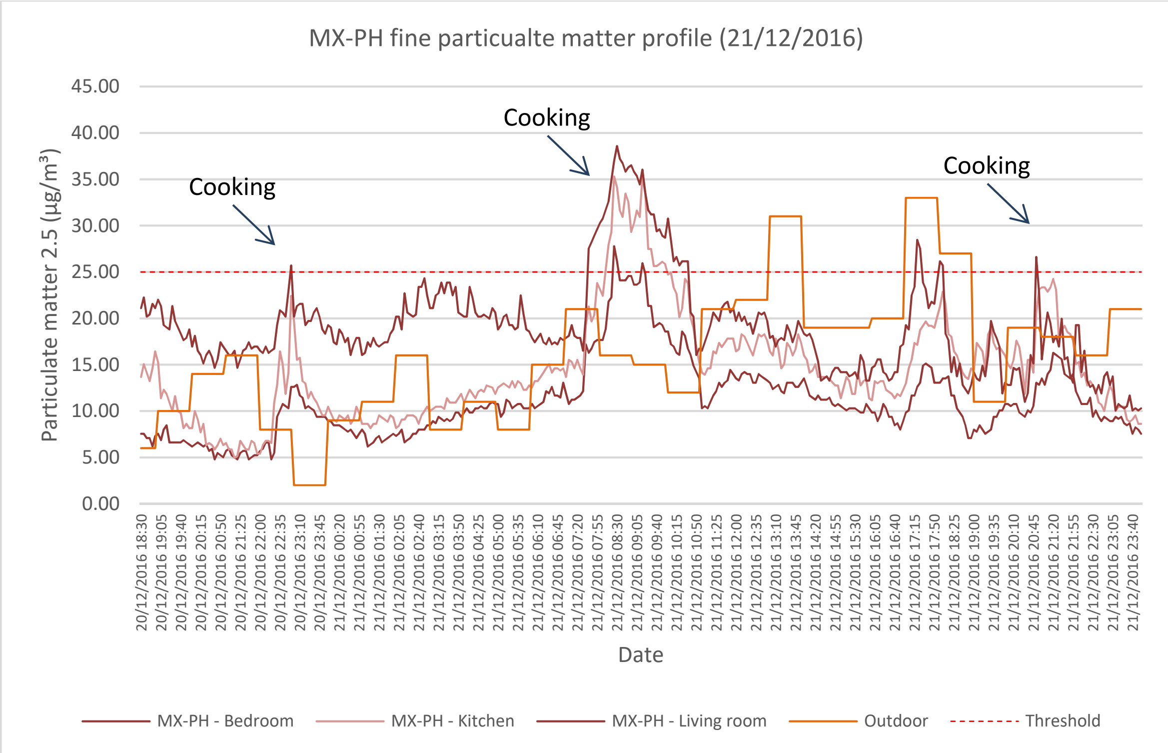


Figure 5.37 Example of $PM_{2.5}$ dissipation in the MX-PH. (21/12/2016).

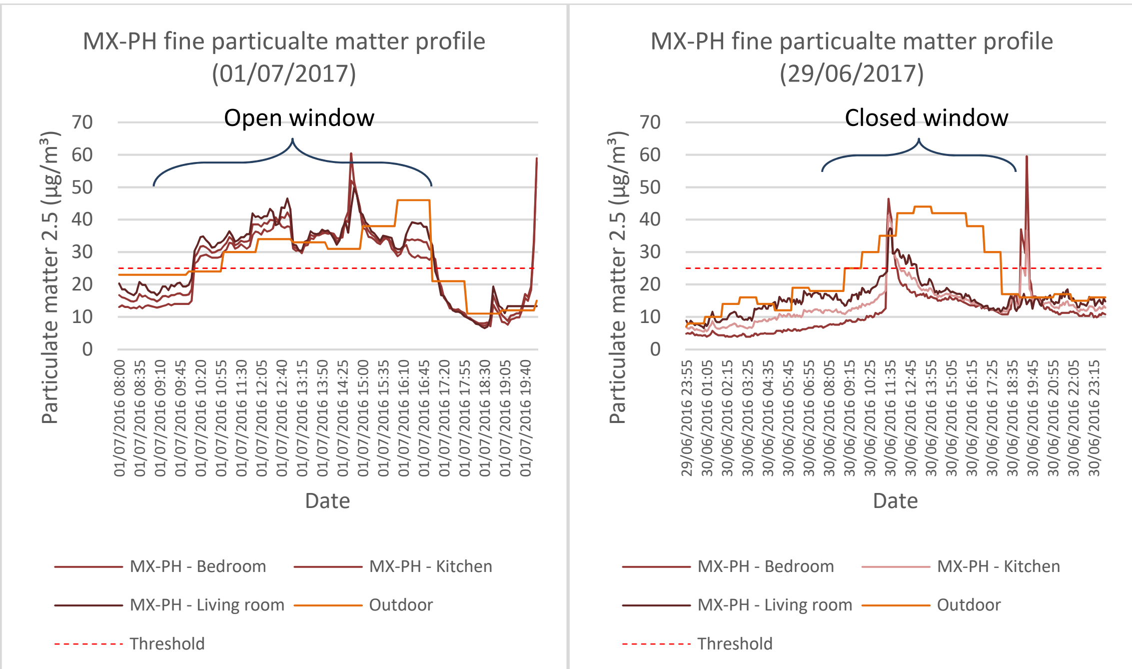


Figure 5.38 Example of the impact of the window opening in MX-PH. Left, open window (01/07/2016), right closed window (29/06/2016).

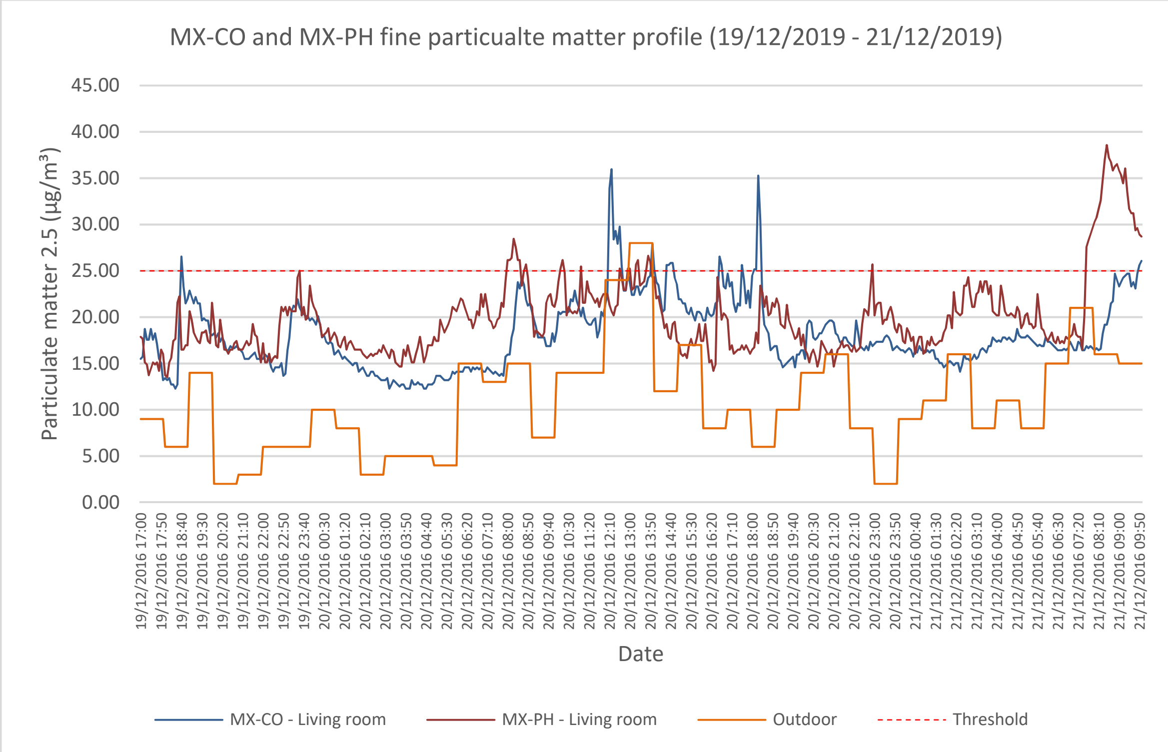


Figure 5.39 Example of indoor PM2.5 at low outdoor PM2.5 (19/12/2019-21/12/2019).

Table 5.9 PM2.5 summary of analysis of time periods with exposition above 25µg/m³ in the MX-CO, and MX-PH. Negative difference values indicate that the exposition is lower during occupied/unoccupied periods.

		>25µg/m³				
		Complete period (a)	Occupied period (b)	Difference (b-a)	Unoccupied period (c)	Difference (c-a)
MX-CO	Bedroom	49.92%	38.72%	-11.20%	56.71%	6.79%
	Kitchen	35.69%	45.35%	9.67%	34.53%	-1.16%
	Living room	37.84%	33.26%	-4.59%	40.09%	2.25%
MX-PH	Bedroom	13.49%	7.93%	-5.56%	17.09%	3.60%
	Kitchen	16.13%	21.31%	5.18%	15.51%	-0.62%
	Living room	15.23%	14.52%	-0.70%	14.52%	-0.71%

Indoor PM2.5 levels in MX-PH (9.78-10.60µg/m³) were significantly lower than those in MX-CO (19.05-22.78µg/m³) at low outdoor PM2.5 concentrations (≤10µg/m³). Therefore, a significant difference in the performance of the homes was observed in reducing indoor PM2.5 concentrations at low outdoor PM2.5 concentrations. PM2.5 concentrations above 25µg/m³ in both bedrooms were lower during occupied periods (MX-CO 38.72%, MX-PH 7.93%) than those for the complete period (MX-CO 49.92%, MX-PH 13.49%). Similar results were observed in both living rooms, while kitchen PM2.5 above 25µg/m³ were higher during occupied periods as observed in Table 5.9.

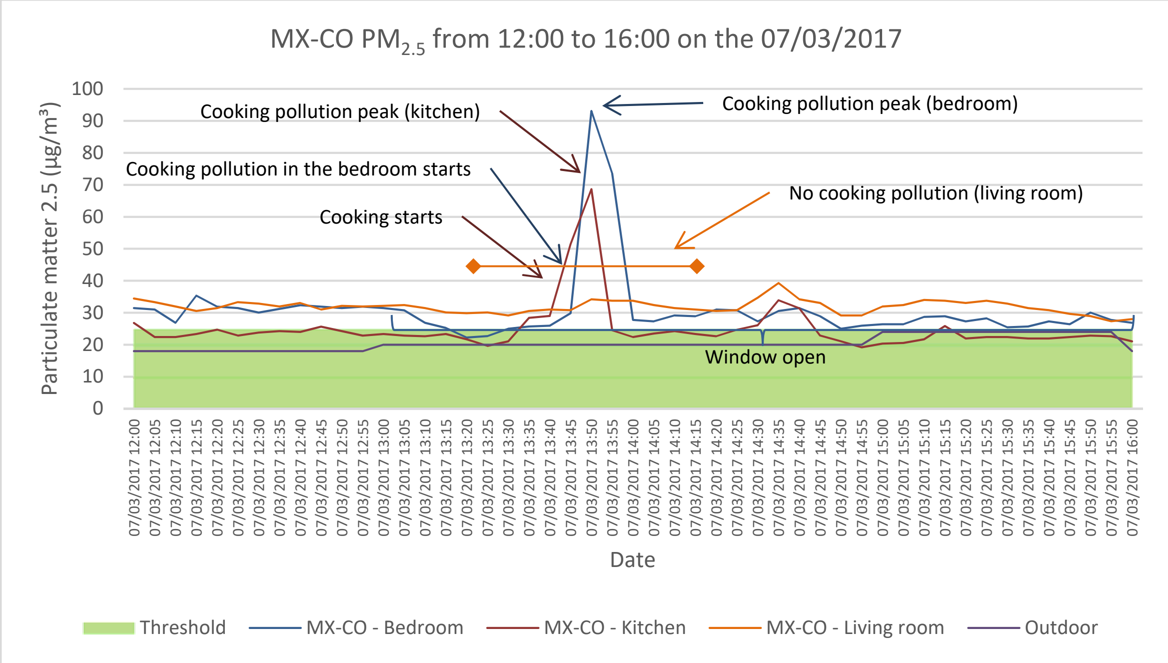


Figure 5.40 Example of $PM_{2.5}$ pollution peaks for cooking in the MX-CO. Example of the $PM_{2.5}$ pollution dissipation with windows open in the MX-CO.

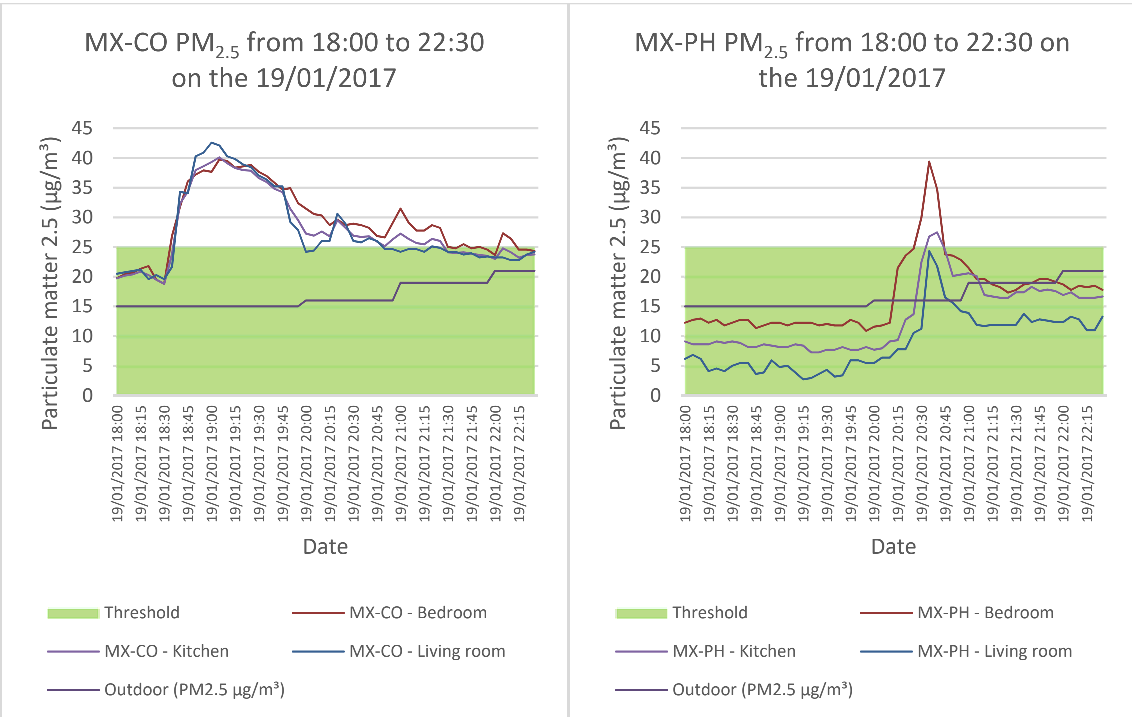


Figure 5.41 Example of the differences in the $PM_{2.5}$ pollution dissipation with windows closed. The pollution peak in the MX-CO (left) took longer time to dissipate compared to the MX-PH (right).

Figure 5.42 and Figure 5.43 suggest that short peaks were associated with cooking, especially at MX-CO. The analysis shows clear differences between the seasons, whereby summer indoor $PM_{2.5}$ concentrations in MX-PH (13.45-14.50µg/m^3) and MX-CO (21.74-27.47µg/m^3) were the lowest, while ambient $PM_{2.5}$ concentrations during autumn (17.56µg/m^3) were lower than those observed during summer (19.64µg/m^3). This could be associated with the fact that during summer, windows may remain open longer, even though indoor temperature levels are higher during spring. Levels measured for MX-PH (14.16-16.06µg/m^3) and MX-CO (25.68-29.48µg/m^3) during winter were the second lowest $PM_{2.5}$ concentrations compared to the other seasons, when ambient concentrations were 24.52µg/m^3. Indoor $PM_{2.5}$ levels were higher during the transitional seasons, and spring was the highest (MX-PH from 19.71-21.72µg/m^3 and MX-CO from 28.59-32.30µg/m^3), perhaps associated with the highest seasonal ambient concentrations (27.84 µg/m^3), followed by autumn (MX-PH 16.00-16.48µg/m^3 and MX-CO 28.18-30.63µg/m^3). Outdoor levels were 17.56µg/m^3 during autumn, 19.64µg/m^3 in summer, 24.52µg/m^3 during winter and 27.84µg/m^3 in spring.

Table 5.10 Monthly $PM_{2.5}$ ambient and indoor differences.

		January (µg/m^3)	February (µg/m^3)	March (µg/m^3)	April (µg/m^3)	May (µg/m^3)	June (µg/m^3)	July (µg/m^3)	August (µg/m^3)	September (µg/m^3)	October (µg/m^3)	November (µg/m^3)	December (µg/m^3)
MX-CO	Bedroom	5.4	3.2	0.4	9.7	4.6	5.8	12.9	9.7	11.9	11.2	7.1	7.0
	Kitchen	1.2	-0.7	0.7	2.3	2.0	0.3	4.0	10.9	11.3	9.6	3.2	3.7
	Living room	1.6	5.6	-2.6	0.3	2.7	4.2	9.7	12.6	13.7	13.0	2.4	5.4
MX-PH	Bedroom	-9.6	-6.1	-8.8	-9.5	-7.5	-7.1	-4.0	-4.4	1.5	-1.9	-7.7	-6.5
	Kitchen	-6.8	-4.9	-7.3	-6.2	-6.5	-5.9	-3.0	-4.4	-0.0	0.8	-4.9	-5.2
	Living room	-7.0	-2.8	-8.8	-10.0	-5.5	-5.9	-4.0	-5.4	2.1	-0.1	-4.5	-5.5

A previous study that looked into the relationship between indoor and outdoor $PM_{2.5}$ concentrations in Mexico City found that they were moderately similar at $r_s=0.56$ ($P<0.000$) regardless of the season (Cortez-Lugo *et al.*, 2008). In this study, we noticed comparable relationships between outdoor and indoor $PM_{2.5}$ concentrations at MX-CO $r_s=0.539\text{-}0.611$ ($P<0.001$) and MX-PH $r_s=0.539\text{-}0.587$ ($P<0.001$). Further statistical analysis noted clear differences between outdoors and indoors. MX-CO's annual mean levels were between 3.65µg/m^3 and 7.04µg/m^3 higher than those outdoors, compared to 5.22µg/m^3 to 6.54µg/m^3 below outdoor levels in MX-PH. In fact, this was true for all months and rooms, with just a few exceptions (Table 5.10). The results of this analysis suggest that the difference between the MX-CO and MX-PH are related to the occupant behaviours, architectural differences and ventilation strategies.

		Bedroom																										
	Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Hour	
January	MX-CO	36	31	27	27	26	25	26	29	39	35	38	44	38	35	37	33	30	29	28	26	29	27	28	41	32	MX-CO	January
	MX-PH	14	14	14	15	14	14	14	15	16	17	18	19	17	16	17	17	17	16	17	16	16	15	16	15	16	MX-PH	
	Ambient	24	21	22	23	25	27	30	34	35	39	43	42	38	37	34	31	28	26	25	26	25	23	24	24	29	Ambient	
February	MX-CO	44	39	32	27	23	21	21	25	32	33	35	32	29	27	28	28	26	26	25	25	23	21	26	38	29	MX-CO	February
	MX-PH	12	12	11	10	11	11	12	15	18	19	19	17	15	13	11	12	14	13	13	13	15	13	12	13	14	MX-PH	
	Ambient	17	18	17	18	19	21	24	26	27	32	34	31	28	27	26	26	26	25	21	19	20	18	19	18	23	Ambient	
March	MX-CO	23	23	24	23	22	21	22	28	32	33	34	35	32	30	28	26	24	22	22	22	23	22	22	24	26	MX-CO	March
	MX-PH	16	14	13	12	12	12	12	16	21	29	25	24	20	17	16	14	14	13	13	13	14	14	21	18	16	MX-PH	
	Ambient	17	18	17	18	22	22	25	25	28	32	36	34	30	27	25	22	22	19	17	18	15	17	18	17	23	Ambient	
April	MX-CO	28	29	29	26	25	24	24	28	30	32	35	34	30	28	28	27	26	24	24	24	24	24	24	27	27	MX-CO	April
	MX-PH	17	16	17	16	17	18	19	20	22	23	24	23	20	18	18	17	17	17	17	16	16	16	16	16	18	MX-PH	
	Ambient	25	22	25	25	26	28	29	32	34	36	37	34	26	27	26	27	24	25	24	22	23	23	24	24	27	Ambient	
May	MX-CO	47	47	46	46	46	46	46	46	44	43	40	39	38	39	40	40	41	41	42	43	45	46	49	48	44	MX-CO	May
	MX-PH	22	21	21	20	20	21	23	28	31	33	33	33	30	28	26	25	22	22	21	22	23	22	22	22	25	MX-PH	
	Ambient	28	27	31	29	29	30	33	37	38	43	46	46	43	39	41	36	34	33	31	29	30	28	29	26	34	Ambient	
June	MX-CO	25	23	21	21	20	20	20	21	25	28	32	36	38	40	37	34	32	27	23	22	26	25	23	23	27	MX-CO	June
	MX-PH	13	13	11	11	11	11	12	14	15	18	20	22	22	21	19	16	15	13	12	13	12	12	13	13	15	MX-PH	
	Ambient	17	17	17	17	17	18	20	21	22	26	30	33	36	36	32	28	24	22	19	17	17	15	16	17	22	Ambient	
July	MX-CO	25	23	21	19	18	18	18	19	23	30	34	39	40	39	35	30	27	23	20	21	20	19	20	25	25	MX-CO	July
	MX-PH	10	10	9	9	9	9	9	10	12	15	20	21	19	19	17	14	12	10	10	12	11	11	10	10	12	MX-PH	
	Ambient	13	12	12	13	14	16	19	19	20	23	27	30	32	32	31	28	23	17	15	14	14	14	14	14	19	Ambient	
August	MX-CO	41	36	30	28	26	24	24	24	28	33	33	35	37	39	37	35	32	26	24	22	23	23	29	36	30	MX-CO	August
	MX-PH	13	13	13	13	13	13	13	13	13	14	13	14	15	15	15	14	13	13	13	13	13	13	13	13	13	MX-PH	
	Ambient	11	11	11	12	13	14	15	16	18	19	23	25	29	30	28	26	21	18	15	14	12	13	11	12	17	Ambient	
September	MX-CO	28	26	24	22	21	21	21	22	24	27	26	28	30	29	31	34	36	25	21	21	21	23	24	24	25	MX-CO	September
	MX-PH	9	9	9	9	9	9	9	10	11	14	17	19	18	17	15	13	12	12	10	10	9	8	8	9	11	MX-PH	
	Ambient	12	11	12	11	12	12	14	15	16	18	20	23	25	25	24	22	19	18	13	11	11	11	12	12	16	Ambient	
October	MX-CO	32	29	28	25	22	21	21	25	27	29	35	34	32	30	29	27	23	21	20	19	19	19	22	33	26	MX-CO	October
	MX-PH	12	12	13	13	14	17	17	17	21	23	22	20	20	19	19	16	14	13	12	11	11	12	12	13	16	MX-PH	
	Ambient	8	9	9	11	12	13	14	16	16	18	20	23	23	22	20	17	16	12	11	10	8	9	9	9	14	Ambient	
November	MX-CO	33	31	27	25	24	24	28	32	38	43	46	48	45	40	40	41	41	35	31	31	30	30	28	31	34	MX-CO	November
	MX-PH	15	16	17	17	17	17	18	20	25	31	31	31	31	28	26	23	22	19	17	19	19	17	16	15	21	MX-PH	
	Ambient	17	17	18	18	18	20	22	23	25	30	33	34	33	32	31	28	28	24	21	17	16	16	16	16	23	Ambient	
December	MX-CO	35	31	29	27	25	25	26	27	27	30	30	29	29	26	26	26	25	24	25	26	31	29	30	34	28	MX-CO	December
	MX-PH	12	12	11	11	11	11	12	13	16	17	20	19	17	15	14	12	12	11	11	12	12	12	12	13	13	MX-PH	
	Ambient	18	19	18	17	18	20	24	24	26	28	29	27	25	25	23	19	19	18	18	17	18	17	18	17	21	Ambient	
	Scale	0	2	4	6	8	10	13	15	17	19	21	23	25	27	29	31	33	35	37	40	42	44	46	48	50	Scale	

Figure 5.42 Hourly $PM_{2.5}$ average per month in the bedrooms in MX-CO, MX-PH and ambient.

Hour		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Hour	
		Living room																									
January	MX-CO	32	28	25	29	28	26	26	30	43	37	45	40	34	31	33	32	29	27	27	27	27	27	28	35	MX-CO	January
	MX-PH	14	14	14	16	15	16	16	17	18	17	19	19	17	15	15	14	14	14	15	14	14	14	15	14	MX-PH	
	Ambient	24	21	22	23	25	27	30	34	35	39	43	42	38	37	34	31	28	26	25	26	25	23	24	24	Ambient	
February	MX-CO	27	26	23	24	23	23	23	29	33	34	31	26	24	23	24	24	23	22	22	21	21	20	21	26	MX-CO	February
	MX-PH	15	16	16	15	16	17	18	21	21	21	21	17	15	13	13	14	16	14	15	15	15	14	15	15	MX-PH	
	Ambient	17	18	17	18	19	21	24	26	27	32	34	31	28	27	26	26	26	25	21	19	20	18	19	18	Ambient	
March	MX-CO	25	25	25	25	25	26	27	34	33	34	36	35	32	31	29	27	27	26	26	26	26	26	26	26	MX-CO	March
	MX-PH	20	19	18	17	18	18	19	21	24	30	28	27	23	19	19	17	16	16	15	15	15	16	22	21	MX-PH	
	Ambient	17	18	17	18	22	22	25	25	28	32	36	34	30	27	25	22	22	19	17	18	15	17	18	17	Ambient	
April	MX-CO	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	MX-CO	April
	MX-PH	15	17	17	17	18	19	22	24	23	24	22	22	19	17	17	16	16	16	16	15	15	16	16	16	MX-PH	
	Ambient	25	22	25	25	26	28	29	32	34	36	37	34	26	27	26	27	24	25	24	22	23	23	24	24	Ambient	
May	MX-CO	35	33	30	29	28	27	27	31	43	41	45	41	39	37	36	35	33	32	31	33	34	34	33	34	MX-CO	May
	MX-PH	22	21	21	21	21	23	25	27	29	32	32	33	30	27	24	23	21	20	21	20	22	21	20	21	MX-PH	
	Ambient	28	27	31	29	29	30	33	37	38	43	46	46	43	39	41	36	34	33	31	29	30	28	29	26	Ambient	
June	MX-CO	22	22	20	19	19	18	18	18	22	30	34	36	40	38	36	32	27	23	20	20	21	20	20	21	MX-CO	June
	MX-PH	15	15	15	15	15	15	17	18	19	20	24	25	24	22	19	16	15	13	11	13	13	13	14	14	MX-PH	
	Ambient	17	17	17	17	17	18	20	21	22	26	30	33	36	36	32	28	24	22	19	17	17	15	16	17	Ambient	
July	MX-CO	24	22	20	19	19	19	19	19	22	29	34	35	34	33	30	27	24	20	18	19	18	18	20	23	MX-CO	July
	MX-PH	13	13	13	13	13	14	13	14	13	13	14	14	14	14	14	14	14	13	13	13	13	13	13	13	MX-PH	
	Ambient	13	12	12	13	14	16	19	19	20	23	27	30	32	32	31	28	23	17	15	14	14	14	14	14	Ambient	
August	MX-CO	33	30	26	26	23	21	20	20	24	30	42	38	37	33	32	29	23	21	20	19	22	21	26	34	MX-CO	August
	MX-PH	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	MX-PH	
	Ambient	11	11	11	12	13	14	15	16	18	19	23	25	29	30	28	26	21	18	15	14	12	13	11	12	Ambient	
September	MX-CO	29	27	26	25	25	25	25	25	28	31	32	33	33	31	30	33	39	28	24	25	25	25	26	29	MX-CO	September
	MX-PH	8	8	8	8	8	8	9	10	11	12	16	18	17	15	13	11	10	9	9	8	8	8	8	8	MX-PH	
	Ambient	12	11	12	11	12	12	14	15	16	18	20	23	25	25	24	22	19	18	13	11	11	11	12	12	Ambient	
October	MX-CO	28	28	26	24	23	23	23	24	30	33	35	35	35	33	32	30	28	25	24	22	22	22	27	32	MX-CO	October
	MX-PH	13	13	14	14	15	18	18	19	23	25	23	21	21	18	18	16	14	13	12	11	11	12	12	13	MX-PH	
	Ambient	8	9	9	11	12	13	14	16	16	18	20	23	23	22	20	17	16	12	11	10	8	9	9	9	Ambient	
November	MX-CO	33	31	28	27	27	27	28	31	45	50	54	53	48	42	40	40	41	36	32	33	29	29	28	31	MX-CO	November
	MX-PH	18	20	20	21	21	22	23	25	29	34	31	30	31	27	24	23	21	19	18	20	20	19	18	17	MX-PH	
	Ambient	17	17	18	18	18	20	22	23	25	30	33	34	33	32	31	28	28	24	21	17	16	16	16	16	Ambient	
December	MX-CO	27	24	21	19	18	18	18	21	26	27	31	30	27	23	23	23	21	20	19	21	25	22	23	31	MX-CO	December
	MX-PH	16	15	15	15	15	15	17	19	21	22	23	21	19	16	15	14	14	13	14	15	14	15	15	16	MX-PH	
	Ambient	18	19	18	17	18	20	24	24	26	28	29	27	25	25	23	19	19	18	18	17	18	17	18	17	Ambient	
PM2.5 (μg/m3) scale		0	2	4	6	8	10	13	15	17	19	21	23	25	27	29	31	33	35	37	40	42	44	46	48	PM2.5 (μg/m3) scale	

Figure 5.43 Hourly $PM_{2.5}$ average per month in the living rooms in MX-CO, MX-PH and ambient.

5.5.5 Total volatile organic compounds (tVOC)

As part of the indoor environmental monitoring, tVOC measurements were conducted in the bedrooms, kitchens and living rooms of both dwellings. Outdoor measurements were not possible, due to the specifications of the monitoring equipment and the fact that the local pollution monitoring network did not record them. However, a seven-month study found that outdoor concentrations of tVOC[6] in residential areas in Mexico City were approximately 1462μg/m^3 (±763μg/m^3) and 1293μg/m^{3}near to a university campus. Nevertheless, exposure in areas near to petrol stations could rise to 5364μg/m^3 (±4286μg/m^3, Rodolfo Sosa *et al.*, 2009).

[6] TVOC concentrations were measured using a gas chromatograph equipped with a flame ionization detector (GC-FID) as a part of the EPA Method TO-15.

The higher occurrence of pollution above the threshold was observed in the bedroom in MX-CO, during the evening and early morning and night, when occupants used personal cleaning products and the windows remained closed. Concentrations of measured tVOC exceeded the accepted levels (300µg/m^3 (ECA, 1992)) in all rooms of both flats (Figure 5.44). However, it is also important to observe real occupant exposure to levels above the threshold. For instance, bedroom tVOC levels above 300µg/m^3 during typical occupied periods were higher in both dwellings (MX-CO 93.42%, MX-PH 86.13% of the occupied time) than those during the complete period (MX-CO 85.16%, MX-PH 76.02%, Annual mean tVOC concentrations did not vary significantly from room to room at MX-PH (569µg/m^3 (bedroom), 569µg/m^3 (kitchen) 578µg/m^3 (living-room)), perhaps due to the open plan layout. However, they were significantly different at MX-CO: bedroom (786µg/m^3), living room (587µg/m^3) and kitchen (589µg/m^3). MX-CO peak tVOC levels were related to human activities across the three rooms. The use of personal cleaning products, cooking and cleaning had the most significant impact, particularly during periods of poor ventilation - evidenced by the high CO_2 levels and closed windows as stated by the occupants - during early mornings and nights (Figure 5.45). TVOC levels usually remain at low concentrations (~200µg/m^3) at no occupancy (Figure 5.46). It was also observed that when a pollution event occurred on the ground floor, it was likely to be found across the three rooms. Contrastingly, when a pollution event occurred in the bedroom, none or very little would spread to the rest of the house (Figure 5.47).

Table 5.11). Where as the median concentrations of bedroom tVOC were higher in MX-CO ((684ug/m^3) than those in the MX-PH (664ug/m^3), there was no statistical significance in the difference (37ug/m^3), z=-27.39, p=.450. The median difference (214.5ug/m^3) between the kitchens was statically different, between the MX-CO (340ug/m^3) and the MX-PH (543ug/m^3), z=230.16, p<.001. Similarly, the median differences in the living-rooms (198ug/m^3) was statically different, between the MX-CO (260ug/m^3) and the MX-PH (513ug/m^3), z=264.23, p<.001.

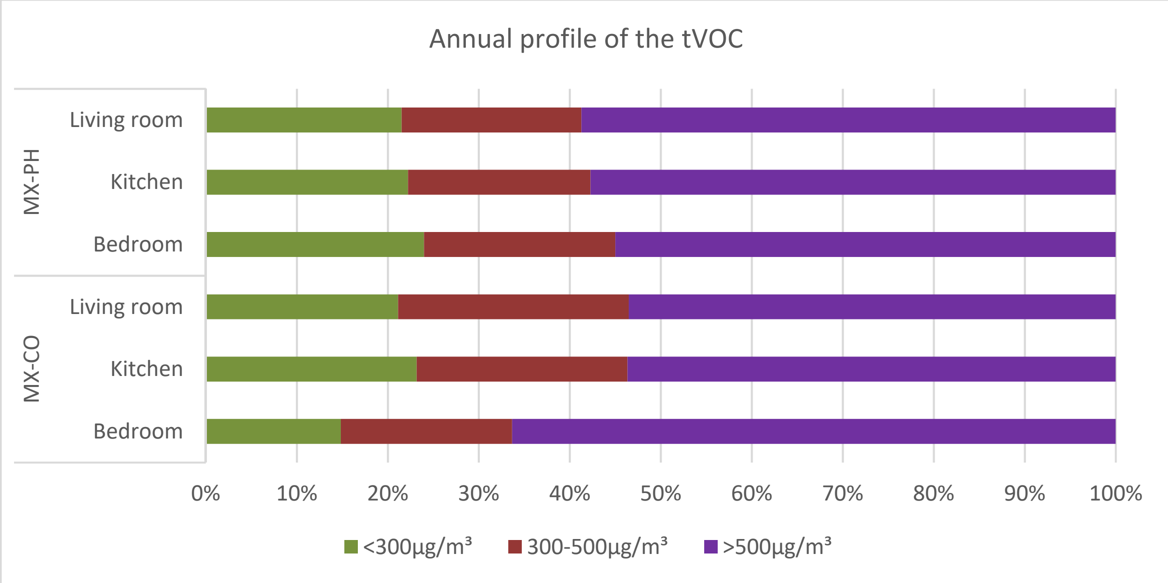


Figure 5.44 Annual tVOC concentrations by exposure range during the monitored time.

Annual mean tVOC concentrations did not vary significantly from room to room at MX-PH (569µg/m^3 (bedroom), 569µg/m^3 (kitchen) 578µg/m^3 (living-room)), perhaps due to the open plan layout. However, they were significantly different at MX-CO: bedroom (786µg/m^3), living room (587µg/m^3) and kitchen (589µg/m^3). MX-CO peak tVOC levels were related to human activities across the three rooms. The use of personal cleaning products, cooking and cleaning had the most significant impact, particularly during periods of poor ventilation - evidenced by the high CO_2 levels and closed windows as stated by the occupants - during early mornings and nights (Figure 5.45). TVOC levels usually remain at low concentrations (~200µg/m^3) at no occupancy (Figure 5.46). It was also observed that when a pollution event occurred on the ground floor, it was likely to be found across the three rooms. Contrastingly, when a pollution event occurred in the bedroom, none or very little would spread to the rest of the house (Figure 5.47).

Table 5.11 TVOC summary of analysis of time periods with levels above 300µg/m^3 in the MX-CO, and MX-PH. Negative difference values indicate that the exposition is lower during occupied/unoccupied periods.

		>300µg/m3				
		Complete period (a)	Occupied period (b)	Difference (b-a)	Unoccupied period (c)	Difference (c-a)
MX-CO	Bedroom	85.16%	93.42%	8.27%	71.67%	-13.49%
	Kitchen	73.12%	71.76%	-1.36%	78.55%	5.42%
	Living room	78.86%	81.01%	2.15%	80.04%	1.18%
MX-PH	Bedroom	76.02%	86.13%	10.11%	71.17%	-4.85%
	Kitchen	77.07%	77.09%	0.02%	78.55%	1.47%

	Living room	78.47%	82.73%	4.26%	77.38%	-1.09%

In MX-PH, a similar effect is observed. When a pollution event happened in the living room or kitchen, it would spread to the bedroom and the bathroom, as the extraction fan was in the bathroom adjacent to the bedroom and the inlet between the kitchen and the living room (Figure 5.48). It was also observed that the purge effect, by opening the patio door, was more effective, as pollution rapidly dissipated (Figure 5.49). This method was used constantly when doing cleaning and so very little pollution can be attributed to cleaning activities, even though the cleaning service (in between different guests) use chemical products. The use of personal cleaning products was observed to have a lesser impact in MX-PH, but it is unclear the kind of products used. TVOC concentrations were not associated entirely with building-related factors, as during non-occupied periods tVOC levels are minimal (Figure 5.50). Figure 5.51 shows the effect of the on/off ventilation technique to tVOC levels.

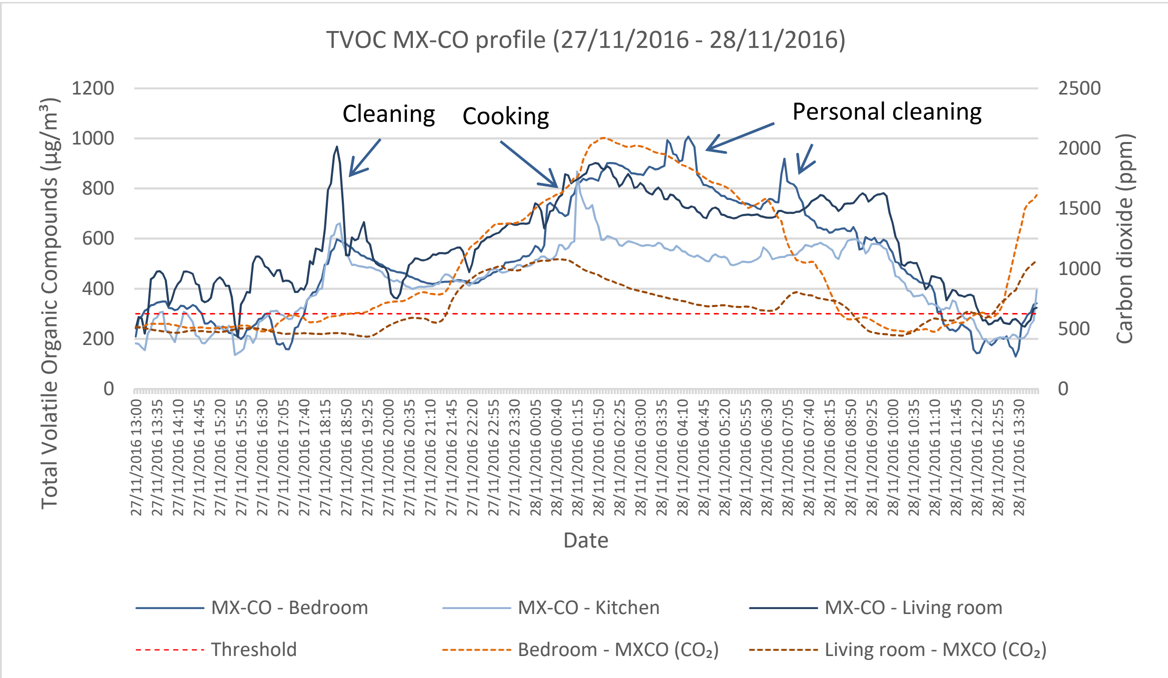


Figure 5.45 Example of the impact of human interaction on tVOC in the MX-CO (27/11/2016-28/11/2016).

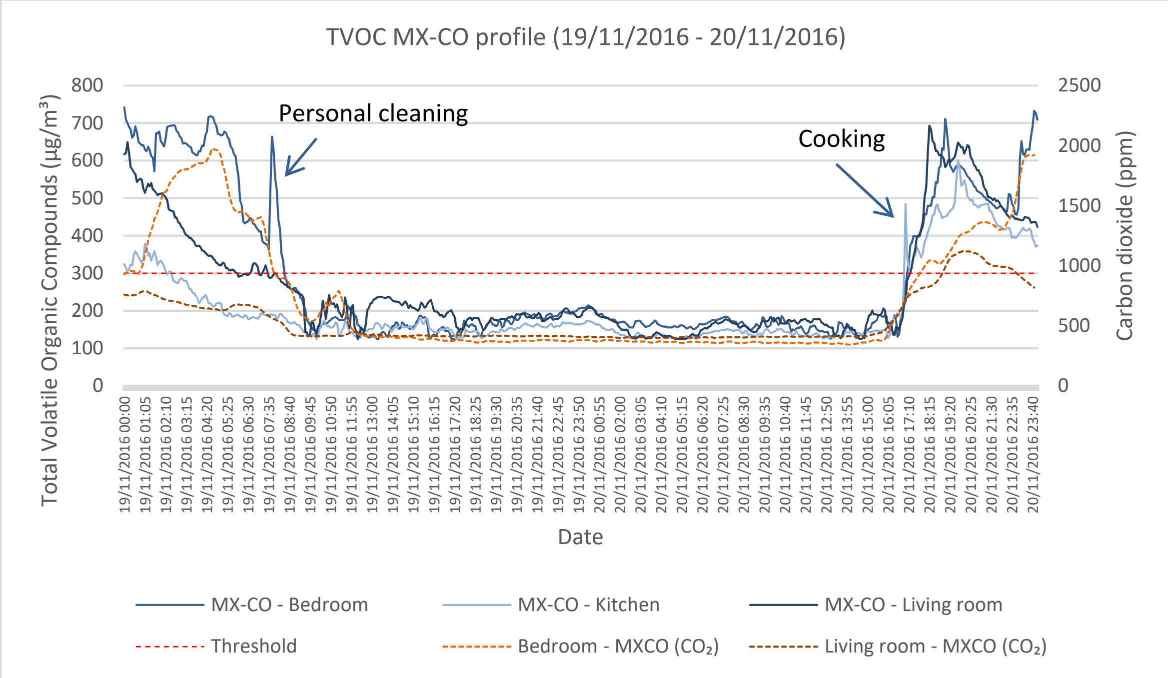


Figure 5.46 Example if the tVOC profile in the MX-CO at no occupancy (19/11/2016-20/11/2016).

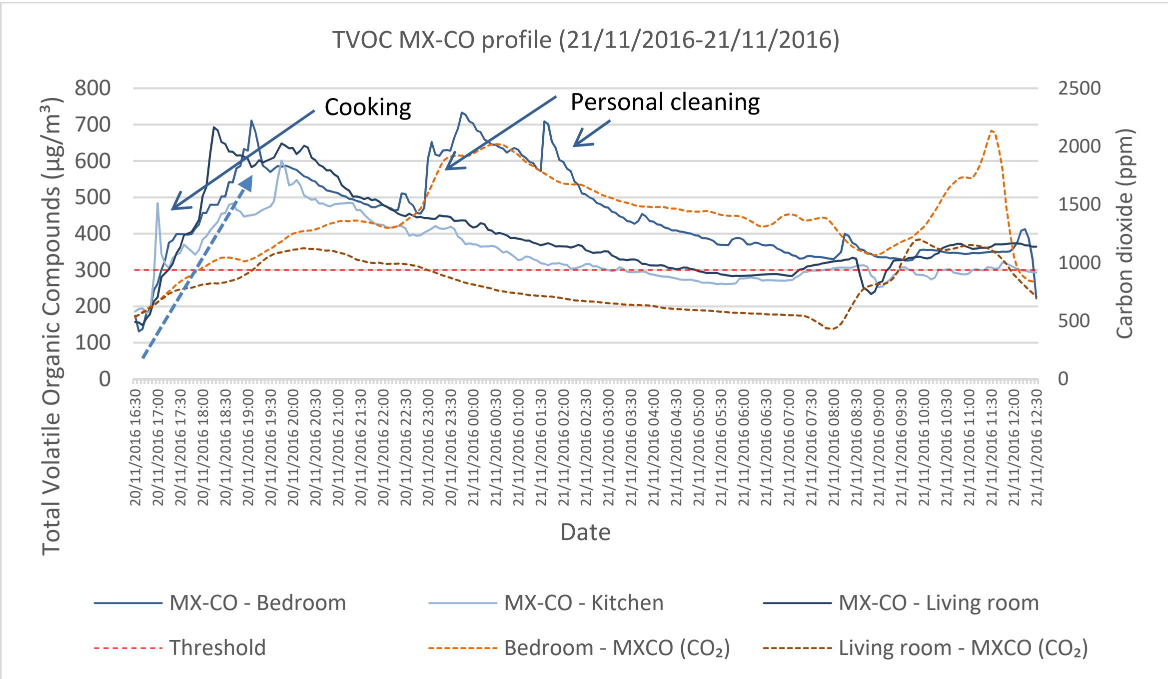


Figure 5.47 Example of the impact of indoor tVOC sources from the MX-CO ground floor to the top floor (20/11/2016-21/11/2016).

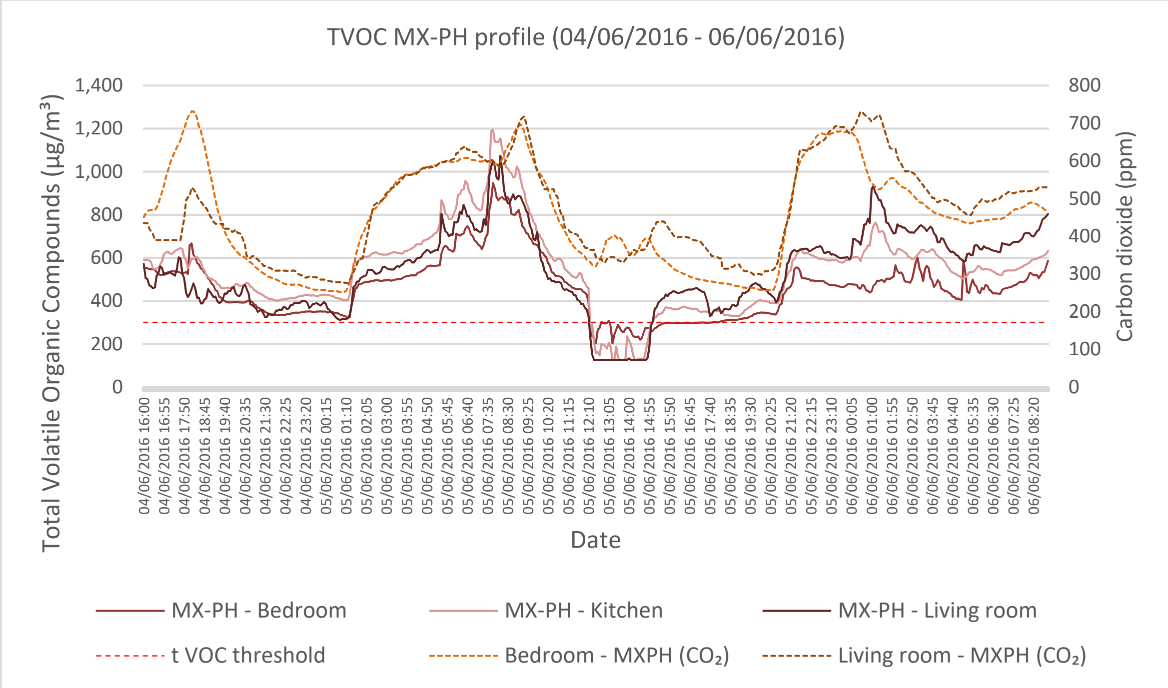


Figure 5.48 Example of tVOC pollution similar in all rooms of MX-PH (16/06/2016-17/06/2016).

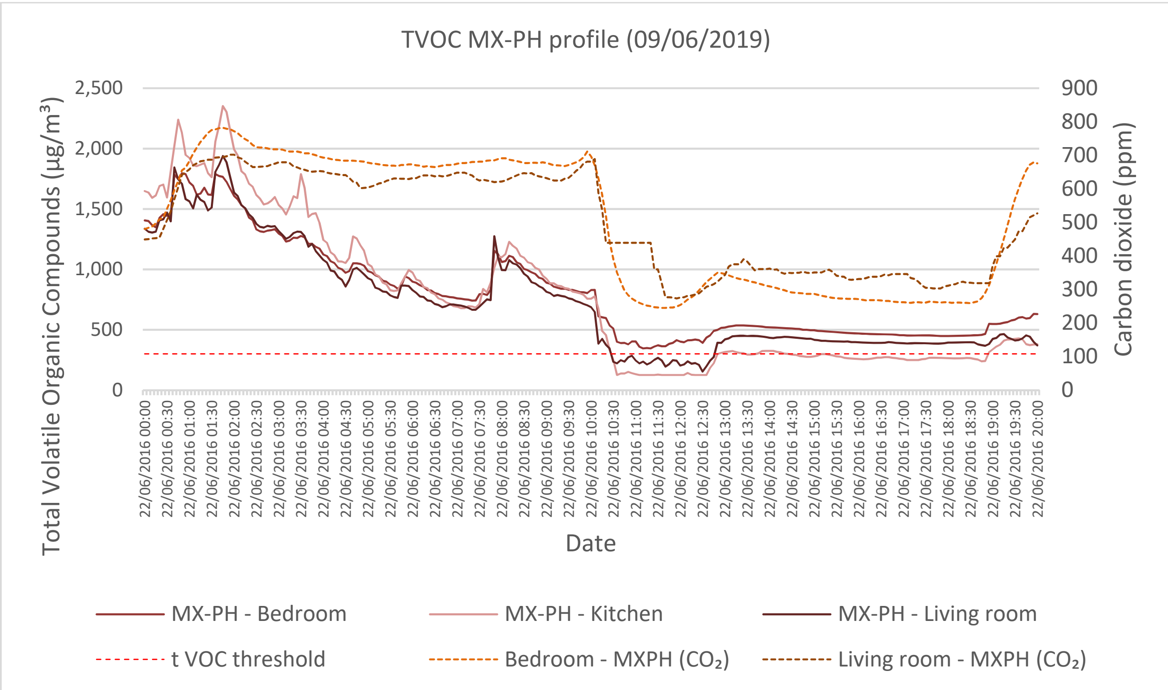


Figure 5.49 Example of purge ventilation in MX-PH (09/06/2016).

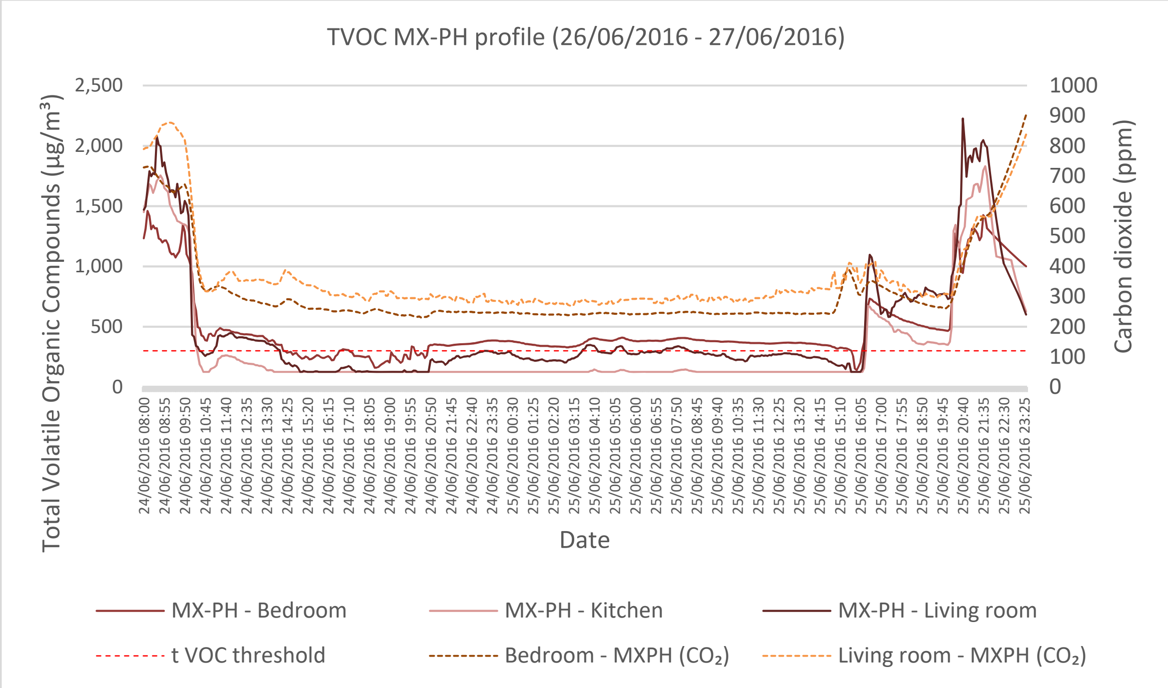


Figure 5.50 Example of period without guests (26/06/2016-27/06/2016).

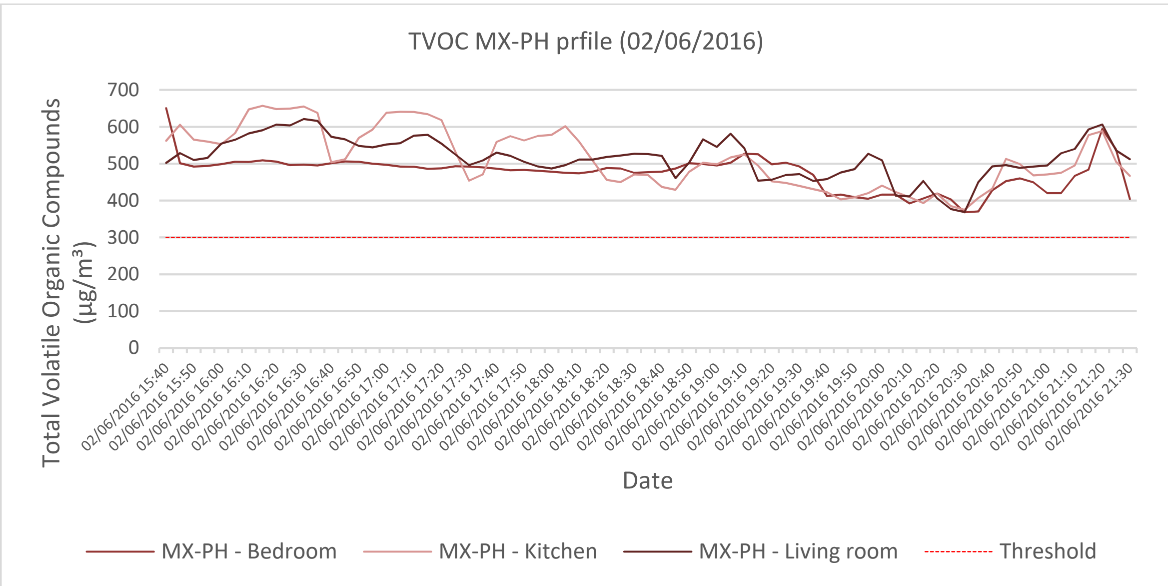


Figure 5.51 Example of effect of the ventilation system on the tVOC (02/06/2016).

Seasonal differences were noted in both homes, with concentrations higher during summer in MX-PH (580.26-634.70µg/m^3) and during spring in MX-CO (796.17-1,149.00µg/m^3). The lower tVOC concentrations were measured during autumn in MX-CO (362.35-526.15µg/m^3) and MX-PH (445.13-532.17µg/m^3). Daily variations were also observed, VOC concentrations were higher during early mornings and the evening, in both homes. This suggests that occupant behaviour is a critical factor for tVOC concentrations as illustrated in Figure 5.53 and Figure 5.54. Pollution peaks in MX-PH that lasted three to four days could be attributed to unusual - Airbnb guest' - behaviour, one instance of which is illustrated in Figure

5.52. These changes for different Airbnb guests made the seasonal mean at MX-PH higher during autumn, while tVOC seasonal mean levels remained lower than those in MX-CO for the rest of the seasons.

Whereas tVOC levels were lower in MX-PH compared to those in MX-CO, it is more likely to be related to difference in occupant behaviours. The occurrence of tVOC levels above 300µg/m^3 were 9.14% (B) and 0.39% (L) lower in the MX-PH compared to the MX-CO during the complete period. Nevertheless, MX-PH kitchen tVOC levels above 300µg/m^{3}were 3.95% higher. Similarly, during occupied time MX-PH bedroom occurrence of levels above 300µg/m^3 were 7.30% lower than those in the MX-CO.

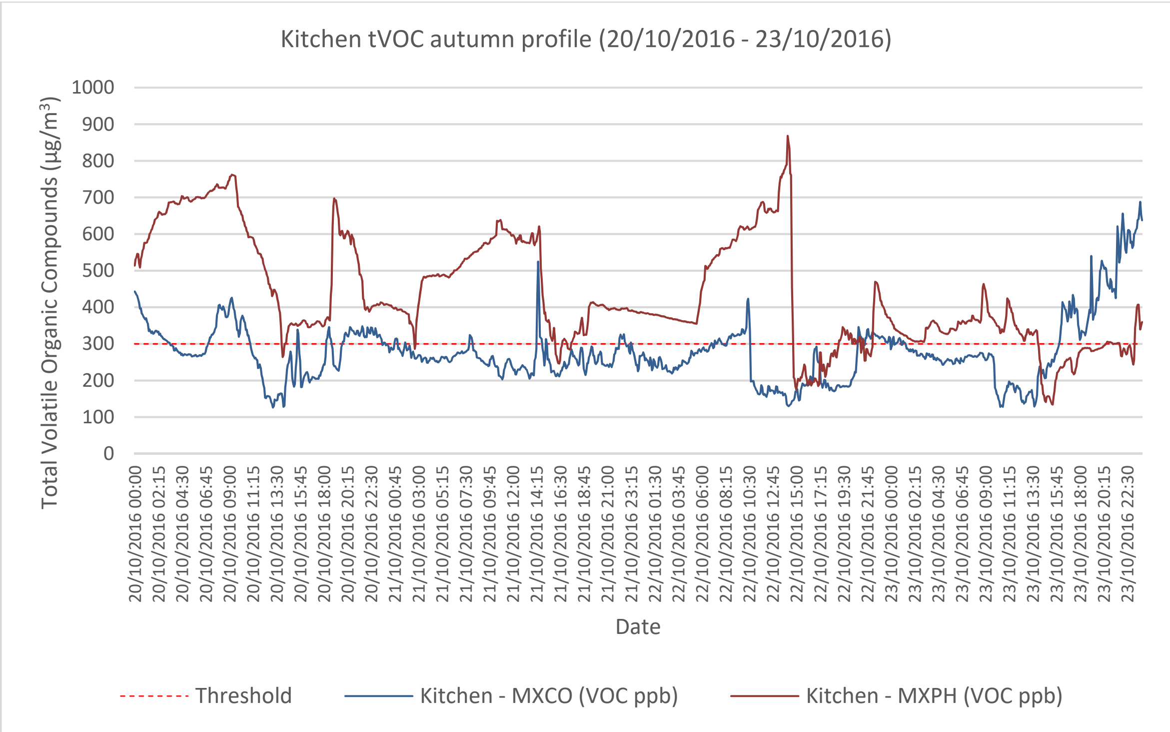


Figure 5.52 Indoor kitchen tVOC concentration comparison during autumn. The high peaks correspond to a different guest in MX-PH.

	Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Hour	
		Bedroom																									
January	MX-CO	867	899	866	879	824	780	763	796	805	732	671	537	430	366	357	389	443	544	657	710	790	780	802	830	MX-CO	January
	MX-PH	579	582	593	603	616	620	640	657	653	646	599	529	503	491	472	458	463	486	502	553	594	580	560	575	MX-PH	
February	MX-CO	1426	1423	1366	1319	1252	1209	1208	1242	1198	1111	928	707	591	522	530	593	648	713	882	1043	1089	1126	1209	1303	MX-CO	February
	MX-PH	858	885	900	925	912	854	838	891	917	907	801	710	600	560	559	549	574	591	616	678	751	779	822	846	MX-PH	
March	MX-CO	1058	1061	1083	1098	1057	1056	1040	1073	981	891	784	647	608	390	374	475	627	658	757	784	899	936	1013	1023	MX-CO	March
	MX-PH	992	1041	1072	1124	1191	1258	1317	1336	1257	1093	816	683	522	459	433	481	510	540	561	617	666	721	796	897	MX-PH	
April	MX-CO	1158	1146	1123	1090	1058	1078	1106	1094	1068	1035	871	742	596	499	424	423	506	587	698	774	832	877	1008	1072	MX-CO	April
	MX-PH	346	362	387	401	415	428	440	451	453	448	405	341	296	267	258	251	261	250	244	255	274	299	321	334	MX-PH	
May	MX-CO	2230	2246	2220	2178	2157	2207	2107	2180	1962	1776	1537	1275	1054	929	857	859	1020	1249	1431	1640	1872	2132	2076	2127	MX-CO	May
	MX-PH	698	740	786	805	816	846	867	864	791	735	645	564	461	398	391	420	418	407	450	514	554	597	616	678	MX-PH	
June	MX-CO	877	878	824	794	793	788	824	826	801	659	528	483	440	423	419	441	519	520	592	626	747	767	779	815	MX-CO	June
	MX-PH	629	633	603	619	634	641	651	705	691	653	540	471	422	398	385	390	422	432	441	443	503	531	568	616	MX-PH	
July	MX-CO	1042	1070	1076	1092	1064	1044	1048	1049	1019	864	729	592	542	525	451	527	584	643	680	757	900	960	966	1098	MX-CO	July
	MX-PH	793	810	846	828	792	780	781	780	750	734	687	623	563	521	524	531	558	579	620	659	699	735	752	781	MX-PH	
August	MX-CO	805	857	807	804	776	776	758	784	755	616	502	440	410	392	374	430	433	507	494	548	656	728	750	783	MX-CO	August
	MX-PH	638	636	631	635	646	649	644	641	629	609	603	586	564	549	538	534	531	528	524	548	557	581	612	624	MX-PH	
September	MX-CO	554	564	567	519	509	495	505	496	471	432	375	331	311	295	287	300	339	357	381	408	424	460	507	532	MX-CO	September
	MX-PH	451	456	458	488	510	497	525	528	441	396	343	320	296	288	271	273	299	316	337	371	375	385	429	429	MX-PH	
October	MX-CO	888	821	800	801	795	791	793	810	722	666	561	457	422	396	398	415	423	489	518	571	679	711	803	837	MX-CO	October
	MX-PH	545	598	613	597	567	566	540	529	542	522	497	455	407	347	308	273	277	294	309	363	396	411	447	492	MX-PH	
November	MX-CO	625	655	635	619	606	573	604	588	489	437	364	305	273	264	291	347	456	477	452	477	518	555	594	605	MX-CO	November
	MX-PH	637	659	692	676	655	644	663	630	551	514	469	420	381	357	349	355	368	384	374	395	426	468	539	583	MX-PH	
December	MX-CO	640	646	654	647	642	626	625	628	593	542	494	467	452	439	431	437	455	487	534	549	577	580	593	616	MX-CO	December
	MX-PH	641	614	619	603	592	615	604	614	566	497	438	362	314	300	297	305	346	383	440	494	534	571	589	642	MX-PH	
tVOC (ppb) scale		125	169	213	256	300	405	511	616	721	826	932	1037	1142	1247	1353	1458	1563	1668	1774	1879	1984	2089	2195	2300	tVOC (ppb) scale	

Figure 5.53 Hourly tVOC averages per month in the MX-CO and MX-PH bedrooms.

	Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Hour	
		Living room																									
January	MX-CO	864	818	766	732	693	666	667	744	843	792	669	483	397	411	361	390	433	469	504	633	797	875	913	933	MX-CO	January
	MX-PH	600	603	608	623	632	636	655	668	650	639	603	541	512	502	479	457	464	479	497	552	590	609	591	597	MX-PH	
February	MX-CO	900	858	839	808	774	752	755	859	929	810	659	482	412	432	410	439	462	514	568	630	692	753	799	864	MX-CO	February
	MX-PH	808	817	844	882	872	867	881	939	928	909	790	699	585	533	506	483	434	493	510	652	756	803	869	849	MX-PH	
March	MX-CO	715	711	706	692	667	653	658	718	739	707	623	521	433	409	422	483	522	542	570	605	631	698	727	709	MX-CO	March
	MX-PH	1002	1050	1072	1131	1189	1241	1286	1302	1188	1012	756	613	459	397	352	352	384	447	509	632	695	761	806	901	MX-PH	
April	MX-CO	513	513	513	513	513	513	513	513	513	513	513	513	513	513	513	513	513	513	513	513	513	513	513	513	MX-CO	April
	MX-PH	356	371	402	411	424	435	449	463	453	446	396	328	282	253	234	214	219	196	212	227	265	299	330	347	MX-PH	
May	MX-CO	1814	1870	1833	1807	1764	1734	1738	1798	1717	1534	1225	955	776	724	606	497	610	790	984	1195	1426	1570	1563	1679	MX-CO	May
	MX-PH	738	812	824	871	886	909	927	936	845	790	674	564	442	367	330	324	326	333	405	516	576	623	654	699	MX-PH	
June	MX-CO	672	657	633	614	602	599	605	625	627	519	430	377	342	321	329	356	371	391	444	487	501	568	620	684	MX-CO	June
	MX-PH	625	634	617	654	649	665	694	773	770	701	528	424	366	363	333	321	371	387	368	385	475	530	568	601	MX-PH	
July	MX-CO	722	702	683	662	643	634	634	649	679	604	503	394	345	312	306	341	373	416	453	544	603	623	659	686	MX-CO	July
	MX-PH	693	662	683	674	645	639	642	656	668	669	654	589	531	514	505	522	547	558	610	634	676	687	697	719	MX-PH	
August	MX-CO	574	557	539	523	503	486	489	501	512	458	395	343	337	316	300	307	321	358	398	451	511	554	563	576	MX-CO	August
	MX-PH	578	578	578	578	578	578	578	578	578	578	578	578	578	578	578	578	578	578	578	578	578	578	578	578	MX-PH	
September	MX-CO	475	462	443	421	404	391	389	406	414	398	372	335	313	314	312	312	355	362	387	412	422	442	453	479	MX-CO	September
	MX-PH	615	631	652	711	748	700	741	766	636	576	495	468	455	432	397	397	409	433	458	545	538	571	599	610	MX-PH	
October	MX-CO	634	595	568	550	535	524	523	553	585	557	453	371	335	326	341	378	409	450	479	491	572	598	643	660	MX-CO	October
	MX-PH	555	626	629	634	613	624	606	601	593	548	519	439	373	318	273	260	252	269	291	346	387	413	441	493	MX-PH	
November	MX-CO	497	481	458	431	403	385	382	407	419	388	314	266	250	236	264	305	342	383	418	416	427	454	474	485	MX-CO	November
	MX-PH	696	716	756	729	715	692	707	681	590	564	543	503	458	431	419	429	447	462	456	477	489	517	590	627	MX-PH	
December	MX-CO	536	519	483	451	429	412	409	448	465	423	384	315	287	284	290	302	325	332	381	428	472	464	491	524	MX-CO	December
	MX-PH	651	628	633	627	617	650	641	648	575	515	450	370	310	285	280	292	341	375	463	522	558	581	599	641	MX-PH	
tVOC (ppb) scale		196	222	248	274	300	383	465	548	631	713	796	878	961	1044	1126	1209	1292	1374	1457	1539	1622	1705	1787	1870	tVOC (ppb) scale	

Figure 5.54 Hourly tVOC averages per month in the MX-CO and MX-PH living rooms.

5.6 IAQ perceptions

Occupants' IAQ perceptions of both flats (N=3) were assessed through online surveys, using bipolar and unipolar scales as suggested by Raw (1995). As discussed in Chapter 4, IAQ perceptions scores could be rated in three different groups: good/ideal (unipolar scale = 1, bipolar scale = 4), requires further investigation (unipolar scale >3, bipolar scale outside 3-5 range) and causes of concern (unipolar scale >5, bipolar scale outside of 2-6 range). Participants completed the surveys between May 2016 and January 2017.

The surveys showed that the mean score at MX-PH, completed by the owners, for the fresh-stuffy scale (M=4.67) for the summer months requires further investigation. It suggests that even though occupants were satisfied overall with the conditions of MX-PH, they did not perceive the air to be significantly fresh. MX-CO occupants rated the fresh-stuffy scale (M=4.67) and still-draughty (M=5.67) poor, as they require further investigation, whereas the odourless-smelly scale (M=5.33) was a cause of concern. The satisfactory overall-unsatisfactory scale (M=4.00) was rated as requiring further investigation. This suggests constant dissatisfaction with IAQ at MX-CO, as participants perceived the air to be stale and draughty and that perceptions of odours were particularly critical; as such, overall IAQ perceptions may lead to dissatisfaction (see Table 5.12).

Similarly, during winter, MX-PH occupants rated the fresh-stuffy unipolar scale at above 3 (M=3.33), requiring further investigation, which suggests that the occupants did not perceive the air to be fresh. However, they were satisfied overall with IAQ. Occupants at MX-CO rated the unipolar scales fresh-stuffy (M=4.67), still-draughty (M=2.33) and odourless-smelly (M=5.00), thus requiring further investigation. Furthermore, the satisfactory overall-unsatisfactory scale (M=5.33) was identified as a cause of concern. Occupants at MX-CO had very poor perceptions of overall IAQ satisfaction, identifying the air as still and smelly, as well as stale (Table 5.13).

Table 5.12 Statistical analysis of IAQ perceptions during summer in MX-CO and MX-PH.

Summer									
IAQ perceptions scale	**House**	**Occupant**	**Result**	**Mean**	**SD**	**Mean + SD**	**Mean - SD**	**Max**	**Min**
Fresh (1) - stuffy (7) scale	MX-PH	A	4	4.67	0.58	5.24	4.09	5.00	4.00
		B	5						
		C	5						
	MX-CO	A	3	3.00	0.00	3.00	3.00	3.00	3.00
		B	3						
		C	3						
Dry (1) - humid (7) scale	MX-PH	A	4	4.00	1.00	5.00	3.00	5.00	3.00
		B	5						
		C	3						
	MX-CO	A	4	4.67	0.58	5.24	4.09	5.00	4.00
		B	5						
		C	5						
	MX-PH	A	3	3.33	0.58	3.91	2.76	4.00	3.00
		B	4						

Still (1) - draughty (7) scale		C	3						
	MX-CO	A	5	5.67	0.58	6.24	5.09	6.00	5.00
		B	6						
		C	6						
Odourless (1) -smelly (7) scale	MX-PH	A	1	2.33	1.53	3.86	0.81	4.00	1.00
		B	4						
		C	2						
	MX-CO	A	5	5.33	0.58	5.91	4.76	6.00	5.00
		B	5						
		C	6						
Satisfactory overall (1) - unsatisfactory overall (7) scale	MX-PH	A	1	1.33	0.58	1.91	0.76	2.00	1.00
		B	1						
		C	2						
	MX-CO	A	3	4.00	1.00	5.00	3.00	5.00	3.00
		B	5						
		C	4						

Participants at MX-PH reported that they did not experience condensation on the windows or the doors, and the measured hygrothermal conditions converge with the occupants' perception, as they both recorded dry environments variation. This may also have helped to reduce the off-gassing from building materials and products. MX-PH occupants experienced odours coming from outdoors; this may be related to the lack of filters in the inlet. However, participants rated the odour scale on the side of odourless; which may suggest that the outdoor odours were not significantly uncomfortable.

Table 5.13 Statistical analysis of IAQ perceptions during winter in MX-CO and MX-PH.

Winter									
IAQ perceptions scale	House	Occupant	Result	Mean	SD	Mean + SD	Mean - SD	Max	Min
Fresh (1) - stuffy (7) scale	MX-PH	A	4	3.33	1.15	4.49	2.18	4.00	2.00
		B	4						
		C	2						
	MX-CO	A	5	4.67	0.58	5.24	4.09	5.00	4.00
		B	5						
		C	4						
Dry (1) - humid (7) scale	MX-PH	A	3	4.00	1.00	5.00	3.00	5.00	3.00
		B	4						
		C	5						
	MX-CO	A	3	3.33	0.58	3.91	2.76	4.00	3.00
		B	4						
		C	3						
	MX-PH	A	4	3.67	0.58	4.24	3.09	4.00	3.00
		B	4						

		C	3						
Still (1) - draughty (7) scale	MX-CO	A	2	2.33	0.58	2.91	1.76	3.00	2.00
		B	3						
		C	2						
Odourless (1) -smelly (7) scale	MX-PH	A	1	2.67	1.53	4.19	1.14	4.00	1.00
		B	4						
		C	3						
	MX-CO	A	5	5.00	0.00	5.00	5.00	5.00	5.00
		B	5						
		C	5						
Satisfactory overall (1) - unsatisfactory overall (7) scale	MX-PH	A	1	1.33	0.58	1.91	0.76	2.00	1.00
		B	1						
		C	2						
	MX-CO	A	5	5.33	0.58	5.91	4.76	6.00	5.00
		B	6						
		C	5						

Participants at MX-CO experienced condensation on the windows and presence of mould in the bathroom and indoor relative humidity levels were above 60%RH were around 10% of the monitored time. Examination of the vapour levels showed that levels of absolute humidity were elevated although occupants did not perceive that way. MX-CO occupants also perceived smells coming from the kitchen, toilets, laundry closet and outdoors. A possible explanation for the indoor odours could be that the windows remain closed during prolonged times causing the air to be stale and stuffy as perceived by the occupants. The associations between the physical IAQ measurements and perceptions are presented in Chapter 8 and discussed in detail in Chapter 9.

5.7 Thermal perceptions

Occupant perceptions of thermal comfort were monitored in a web survey via unipolar and bipolar scales. The results of the statistical analysis were derived from the views of owners of each flat (N=3) and assessed using unipolar and bipolar scales as suggested by Raw (1995). As discussed in Chapter 4, thermal perceptions scores could be rated in three different groups: good/ideal (unipolar scale = 1, bipolar scale = 4), requires further investigation (unipolar scale >3, bipolar scale outside 3-5 range) and causes of concern (unipolar scale >5, bipolar scale outside of 2-6 range).The associations between the physical thermal measurements and perceptions are presented in Chapter 8 and discussed in Chapter 9.

During summer, MX-PH and MX-CO were generally satisfactory (Table 5.14). In fact, both flats produced equal results on the scale of too hot-too cold (M=3.67). Minor differences surfaced between the unipolar scales comfortable-uncomfortable (MX-PH, M=2.00, MX-CO, M=1.67), stable-varies (MX-PH, M=2.67, MX-CO, M=2.33) and satisfactory overall-unsatisfactory overall (MX-PH, M=2.00, MX-CO, M=1.67). However, higher daily variations were observed in the MX-PH (mean summer daily temperature variations bedroom 2.01°C, kitchen 3.10°C and living-room 5.04°C) compared to the MX-CO (mean summer daily temperature variations bedroom 1.20°C, kitchen 1.74°C and living-room 1.74°C) perhaps related to the differences in thermal mass between both homes. These scores suggest that thermal comfort is similar in both flats in summer, possibly due to the adaptive comfort offered by the ability to open or close windows.

Table 5.14 Statistical analysis of thermal comfort perceptions during summer.

Summer									
Thermal perceptions	**House**	**Occupant**	**Result**	**Mean**	**SD**	**Mean + SD**	**Mean - SD**	**Max**	**Min**
Comfortable (1)-uncomfortable (7) scale	MX-PH	A	1	2	1.00	3.00	1.00	3	1
		B	2						
		C	3						
	MX-CO	A	1	1.667	0.58	2.24	1.09	2	1
		B	2						
		C	2						
Too hot (1) - too cold (7) scale	MX-PH	A	4	3.667	0.58	4.24	3.09	4	3
		B	4						
		C	3						
	MX-CO	A	4	3.667	0.58	4.24	3.09	4	3
		B	4						
		C	3						
Stable (1) - varies during the day (7) scale	MX-PH	A	2	2.667	1.15	3.82	1.51	4	2
		B	2						
		C	4						
	MX-CO	A	2	2.333	0.58	2.91	1.76	3	2
		B	3						
		C	2						
Satisfactory overall (1) - unsatisfactory	MX-PH	A	1	2	1.00	3.00	1.00	3	1
		B	2						
		C	3						

overall (7) scale	MX-CO	A	1	1.667	0.58	2.24	1.09	2	1
		B	2						
		C	2						

On the other hand, the results also suggest that thermal comfort during winter (Table 5.15) for the overall thermal satisfaction scale was perceived to be significantly satisfactory at MX-PH (M=1.67) and unsatisfactory at MX-CO (M=6.00). At least one of the MX-CO occupants marked seven on the comfortable-uncomfortable scale (M=6.33) and too hot-too cold scale (M= 6.33), which suggests causes of concern due to being too cold. This contrasts with the measured temperatures during winter, as temperatures in the MX-PH had a higher occurrence of temperatures below 18°C (up to 66% in the living room) as well as higher occurrence of temperatures below 21°C (up to 43% in the bedroom) than the MX-CO. MX-CO occupants stated that the daily temperature variation was a cause of concern (M=3.67, mean winter daily temperature variations bedroom 3.28°C, kitchen 4.67°C and living-room 7.23°C). MX-CO occupants cited using electric radiators during winter, to improve thermal conditions.

Table 5.15 Statistical analysis of thermal comfort perceptions during winter.

Winter									
Thermal perceptions	**House**	**Occupant**	**Result**	**Mean**	**SD**	**Mean + SD**	**Mean - SD**	**Max**	**Min**
Comfortable (1) - uncomfortable (7) scale	MX-PH	A	1	1.667	0.58	2.24	1.09	2	1
		B	2						
		C	2						
	MX-CO	A	6	6.333	0.58	6.91	5.76	7	6
		B	6						
		C	7						
Too hot (1)- too cold (7) scale	MX-PH	A	4	4.333	0.58	4.91	3.76	5	4
		B	4						
		C	5						
	MX-CO	A	6	6.333	0.58	6.91	5.76	7	6
		B	6						
		C	7						
Stable (1) - varies during the day (7) scale	MX-PH	A	1	2.333	1.53	3.86	0.81	4	1
		B	2						
		C	4						
	MX-CO	A	3	3.667	0.58	4.24	3.09	4	3
		B	4						
		C	4						
Satisfactory overall (1) - unsatisfactory	MX-PH	A	1	1.667	0.58	2.24	1.09	2	1
		B	2						
		C	2						
	MX-	A	6	6	0.00	6.00	6.00	6	6

overall (7) scale		B	6						
		C	6						

5.8 Chapter conclusion

This chapter presented the indoor CO_2, $PM_{2.5}$, tVOC and hygrothermal conditions of Mexico City's case study. This case study tested the use of the Foobot to monitor the IAQ in the first certified PassivHaus residential building in Latin America and a standard building practice along with the use of online surveys to assess occupant perceptions of IAQ.

While the PassivHaus dwelling had better IAQ levels, the results suggest that this may be related to occupant behaviours and architectural differences. High pollution peaks were observed in the PassivHaus when the flat was occupied for more people than it was designed to accommodate, and high tVOC levels were detected that might be related to occupants' behaviour. Another very obvious occasion was when the ventilation system was turned off due to noise issues, the windows remained closed and the occupants or owner forgot to turn the system back on before the next handover. Indoor relative pollution levels ($PM_{2.5}$ and tVOC) in the bedroom of the control home are of special concern, as the measured pollution was repeatedly high at night. Here, indoor $PM_{2.5}$ levels might be reduced even further with the correct use and maintenance of the ventilation system.

Indoor pollution events such as cooking and the use of personal cleaning products (sprays, deodorants and cosmetics) were observed to have an impact in both dwellings. This was clearer in the PassivHaus due to the open plan layout; however, this trend was observed in the control flat as well. Carbon dioxide (CO_2) levels indicated that ventilation rates are good in the PassivHaus, but poor performance was observed at night in the bedroom of the control flat. Similar to indoor pollution, the most critical space was the bedroom of the control house, where consistently high levels of CO_2 were measured at night. The PassivHaus performed poorly on some occasions, but these were related to occupant and owner engagement with the ventilation system, which illustrates the importance of a functioning system in PassivHaus construction. It was also observed that CO_2 concentrations at the PassivHaus could be improved if the ventilation system ran continuously instead of the intermittent on/off technique used. Given the climate in Mexico, the use of MVHR systems could not be preferred from an energy perspectivebut would be desirable in terms of IAQ.

Hygrothermal conditions were more favourable in MX-CO and regulated due to the thermal mass in the building. Thermal comfort could be compromised in the PassivHaus, lightweight construction without thermal mass, as higher daily variances (2-4°C), higher occurrence of high temperatures (>25°C) and higher occurrence of low temperatures (<18°C) were more frequent than in the control flat. However, the control home occupants stated using electric radiators during winter, whereas the PassivHaus did not require any active heating. Thermal comfort was of special concern in the PassivHaus when assessing overheating in terms of static criteria, but not so much when the adaptive method was used.

The frequency of relative humidity below 40%RH was higher in the PassivHaus, but the owners did not report being dissatisfied with humidity in the air, though they did mention suffering from dry skin and eyes. Relative humidity levels between 40%RH to 60%RH were more common at the control house. This correlates with reported condensation on the windows and walls and the lower prevalence of dry skin and eyes. However, the PassivHaus owners self-assessed their health better than those in the conventional home, which could be related to a better indoor environment at home but may have other causes not discussed in this work.

Chapter 6 San Francisco case study

6.1 Introduction

This chapter discusses the results of the second case study, San Francisco, a warm-summer mediterranean climate location. This case study may not be the first to assess indoor pollution in a PassivHaus in San Francisco, but is the first where indoor pollution has been monitored for ten months simultaneously in a PassivHaus and a control house. In this case study, the monitoring methodology was tested without site visits. The first part of this chapter describes the building and household characteristics of the dwellings.

The second part presents and compares the measured indoor and ambient temperature, relative humidity, $PM_{2.5}$ and tVOCs. They were measured in the main bedrooms, living rooms and kitchens of both homes, using the methodology described in Chapter 4, and compared between both homes and ambient levels. Ambient parameters were collected from US agencies. The parameters were assessed according to the guidelines presented in Chapter 2. The chapter reports the result of this and examines the occupants' perceptions of IAQ and thermal comfort.

6.2 Background

This monitoring project represents the most remote location where the monitoring protocol was applied as researcher access to the property was not possible. The recruitment of participants was challenging, but possible through a PassivHaus Affiliate from MEARU's network. The PassivHaus owner kindly introduced us to one of his neighbours with a house similar in size and density so that they could be compared. Both homes are located in the Noe Valley in San Francisco, which is characterised by its row housing typology in the San Francisco Bay Area (Cerny, 2007, p. 78). One of the characteristics of this location is that the adjacent neighbourhood, Twin Peaks, partially blocks coastal fog and cool winds from the Pacific, for which the rest of San Francisco is known, thereby creating a microclimate that is usually sunnier and warmer than the surrounding neighbourhoods. However, this also creates a 'trap' for the air pollution, creating a microenvironment with relatively high air pollution on which the population is significantly vulnerable to air pollution's health impacts (Bay Area Air Quality

Management District, 2018). Winds also drag the coast pollution with them to the East side of the city. The houses are located near two main roads that cross the Noe Valley west to east and north to south. Noe Valley is mostly a residential neighbourhood with two main commercial areas to the north and the east. San Francisco has been ranked - by the American Lung Association - among the 10 most polluted cities in the US for short term (24-h) and long term (annual) $PM_{2.5}$ exposure (American Lung Association, 2018).

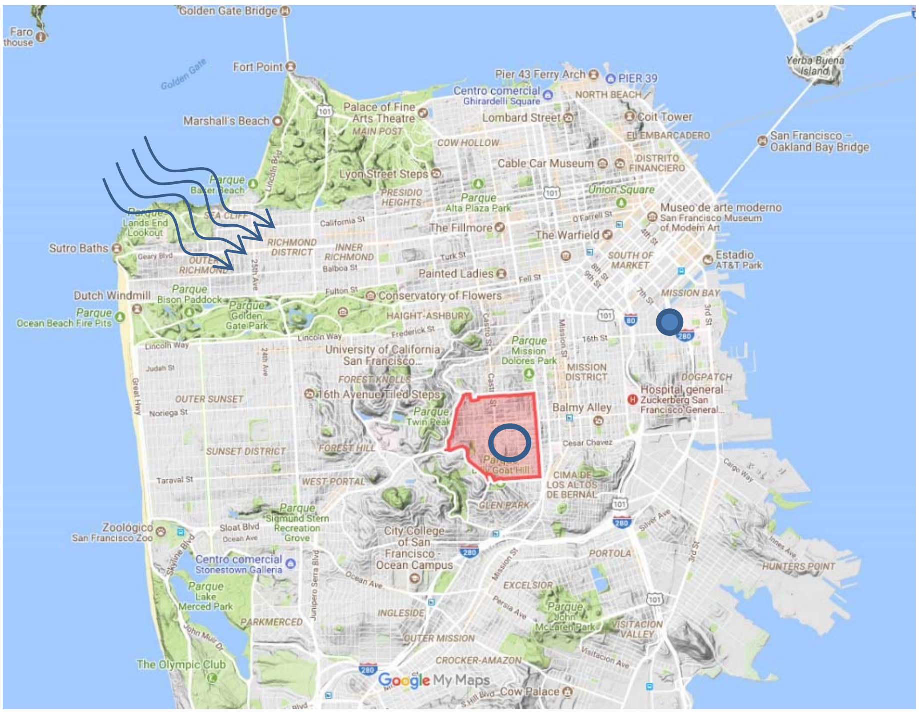


Figure 6.1 Location of Noe Valley in San Francisco. The circle indicates the location of the homes and the dot the location of the outdoor monitoring point. Source: Google My Maps (accessed June 2018).

The PassivHaus and control house are wood frame constructions, a common practice for small US homes. Both homes are located within 335m of each other. Outdoor air temperature and relative humidity were collected from the National Centres for Environmental Information monitoring station (San Francisco Downtown at 3.14km from the homes) and $PM_{2.5}$ from the Bay Area Air Quality Management District (Arkansas Street station at 3.5km, Figure 6.1 and Figure 6.2). During this study, two major fires hit San Francisco's Bay Area (31/08/2017-05/09/2017 and 08/10/2017-18/10/2017) when high outdoor $PM_{2.5}$ was recorded.

Figure 6.2 Location of the SF-CO and SF-PH in the Noe Valley. Source: Google Maps (accessed November 2018).

According to the Department of Building Inspection of the City and Council of San Francisco, the local building code for ventilation is based on the ASHRAE 62.2 standard. As stated in California's Mechanical Code, "*402.1.2 Dwelling Requirements for ventilation air rate for single-family dwellings shall be in accordance with this chapter or ASHRAE 62.2*" (CBSC 2016, p.63). Naturally ventilated buildings should include means of mechanical ventilation if the windows can be closed during occupancy, the means to operate the windows shall be readily accessible when a room is occupied and that mechanical ventilation is not needed where heating or cooling equipment do not serve a zone. For a space to be considered naturally ventilated needs to have a permanent "*…open to operable wall opening directly to the outdoors, the openable area of which is a minimum of 4 per cent of the net occupiable floor area […] where interior rooms, or portion of rooms, without direct opening to the outdoors are ventilated through adjoining rooms, the opening between rooms shall be permanently unobstructed and shall have a free area of not less than 8 per cent of the area of the interior room nor less than 25 square feet (2.5m^2) [ASHRAE 62.1:6.4.2]*" *(CBSC 2016, p.64).* The code also refers to specific distances between the opening and the farthest wall according to openings on the walls – a single side opening (2H), a double side opening (5H) and corner openings (5H), where H is the ceiling height.

The control house was built under these regulations, but it did not use any means of mechanical ventilation and the window areas were slightly higher than the minimum, as stated by the occupants. Natural ventilation techniques resulted in stack and cross-ventilation. The PassivHaus dwelling met the requirements for mechanical ventilation, as it had both fixed and tilt-and-turn windows. The ventilation unit, Air Pohoda iERV-240 MVHR system, provides ventilation from $1.65m^3$ to $5.52m^3$ per minute. This unit, designed especially for hot and humid summers and cold winters,can be adjusted manually to regualte the moisture content (Jablotron, 2014).

6.3 Methods

Building monitoring was performed between 10th May 2017 to 25th February 2018. However, results presented herein were for a shorter period, eliminating the first 21 days to account for the Foobot adaptation period and so that the occupants could familiarise themselves with the Foobots. Therefore, the results discussed in this chapter run from 1st June 2017 to 25th February 2018. The Foobots were posted directly to the participants by AirBoxLab, a printed guide and welcome package were sent from Glasgow and online surveys were emailed to the participants as described in Chapter 4. Air temperature, relative humidity, $PM_{2.5}$ and tVOC were monitored simultaneously in the main bedrooms, living rooms and kitchens of both dwellings. Ambient air temperature and relative humidity were obtained directly through public information requests to the US authorities.

6.4 Dwellings and household characteristics

The PassivHaus dwelling (SF-PH) was built in 2015 and the control house (SF-CO) in 2011. SF-PH faced south and did not have direct access to the garage, whereas the SF-CO faced north and its garage was located in the basement (Figure 6.3). Both homes were similar in size, as confirmed by the owners. Floor layouts from the SF-CO could not be obtained, SF-PH layouts are shown in Figure 6.4. Table 6.1 shows the characteristics of the PassivHaus (SF-PH) and the control (SF-CO) dwellings.

Figure 6.3 Front façades of the SF-PH (left) and SF-CO (right). Source: Google Maps 2018.

Figure 6.4 SF-PH floor plans.

Table 6.1 Building characteristics of SF-PH and SF-CO.

Building characteristic	SF-PH	SF-CO
Airtightness	0.60 $m^3/h*m^3$	Not tested
Floor area	182 m^2	172
Main door	Aluminium cladding (PassivHaus certified)	Wood and glass panel
U_g-value (window)	1.41 W/(m^2K)	3.12 W/(m^2K)
U-value (floor slab)	0.158 W/(m^2K)	0.3 W/(m^2K)
U-value (roof)	0.158 W/(m^2K)	0.3 W/(m^2K)
U-value (wall)	0.283 W/(m^2K)	0.320 W/(m^2K)
Ventilation	MVHR system (Air Pohoda iER-240) filters F7 and G4	Natural ventilation
Window type	Double 6mm, aluminium cladding (PassivHaus certified)	Double panel, wood frame
Building Standard	PassivHaus	San Francisco's Standard Building Regulation

The PassivHaus external walls have a Gypsum board (5/8”, 15.8 mm) to the interior of the house, the wood frame is made from 2”x4” @16” (50.8x101.6 mm @406.4 mm) and the cavities filled with blown fiberglass insulation, a ½” (12.7 mm) plywood and continuous air barrier, followed by a coat of over sheathing, two layers of 1” (25.4 mm, two layers) of EPS rigid foam board, vertical 1”x3” (25.4x76.2mm) wood for firring to get either salvage siding ripped and flipped or cement fibre panel boards. The roof has the same Gypsum board (5/8”, 15.8 mm) to the inside, followed by fibreglass batting to fill the attic cavity, 9” (228.6 mm) of open-cell spray foam applied to the underside of the wood frame (2”x10”, 50.8x254 mm) for the roof deck, followed by the airtight membrane. The internal walls have a wood frame of 2”x4” @24” (50.8x101.6 mm @609.6 mm) with soundproofing cavity insulation and Gypsum boards to the exteriors. Finally, the floor has a concrete slab of 4” (101.6 mm) to the inside, 10mil (0.25 mm) of polythene membrane, two layers of 1” (2x25.4 mm) of EPS rigid foam board, supported by a coarse graven allowing drainage.

The control house layouts and technical information were not gathered completely. Nevertheless the owner (who is a PassivHaus designer) described the construction. The external wall was made with layer of ½” (12.7 mm) plywood panel to the indoor on a 2”x4” (50.8x101.6 mm) wood frame with battered insulation in the cavities, vertical 1”x2” (25.4x50.8mm) wood for furring and receive horizontal 1”x8” (25.4x203.2 mm) wood to the outside. The roof to the inside had the plywood layer, the 2”x4” @16” (50.8x101.6 mm @406.4 mm) joists filled with batt insulation, the attic does not have any filling and the roof rafters (2”x4” @16”, 50.8x101.6 mm @406.4 mm) hold to the inside another plywood board and is filled with batt insulation, the external finish is with ½” (12.7 mm) CDX plywood 6”/6”/12” (152.4x152.4x304.8 mm). Internal walls have a 2”x4” (50.8x101.6 mm) wood frame, soundproof insulation filling and covered by plywood boards. The basement flooring has a 3 ½” (88.9 mm) concrete slab, 2” (50.8 mm) of sand bed, and 6 mm of a vapour retarder membrane.

The houses were occupied by single families at all times and with similar household occupancy: two adults and two young adults (16-25 years) at the SF-PH, and two adults and two children (under 16 years) at the SF-CO. Both households stated that none of the occupants smoked. On average, the control house was occupied 2 hours more than the PassivHaus dwelling during weekdays and 10 hours less during weekend days, as indicated by the occupant diary (Table 6.2). During weekdays, PassivHaus’s occupants stated that the house was normally vacant from 09:00 to 17:30; in the control home however, this was between 09:00 to 15:30. Weekend patterns were very different, SF-CO occupants stated to spend only a few hours during the weekends (12 hours, during night and early morning), whereas the MX-PH occupants spent 22 hours (only out between 17:30 to 19:30).

Table 6.2 Households profiles.

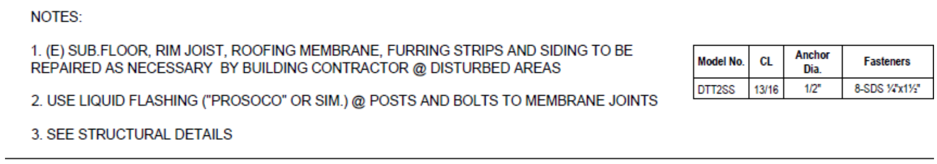
Household profile	SF-PH	SF-CO
No. occupants	2 adults (45 years old or older). 2 young adults (between 16-25 years old)	1 adult (45 years old or older). 1 adult (between 35-45 years old) 2 children (under the age of 16)
Number of pets	1 (cat)	1 (small dog)
Cooking fuel	Electric	Gas
Heating fuel	None	Electric (only January and February)
No. smokers indoors	0	0
No. smokers outdoors	0	0
Average of occupied hours during weekdays	16 per day	18 per day
Average of occupied hours during weekend days	22 per day	12 per day

6.5 Results

6.5.1 Ventilation and heating

The SF-PH household stated on the online surveys to open the windows regularly during summer, but closed them during winter. They relied on the MVHR system for ventilation most of the time. The Air Pohoda iER-240 (MVHR system) used filters F7 for the outside incoming air and G4 for the air returning to the MVHR system. The ventilation layout is shown in Figure 6.4. The system commissioning reported a balance between extraction and supply air flow rates (Table 6.3). The MVHR in the SF-PH needed to be recommissioned, as stated by the occupants: "*Supply and return flows were not properly balanced, we had tried to balance the system by changing the fan speeds on the MVHR system, but that was causing problems with the heat exchange*". Their solution was to change "*one of our return flows for supply (basement storeroom), and this balanced the system and solved the problem*". The system extract air from the master bathroom, the laundry, the shared bathroom on the 1st floor, the toilet on the ground floor, the kitchen and the bathroom in the basement. Air was supplied to the master bedroom, bedrooms (west and east), dining room, living room, basement playroom, basement office and basement storage (changed from extract to supply).

SF-PH occupants rarely used the boost functions for the MVHR system. The SF-CO relied entirely on window and door operation to regulate ventilation, which would only be achieved when there was someone at home for security concerns. They stated having an extraction fan in the bathroom and using it during and after showering. They used stack ventilation opening the living room window on the ground floor and one of the bedroom windows on the upper floor.



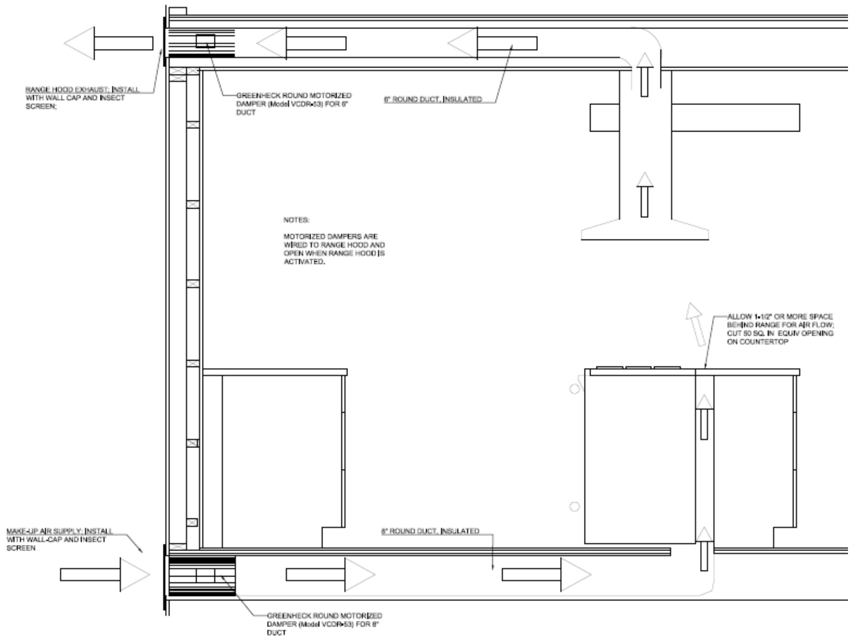


Figure 6.5 SF-PH cooking hood installation details.

Table 6.3 MVHR recommissioning (2017) report summary.

Fan setting (%)	20	40	60	95
Extract	27.5 l/s (1.65m^3/min)	45 l/s (2.70m^3/min)	60.5 l/s (3.63m^3/min)	89.66 l/s (5.38m^3/min)
Supply	27.16 l/s (1.63m^3/min)	46 l/s (2.76m^3/min)	62.33 l/s (3.74m^3/min)	91.83 l/s (5.51m^3/min)
Percentage difference (extract-supply)	1.5%	-2.1%	-2.9%	-2.6%

SF-PH owners had been living in the PassivHaus since 2015, and it was clear that they had learned how to use and operate the MVHR system. However, some small behavioural changes could still improve the performance of the system. The SF-PH occupants did not have any complaints about the MVHR system other than the previously mentioned balance problem. In fact, they felt satisfied since its recommissioning in 2017. The SF-PH occupants had a cooker extract and used it regularly during cooking but not afterwards. The cooker extract installation allowed for fresh air supply and air extract to allow for a better pollution extraction as shown in Figure 6.5. SF-CO occupants used the cooker hood occasionally during cooking and rarely after cooking. The SF-CO occupants complained about damp and mould in the living room, and they also stated that draughts caused by natural ventilation were uncomfortable and that for that reason the windows remained closed most of the time during winter.

The frequency of opening windows during summer and winter are shown in Figure 6.6. The households show a different pattern of window use, with the SF-CO occupants tending to open the windows in the morning and closing them as the day progresses, whereas the SF-PH occupants kept their windows open during the day. Both dwellings reported opening the windows more frequently during summer than in winter. No specific comments on thermal comfort were made about the window operation, but it was evident that window opening was related to the ambient conditions.

Both homes had the option to be heated by radiators. The SF-PH only used basement heating with a hydronic radiant floor heating and a gas boiler connected to the pipes embedded into the concrete slab linked to the thermostat, located in the basement, set at 68°F (20°C). SF-CO had a central heating system with radiators with a gas boiler was used throughout the house, the thermostat was set at 70°F (21.11°C). Both homes used heating during winter and the SF-CO also during spring (Table 6.4). Both homeowners had good knowledge of the heating system and how to regulate and to engage with the building systems to control the indoor environment, especially to regulate indoor temperatures.

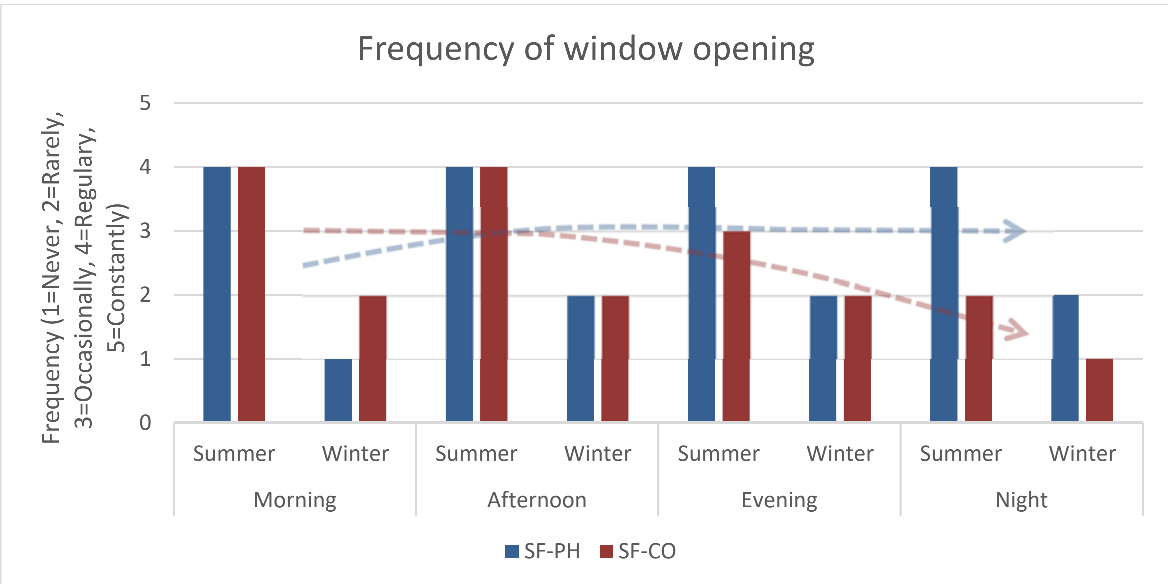


Figure 6.6 Reported frequency of window opening during summer and winter.

Table 6.4 Heating schedules for SF-PH and SF-CO.

Heating schedule	SF-PH	SF-CO
Spring	---	06:00 – 09:00, 16:00-21:00
Summer	---	---
Autumn	---	---
Winter	06:00 – 09:00	06:00 – 09:00, 13:00-21:00

6.5.2 Hygrothermal conditions

Temperature and relative humidity are essential in terms of the immediate perception of IAQ and in the context of this study as explained in Chapter 2. A summary of the results is shown in Table 6.5.

6.5.2.1 Overheating and cold temperatures

As observed in Table 6.6, the assessment of the indoor thermal comfort using both static and dynamic criteria suggests that both homes may have a high risk of overheating. For instance, during the monitored period living room air temperatures of both homes exceeded the recommended 25°C during 5% of the occupied time and 28°C during 1% of the occupied time, as well the hours of exceedance (criterion 1) and upper temperature limits (criterion 3) of the Adaptive method. However, the incidences of overheating were lower in SF-PH. The overheating assessment shows that high temperatures were more frequent during autumn than during summer, which may be related to window opening behaviour. SF-PH occupants used heating only in the basement during winter and windows were likely to be closed especially during the morning. SF-CO occupants used heating during spring and winter. Windows were likely to be closed at night, which might have helped raise indoor temperatures. Section 701 of the Housing Code of San Francisco establishes that a habitable room should have the means to maintain a "*[…] temperature of 70 degrees Fahrenheit [21.11°C] at a point midway between the heating unit and the farthest wall and which point is four feet six inches above the floor*" (City and County of San Francisco, 2017).

Air temperatures below 18°C and between 18°C and 20°C were observed in both houses, but the occurrence of these temperatures was more frequent in SF-CO (Figure 6.7). Daily temperature analysis shows that the temperatures were more stable in SF-PH than in SF-CO. This could be related to the differences in the heating techniques, ventilation techniques, insulation and occupant behaviours. Daily air temperature variations in SF-CO (M=4.49°C, ±2.96°C) were greater than those measured in SF-PH (M=2.80°C, ±2.14°C).

Table 6.5 Statistical analysis of temperature, relative humidity and absolute humidity.

Room	Parameter	Statistical analysis	SF-CO				SF-PH			
			Winter	Summer	Autumn	All period	Winter	Summer	Autumn	All period
Bedroom	Air temperature	Minimum	10.49	16.02	13.09	10.49	16.57	16.96	19.31	16.57
		Maximum	22.89	28.43	32.60	32.60	26.55	26.45	30.28	30.28
		Mean	16.68	20.15	19.94	18.96	20.82	21.84	23.16	21.96
		Standard Dev.	1.76	1.79	2.76	2.67	1.76	1.07	1.84	1.85
	Relative Humidity	Minimum	42.33	53.02	39.00	39.00	42.39	53.58	33.20	33.20
		Maximum	76.26	77.55	78.44	78.44	75.80	79.60	75.54	79.60
		Mean	62.00	67.48	63.84	64.49	58.36	63.55	58.70	60.25
		Standard Dev.	6.79	3.55	5.91	6.01	6.01	2.76	6.36	5.79
	Absolute Humidity	Minimum	5.28	9.14	7.42	5.28	7.25	10.72	6.52	6.52
		Maximum	12.78	16.73	16.35	16.73	13.62	15.23	17.71	17.71
		Mean	8.84	11.79	11.04	10.59	10.58	12.23	12.17	11.68
		Standard Dev.	1.30	1.12	1.67	1.86	1.14	0.72	1.42	1.36
Kitchen	Air temperature	Minimum	12.41	16.34	14.93	12.41	16.60	18.38	19.09	16.60
		Maximum	23.69	30.59	32.81	32.81	25.34	26.26	28.89	28.89
		Mean	18.61	21.33	21.86	20.64	20.56	22.03	22.51	21.72
		Standard Dev.	1.87	2.05	2.68	2.64	1.48	1.00	1.64	1.62
	Relative Humidity	Minimum	38.79	47.24	37.65	37.65	38.44	50.09	30.44	30.44
		Maximum	73.40	74.91	74.03	74.91	75.43	73.13	79.74	79.74
		Mean	56.88	63.81	58.66	59.84	56.12	60.59	58.60	58.48
		Standard Dev.	6.37	3.27	5.88	6.09	5.00	2.78	5.76	5.02
	Absolute Humidity	Minimum	5.79	9.13	7.56	5.79	7.00	10.22	6.40	6.40
		Maximum	13.46	17.21	16.57	17.21	13.10	14.77	17.13	17.13
		Mean	9.10	11.95	11.34	10.83	10.04	11.79	11.73	11.21
		Standard Dev.	1.40	1.20	1.68	1.89	1.14	0.69	1.49	1.40
Living room	Air temperature	Minimum	11.50	15.62	13.79	11.50	16.25	18.44	18.54	16.25
		Maximum	23.66	30.25	33.57	33.57	24.70	25.67	29.79	29.79
		Mean	17.71	20.29	20.83	19.65	19.85	21.58	22.61	21.37
		Standard Dev.	2.01	1.93	2.72	2.63	1.52	1.12	2.00	1.95
	Relative Humidity	Minimum	40.40	51.15	38.37	38.37	38.36	52.53	31.93	31.93
		Maximum	78.30	75.35	78.17	78.30	75.65	74.02	71.75	75.65
		Mean	59.23	66.36	61.26	62.35	57.48	62.23	58.35	59.39
		Standard Dev.	7.21	3.45	6.32	6.57	5.72	2.82	6.10	5.49
	Absolute Humidity	Minimum	5.54	8.94	7.36	5.54	6.69	9.98	7.48	6.69
		Maximum	12.95	17.30	16.75	17.30	12.92	14.57	17.08	17.08
		Mean	8.98	11.70	11.15	10.64	9.86	11.80	11.75	11.16
		Standard Dev.	1.44	1.15	1.66	1.84	1.11	0.72	1.52	1.47

There was a statistical significant difference between the indoor-outdoor differences between the SF-CO and SF-PH in the:

- Bedrooms of 2.99°C (95% CI, 2.98°C to 3.01°C), $t(77,689)=408.95$, $p=.001$.

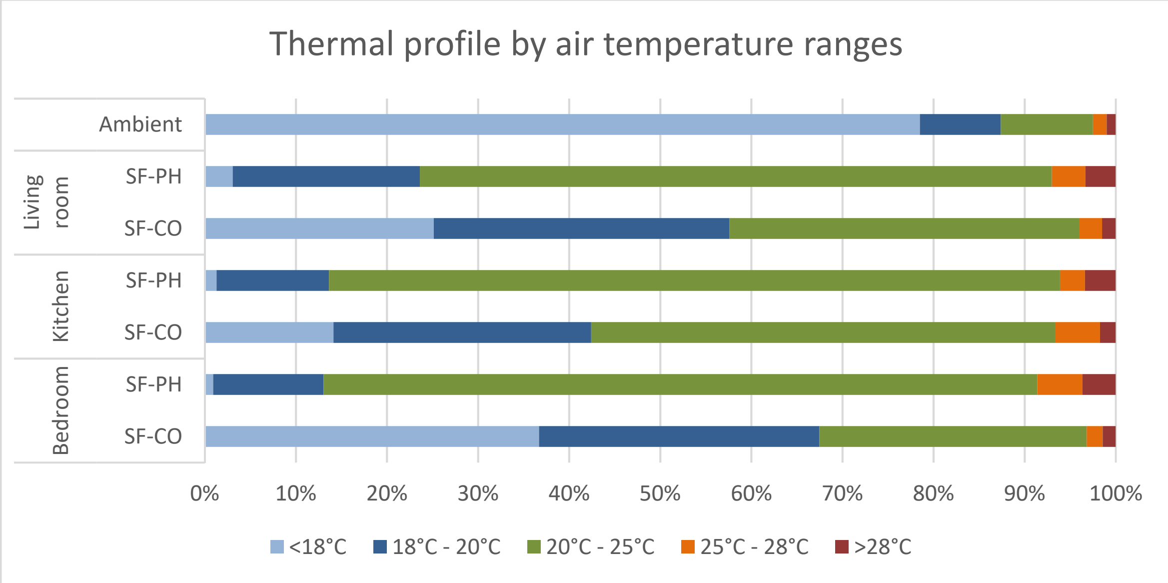


Figure 6.7 Thermal profile by air temperature range per room for the monitoring period in both dwellings.

Table 6.6 Overheating and cool temperature analysis.

Room	Criterion	SF-CO				SF-PH			
		Summer	Autumn	Winter	All	Summer	Autumn	Winter	All
Bedroom	PassivHaus						•		
	CIBSE A	•	•		•		•		
	CIBSE B	•	•		•		•		
	Adaptive approach Criterion 1	•	•	N/A	•	•	•	N/A	•
	Adaptive approach Criterion 2		•		•				
	Adaptive approach Criterion 3	•	•	•	•	•	•	•	•
	18˚C to 20˚C <10%	×	×	×	×			×	×
	<18˚C <10%	×	×	×	×				
Kitchen	PassivHaus		•				•		
	CIBSE A	•	•		•	•	•		•
	CIBSE B	•	•		•	•	•	•	•
	Adaptive approach Criterion 1	•	•	N/A	•	•		N/A	•
	Adaptive approach Criterion 2								
	Adaptive approach Criterion 3	•	•	•	•	•	•	•	•
	18˚C to 20˚C <10%	×	×	×	×			×	×
	<18˚C <10%			×	×				
Living room	PassivHaus						•		
	CIBSE A		•		•	•	•		•
	CIBSE B	•	•		•	•	•		•
	Adaptive approach Criterion 1	•	•	N/A	•	•		N/A	•
	Adaptive approach Criterion 2		•		•				
	Adaptive approach Criterion 3	•	•	•	•	•	•	•	•
	18˚C to 20˚C <10%	×	×	×	×			×	×
	<18˚C <10%	×	×	×	×				

- Living rooms of 4.40°C (95% CI, 2.39°C to 2.42°C), t(77,689)=405.09, *p*=.001.

- Kitchen of 1.08°C (95% CI, 1.07°C to 1.09°C), t(77,689)=180.06, *p*=.001.

SF-CO summer daily variations were smaller (M=3.85°C, ±2.55°C) than those during winter (M=5.29°C, ±2.71°C), whereas in SF-PH they were higher in autumn (M=3.12°C, ±2.22°C) and lower in summer (M=2.34°C, ±1.59°C, Figure 6.7 and Table 6.7).

Table 6.7 Seasonal daily variations in the SF-CO, SF-PH and ambient. The blue background is the data from SF-CO, the red from SF-PH and the green from ambient.

			Seasonal daily mean variation (°C)	Extreme daily variations	
				Min (°C)	Max (°C)
Summer	SF-CO	Bedroom	3.49	0.68	8.14
		Kitchen	4.12	1.75	8.77
		Living room	3.94	0.57	9.38
	SF-PH	Bedroom	2.17	0.48	5.87
		Kitchen	2.34	0.59	5.16
		Living room	2.53	0.66	4.46
	Ambient		8.14	2.20	17.80
Autumn	SF-CO	Bedroom	3.89	1.76	7.98
		Kitchen	4.24	1.65	6.92
		Living room	4.98	1.95	9.82
	SF-PH	Bedroom	3.85	0.99	8.37
		Kitchen	2.07	0.83	4.78
		Living room	3.45	0.90	7.41
	Ambient		8.77	3.30	17.20
Winter	SF-CO	Bedroom	4.93	2.13	8.41
		Kitchen	5.03	2.16	8.68
		Living room	5.94	2.47	9.66
	SF-PH	Bedroom	3.52	0.47	6.54
		Kitchen	2.16	0.30	3.78
		Living room	3.13	0.63	4.68
	Ambient		7.17	1.60	13.30
All	SF-CO	Bedroom	4.08	0.68	8.41
		Kitchen	4.45	1.65	8.77
		Living room	4.93	0.57	9.82
	SF-PH	Bedroom	3.17	0.47	8.37
		Kitchen	2.19	0.30	5.16
		Living room	3.03	0.63	7.41
	Ambient		8.04	1.60	17.80

Figure 6.9 and Figure 6.10 compare the indoor and ambient air temperatures during summer and winter in the bedrooms and living rooms of both dwellings. The low variance in air temperatures observed during winter may be due to the use of radiators to maintain indoor temperatures. In SF-CO living room, temperatures dropped significantly during the night, as no heating was used during sleeping times. Heating during winter was turned on from 06:00 to 09:00 in the mornings and from 13:00 to 21:00 during the afternoon.

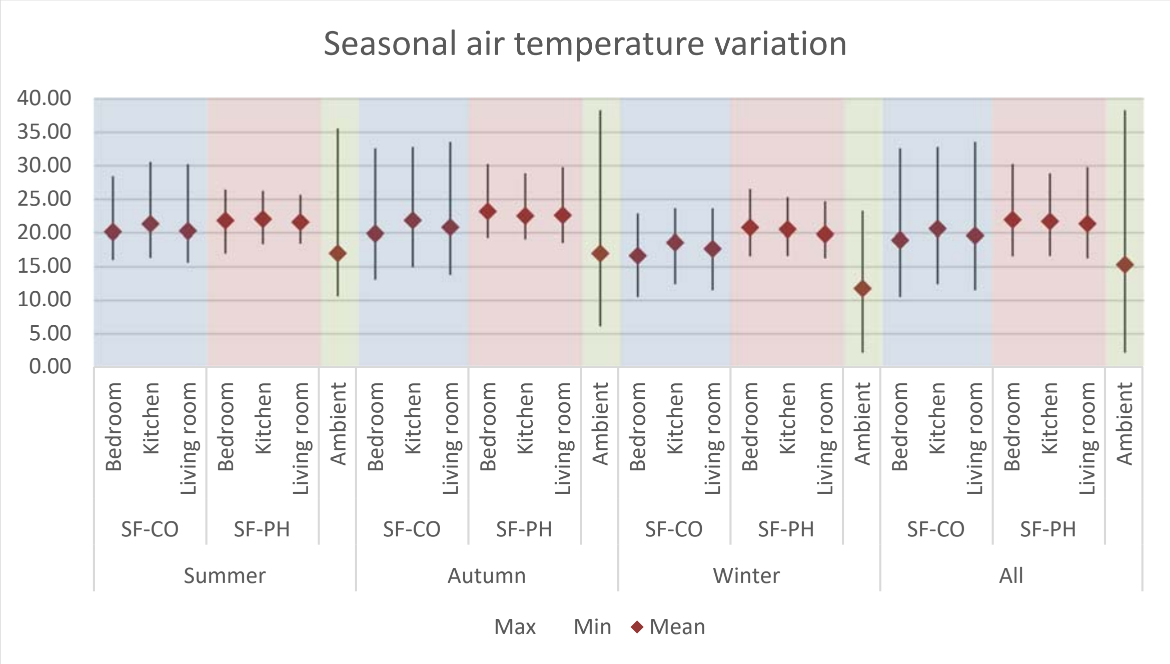


Figure 6.8 Seasonal variations in the SF-CO, SF-PH and ambient air temperature. The blue background is the data from SF-CO, the red from SF-PH and the green from ambient.

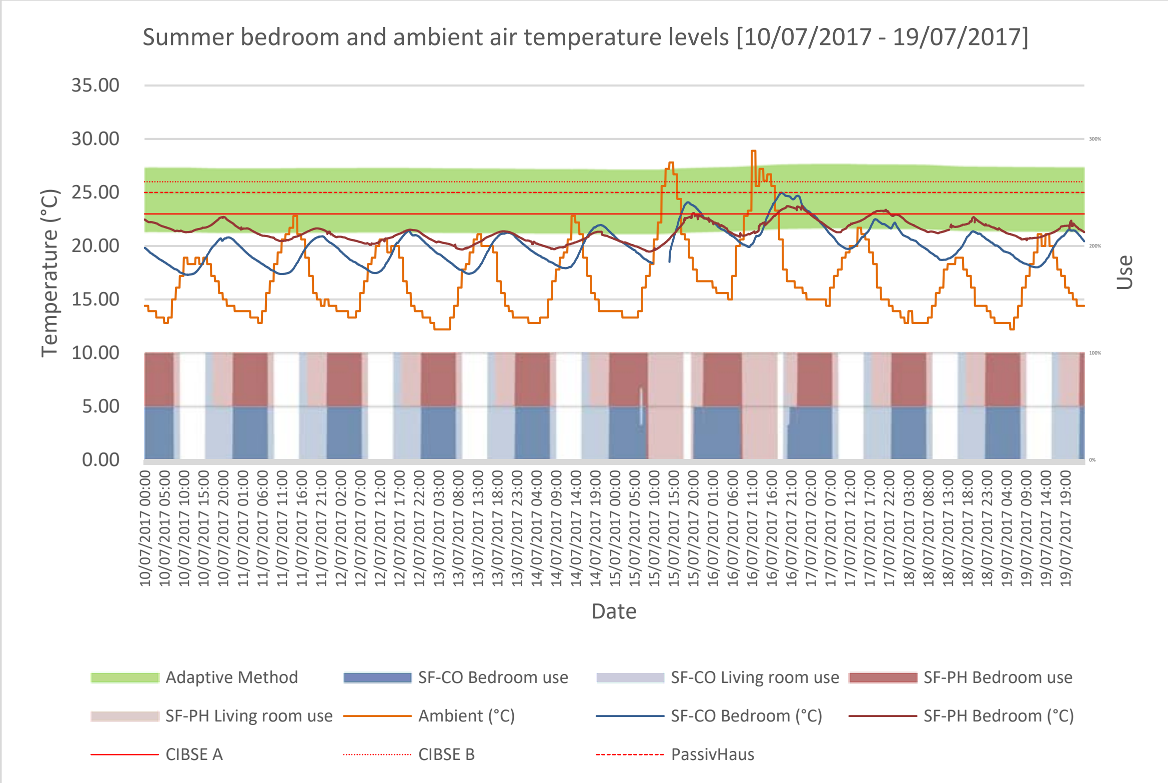


Figure 6.9 Summer ambient and bedroom air temperatures in the SF-CO and SF-PH.

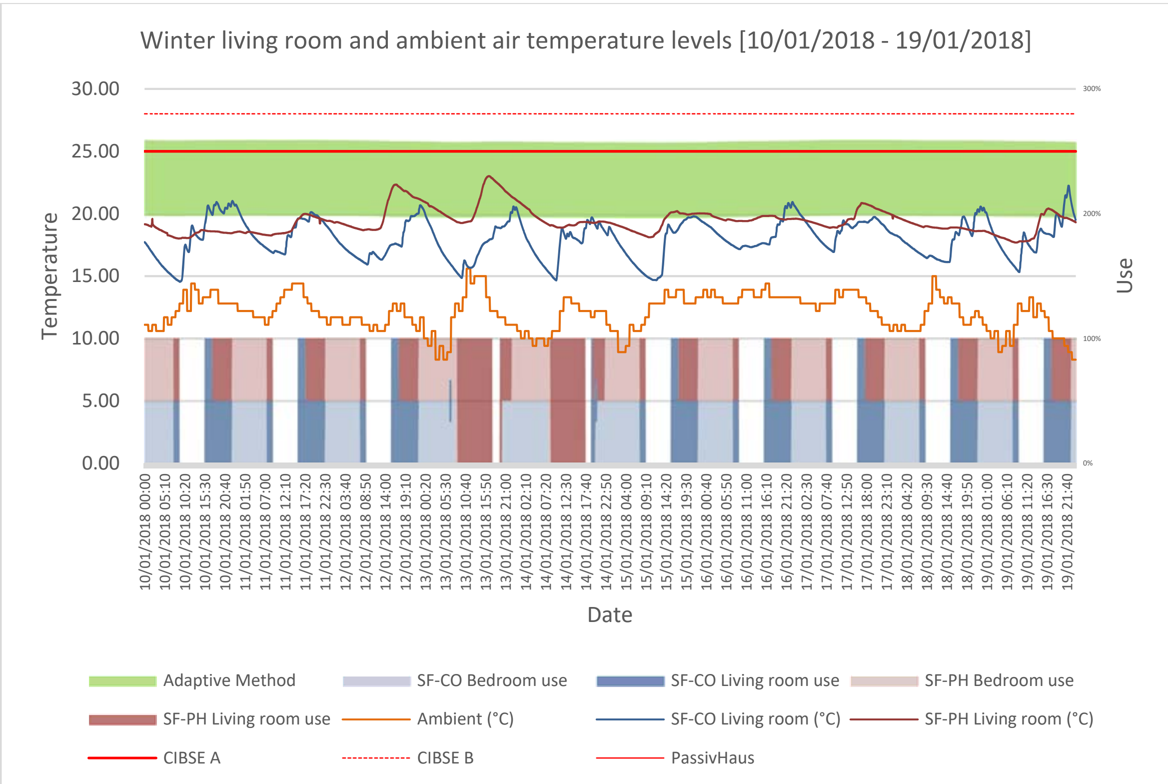


Figure 6.10 Winter ambient and living room air temperature levels in the SF-CO and SF-PH.

6.5.2.2 Humidity

Relative humidity levels above 60%RH were measured in both dwellings. In SF-CO, levels above 60%RH were measured between 57.30% (kitchen), 67.62% (living-room) and 76.81% (bedroom) of the monitored time in the three rooms, whereas in SF-PH this threshold was exceeded during 42.37% (kitchen), 53.82% (living-room) and 59.55% (bedroom). Perhaps this was related to the high ambient relative humidity levels (74.42% of the time above 60%RH). The psychrometric analysis showed that the moisture content outdoor was lower than those found indoor of the homes. Summer levels were the most critical in terms of moisture content in both dwellings (Figure 6.11), whereas Autumn was more comfortable (Figure 6.12). The occurrence of ideal relative humidity levels (40%RH to 60%RH) was more common in SF-PH than in SF-CO and were likely to be related to occupant behaviour. Levels below 40%RH were observed in all rooms in both homes for less than 0.50% of the monitored time compared to 5.44% of the time outdoors. Seasonal variations were observed in both homes; for instance, the occurrence of relative humidity levels above 60%RH was more common during summer, whereas a higher occurrence of ideal levels was observed during winter, which is perhaps related to window opening behaviour. This suggests that the humidity levels in San Francisco are significantly associated with those outdoors.

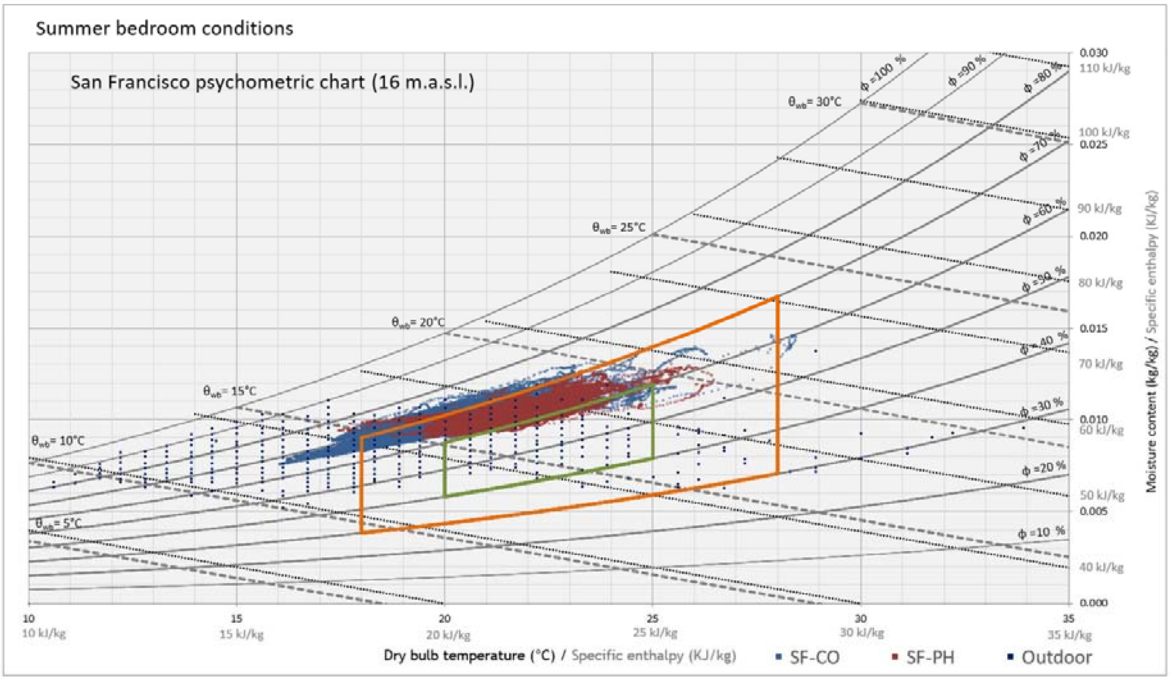


Figure 6.11 Summer psychrometric evaluation of the conditions indoors. The green rectangle delimitates the ideal range and the orange the extended range.

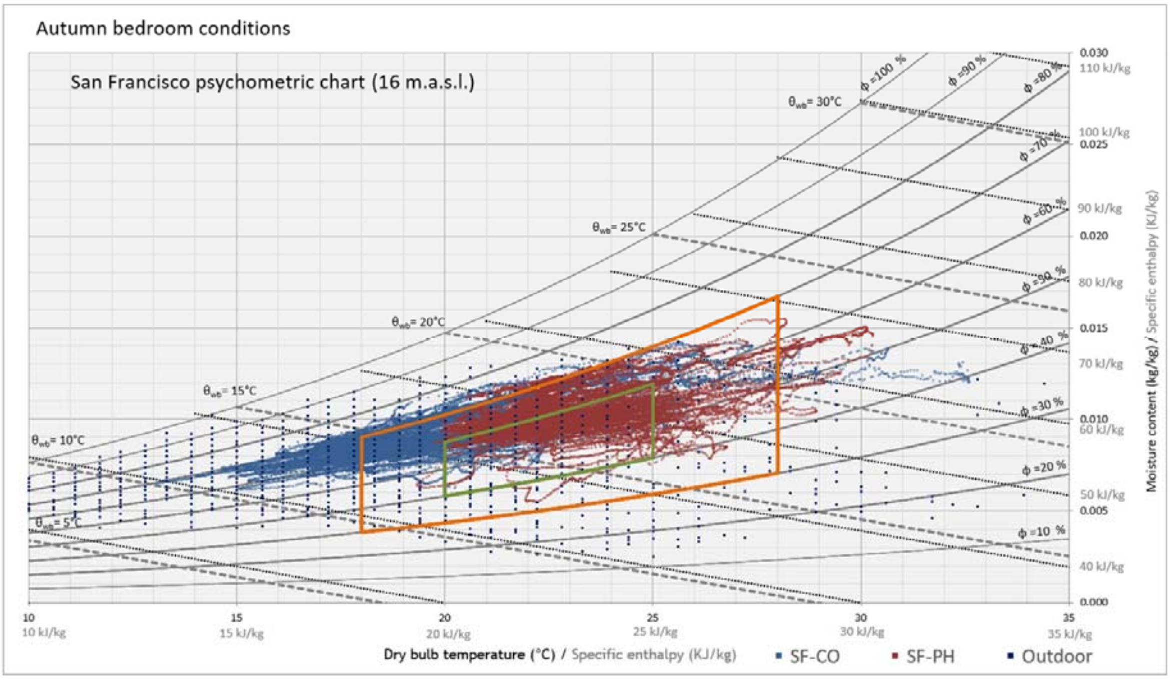


Figure 6.12 Autumn psychrometric evaluation of the conditions indoors. The green rectangle delimitates the ideal range and the orange the extended range.

Figure 6.13 compares relative humidity profiles of each room and ambient levels. Ambient relative humidity levels between 40%RH and 60%RH were only evidenced 18.10% of the monitored time, whereas indoor levels in SF-CO varied from 23.17% to 42.60% and 40.23% to 57.33% in SF-PH.

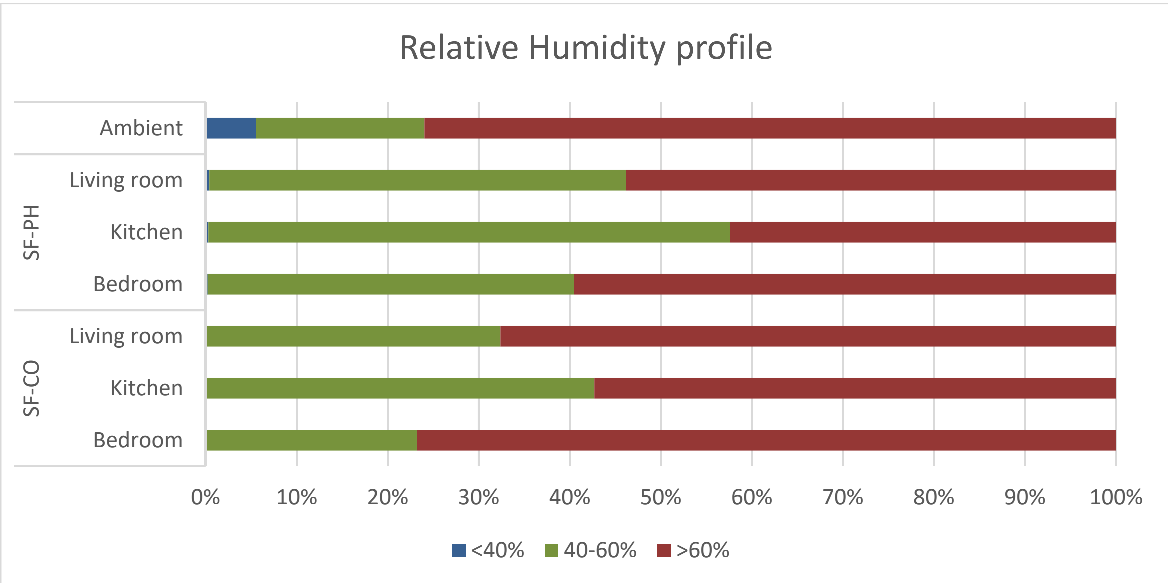


Figure 6.13 Relative humidity profile by range.

An examination of vapour pressure levels showed the higher temperature levels in SF-PH indeed masked humidity levels. Absolute humidity levels were higher in SF-PH, especially in the bedroom than those in SF-CO. Vapour excess (indoor-ambient differences) showed that every room in both homes had a higher moisture content than the outdoors, regardless of the time of the year (Table 6.8). However, higher levels of vapour pressure were measured during summer, whereas drier environments were measured during winter.

Following an examination of humidity 12g/kg for 20% of the occupied time, as defined by the PassivHaus standard, humidity was observed in all rooms during more than 20% of the time (Table 6.8). Whereas both homes exceeded the PassivHaus threshold, the results show that vapour pressure levels were higher in the bedroom of SF-PH than those in SF-CO, regardless of the season. Absolute humidity levels in the kitchen and the living room were higher in SF-CO than those in SF-PH. Levels above the 7g/kg were observed for more than 97% of the time in both homes. Mean indoor vapour pressure levels were between 10.58g/kg and 10.82g/kg in SF-CO, and 11.15g/kg to 11.68g/kg in SF-PH. These levels may present ideal conditions for dust mite proliferation, as explained by Korsgaard (1983) and Korsgaard & Hallas (1979).

Table 6.8 Vapour excess in SF-CO and SF-PH. There were no negative values, so excesses in the dwellings were above ambient levels.

		Summer			Autumn			Winter			All		
		Vapour excess (%), all time		>12 g/kg only occupied hours	Vapour excess (%), all time		>12 g/kg only occupied hours	Vapour excess (%), all time		>12 g/kg only occupied hours	Vapour excess (%), all time		>12 g/kg only occupied hours
		>7 g/kg	>12 g/kg		>7 g/kg	>12 g/kg		>7 g/kg	>12 g/kg		>7 g/kg	>12 g/kg	
SF-CO	Bedroom	0.1	39.8	40.0%	12.5	12.2	26.6%	36.6	0.2	0.1%	16.0	17.7	22.6%
	Kitchen	0.1	45.5	56.5%	12.5	17.2	32.5%	37.7	2.3	3.6%	16.4	22.1	31.5%
	Living room	0.1	37.9	55.3%	12.5	14.5	35.4%	35.3	1.4	3.7%	15.6	18.3	32.2%
SF-PH	Bedroom	0.1	59.1	60.0%	12.4	34.8	42.6%	43.1	10.6	8.4%	18.1	35.3	37.5%
	Kitchen	0.1	39.5	39.5%	12.4	23.3	35.2%	43.1	4.6	3.4%	18.1	22.8	26.4%
	Living room	0.1	40.0	50.4%	12.5	24.5	40.0%	42.8	2.3	2.9%	18.0	22.7	31.5%

Several studies have presented evidence on the proliferation of different species of house dust mite populations in the US. For instance, Wharton (1970), Arlian et al. (1982) and Allen et al. (1988) found that the presence of *Df* was more common than *Dp* in homes. In fact, 12 out of the 19 homes studied in Ohio by Arlian et al. (1982) were infested only by *Df,* without any trace of *Dp.* Wharton (1970) collected samples from different parts of the US and found that 21 out of 39 homes were infested only by *Df.* In contrast, Mulla et al. (1975) examined houses in California and found that *Dp* was more common *Df*, though the presence of both mites was observed. They noted that the presence of *Df* increased as they moved further inland, and *Dp* was more common on the coast. Therefore, in this study, it was decided to assess both *Dp* and *Df*. Mite proliferation in indoor spaces can be assessed by employing CEH for house dust mite populations (de Boer and Kuller, 1997). The CEH for *Df* was assessed as suggested by Cunningham (1996), Arlian (1981) and Arlian (1992) and for *Dp* as suggested by de Boer & Kuller (1997) and Ucci et al. (2011). The population equilibrium humidity (PEH) was also used to evaluate the *Dp* population (Crowther *et al.*, 2006). The PEH and CEH were plotted for all seasons. Figure 6.15 is the Winter graph, the season with the best results, and Figure 6.14 the Summer graph, with higher problems..

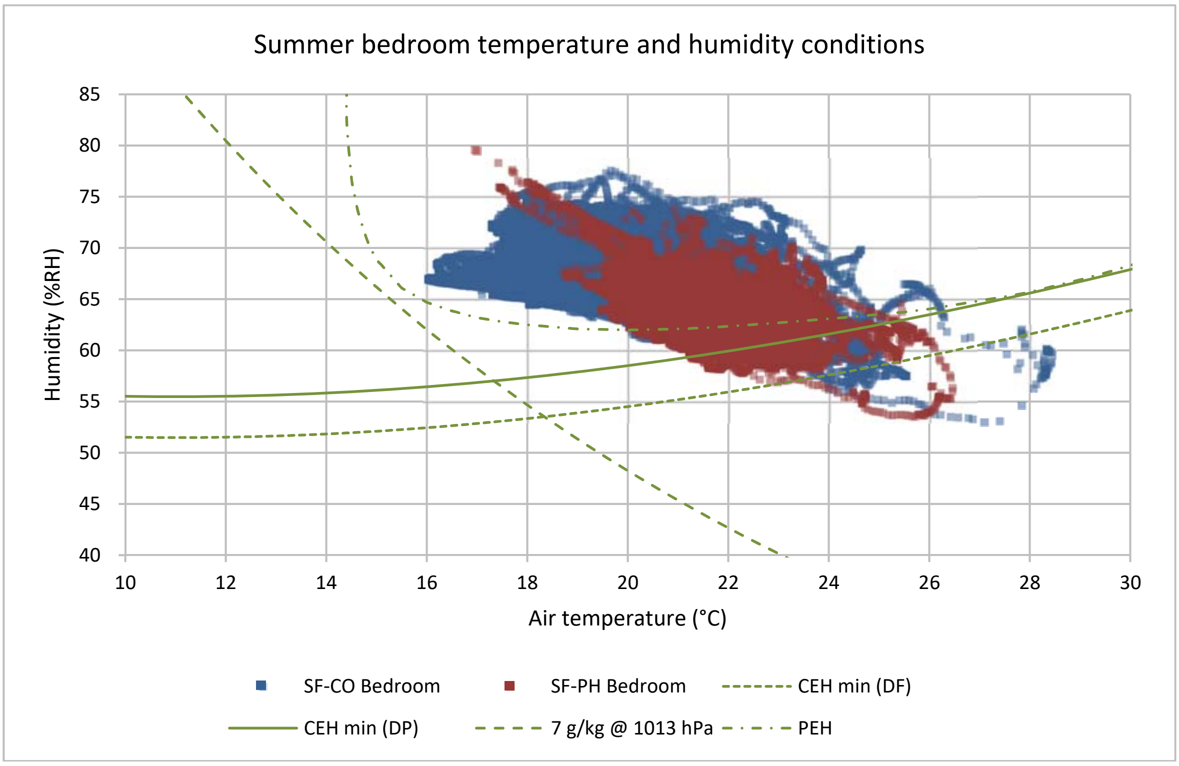


Figure 6.14 Summer bedroom temperature and humidity conditions. The figure shows an analysis of the dust mite population threshold conditions according to the CEH for *Df* and *Dp*.

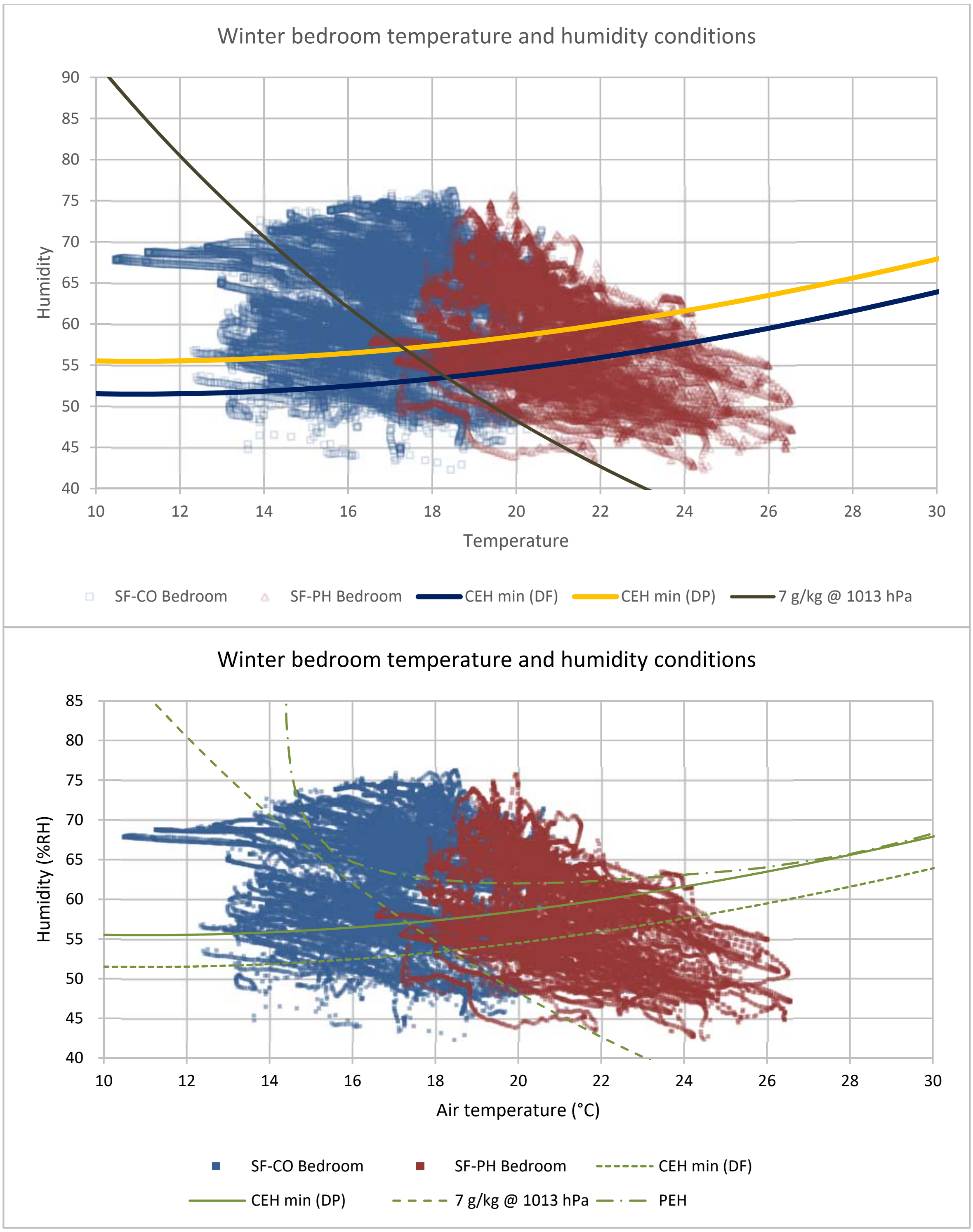


Figure 6.15 Winter bedroom temperature and humidity conditions. The figure shows an analysis of the dust mite population threshold conditions according to the CEH for *Df* and *Dp*.

6.5.3 Particulate matter 2.5µm ($PM_{2.5}$)

. According to the Bay Area Air Quality Management District, 2017 annual $PM_{2.5}$ mean in San Francisco was 9.7µg/m^3, but a maximum of 190µg/m^3 and 102µg/m^3 were measured in October (M=16.1µg/m^3) and September (M=14.3µg/m^3) respectively; both measured in this study. Previous studies looking at associations between indoor and ambient $PM_{2.5}$ concentrations in dwellings suggest that it is common to observe higher indoor $PM_{2.5}$ than outdoors in the US (Williams et al. 2009, Turpin et al. 2007) and California (Offerman, 2009). Arhami et al. (2009) looked at indoor $PM_{2.5}$ concentrations in homes in California, measuring indoor mean $PM_{2.5}$ concentrations of 15.09µg/m^3, which were similar to those measured in SF-CO.

During the monitored period, ambient $PM_{2.5}$ mean level was 11.82µg/m^3, which was lower than the threshold set by the National Ambient Air Quality Standard in the US (15µg/m^3), but higher than the 10µg/m^3 annual mean WHO threshold (WHO, 2000). Mean indoor concentrations were above the WHO value and the ambient levels in both homes - SF-CO (14.02µg/m^3 (living-room), 14.42µg/m^3 (kitchen) and 14.57µg/m^3 (bedroom)) than in SF-PH (11.74µg/m^3 (living-room), 12.33µg/m^3 (kitchen) and 13.53µg/m^3 (bedroom, Figure 6.16)). The $PM_{2.5}$ median differences in each of the rooms:

- whereas the bedroom concentrations in the SF-PH (10.91µg/m^3) were higher than those at the SF-CO (10.67µg/m^3), there was no statistical significance in the difference (0.00013µg/m^3), z=0.97, p=.923.

- the difference (0.84µg/m^3) in the kitchens was statistically different, between the SF-CO (10.13µg/m^3) and SF-PH (9.33µg/m^3), z=-62.31, p<.001.

- the difference (0.63µg/m^3) in the living-rooms was statistically different, between the SF-CO (9.63µg/m^3) and SF-PH (8.89µg/m^3), z=-62.31, p<.001.

Indoor and outdoor $PM_{2.5}$ correlations (SF-PH: bedroom $r_s=0.294$ ($P<0.001$), kitchen $r_s=0.399$ ($P<0.001$) and living-room $r_s=0.343$ ($P<0.001$); SF-CO: bedroom $r_s=0.343$ ($P<0.001$), kitchen $r_s=0.355$ ($P<0.001$) and living-room $r_s=0.375$ ($P<0.001$)) were poorly associated. This suggests that indoor $PM_{2.5}$ pollution from human activities, such as cooking and cleaning, was the primary source of indoor pollution. WHO's recommended maximum daily mean of 25µg/m^3 was exceeded in both dwellings (Table 6.10). The frequency of daily means above 25µg/m^3 was higher in SF-CO. Comparison of the percentage of time above 25µg/m^3 between the complete period and the occupied periods in each room revealed that only $PM_{2.5}$ pollution was lower in the bedroom during the occupied time than those during the complete period (Table 6.9).

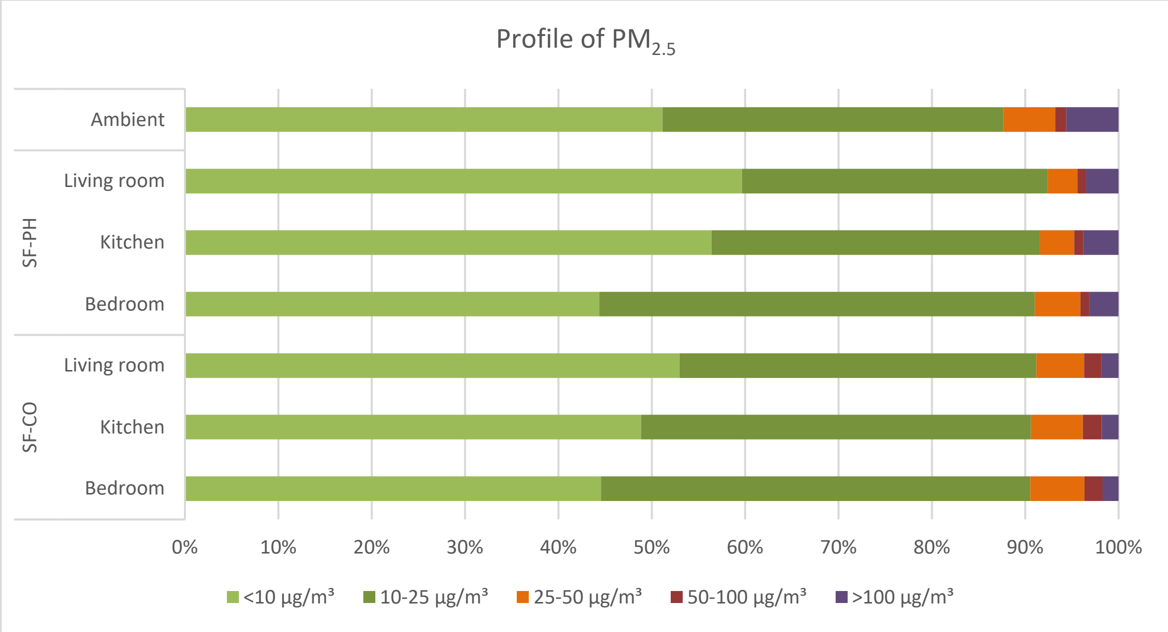


Figure 6.16 Profile of $PM_{2.5}$ concentration by exposure range during the monitored time.

Table 6.9 $PM_{2.5}$ summary of analysis of time periods with exposition above 25µg/m³ in the SF-CO, and SF-PH. Negative difference values indicate that the exposition is lower during occupied/unoccupied periods.

		>25µg/m³				
		Complete period (a)	Occupied period (b)	Difference (b-a)	Unoccupied period (c)	Difference (c-a)
SF-CO	Bedroom	9.39%	5.35%	-4.05%	12.22%	2.83%
	Kitchen	9.39%	11.12%	1.73%	8.75%	-0.64%
	Living rom	8.80%	9.47%	0.67%	8.71%	-0.09%
SF-PH	Bedroom	8.97%	6.24%	-2.73%	10.70%	1.73%
	Kitchen	8.41%	10.11%	1.70%	7.53%	-0.89%
	Living rom	7.59%	7.84%	0.25%	7.56%	-0.03%

Table 6.10 Analysis of $PM_{2.5}$ concentrations.

		Annual mean (µg/m³)	Standard deviation	% of the time above 10µg/m³	No. of days with daily mean above 25µg/m³	% of the year of days above 25 µg/m³
SF-CO	Bedroom	14.57	19.11	55.38%	21	5.75%
	Kitchen	14.43	21.94	51.16%	18	4.93%
	Living room	14.02	24.29	47.02%	18	4.93%
SF-PH	Bedroom	13.53	13.82	55.60%	14	3.84%
	Kitchen	12.33	20.29	43.58%	13	3.56%
	Living room	11.74	18.60	40.31%	13	3.56%
	Ambient	11.82	10.83	51.76%	26	7.12%

Summer (8.35μg/m^3) outdoor $PM_{2.5}$ was lower than those in autumn (13.25μg/m^3) and winter (14.00μg/m^3). Similarly, indoor $PM_{2.5}$ was lower during summer and higher in autumn in both homes. Mean autumn were as high as 14.76μg/m^3 (living-room), 15.15μg/m^3 (bedroom) and 15.25μg/m^3 (kitchen in the SF-CO and 12.03μg/m^3 (living-room), 13.15μg/m^3 (kitchen) and 13.50μg/m^3 (bedroom) in the SF-PH.

Concentrations above 100μg/m^3 were more frequent in SF-PH, as observed in Figure 6.16, possibly due to lower ventilation rates and occupant behaviours. Indoor $PM_{2.5}$ differences between rooms were similar in both homes, with bedrooms the rooms where higher $PM_{2.5}$ concentrations were measured, followed by the kitchens and the living rooms. This realtes to human activities since measured indoor $PM_{2.5}$ concentrations were higher in the early morning when occupants would be grooming and using aerosols or sprays such as deodorants (Figure 6.17). Cooking was also a major source of indoor $PM_{2.5}$ pollution, especially in the SF-CO (Figure 6.18). Studies have measured indoor levels in the US as high as 3,146μg/m^3 (Fortmann, Kariher and Clayton, 2001) and 745μg/m^3 (He *et al.*, 2004) during cooking, depending on the type of food. However, such concentrations could be lower if extraction cooking hoods were used during and afterwards cooking and windows opened as exposed by Leary et al. (2015), which the occupants indicated was something they did. As seen in Figure 6.17, cooking impact's on $PM_{2.5}$ was not very significant in SF-PH due to the use of the cooker hood and its own air supply.

Analysis of excess $PM_{2.5}$ (indoor–ambient) showed that even if both dwellings usually had indoor concentrations above the normal ambient conditions, those measured in SF-PH were lower (Table 6.11). Nevertheless, indoor $PM_{2.5}$ concentrations may be lower than ambient concentrations, at high outdoor concentrations. Figure 6.19 shows that the level of protection of the SC-PH increased at higher outdoor $PM_{2.5}$ levels during one of the fires in the San Francisco Bay Area due to the filter protection in the MVHR system. SF-PH may have lower indoor $PM_{2.5}$ by ~17% compared to the control house at normal outdoor concentrations, but higher reduction are possible at higher outdoor $PM_{2.5}$. However, the occurrence of indoor levels peaks was more common in SF-PH (Figure 6.16). These peaks are related to activities such as cooking. It was also interesting to notice that in the SF-PH the bedroom $PM_{2.5}$ levels were higher than in the rest of the house as observed in Figure 6.20.

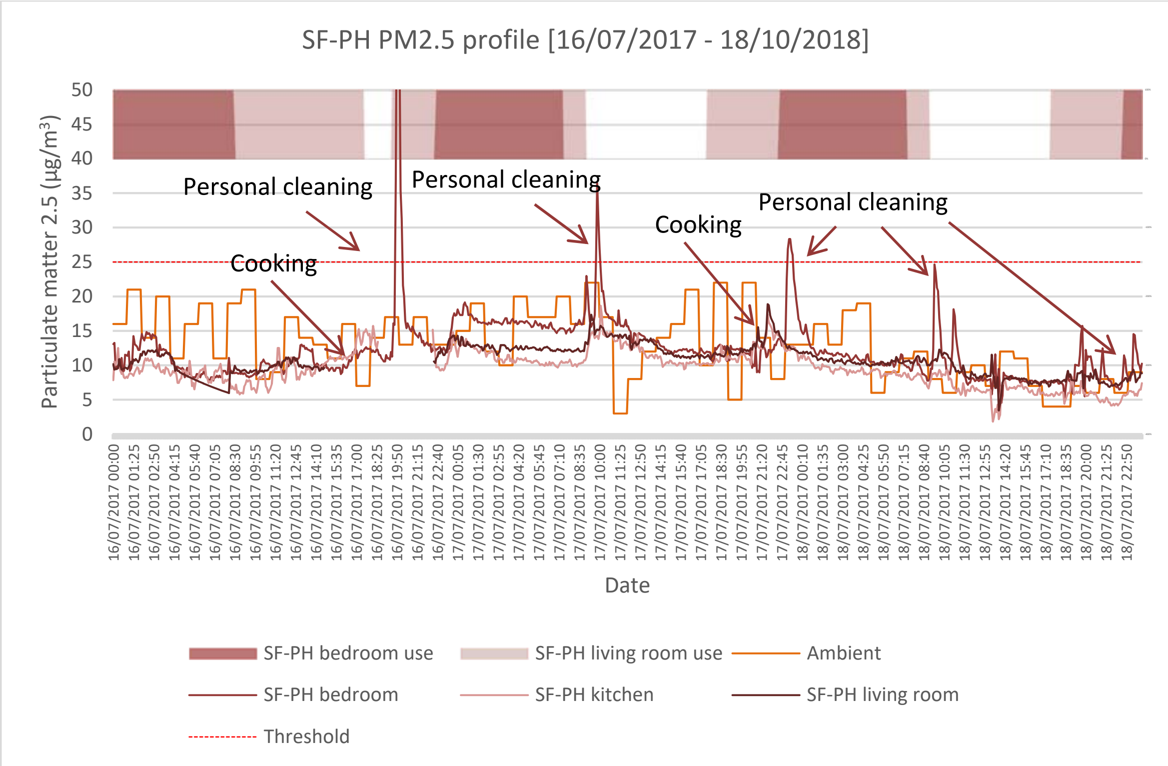


Figure 6.17 Example of the impact of human activities in the SF-PH (16/07/2017-18/07/2017)

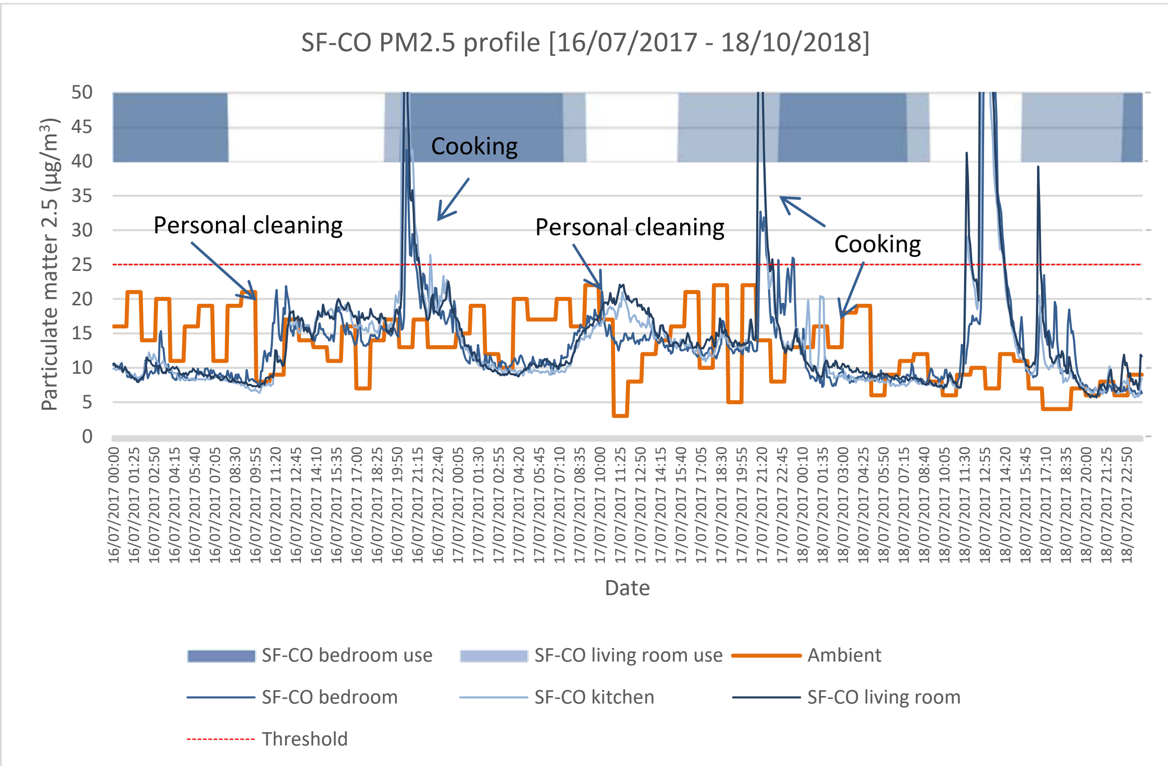


Figure 6.18 Example of the impact of human activities in the SF-CO (16/07/2017-18/07/2017)

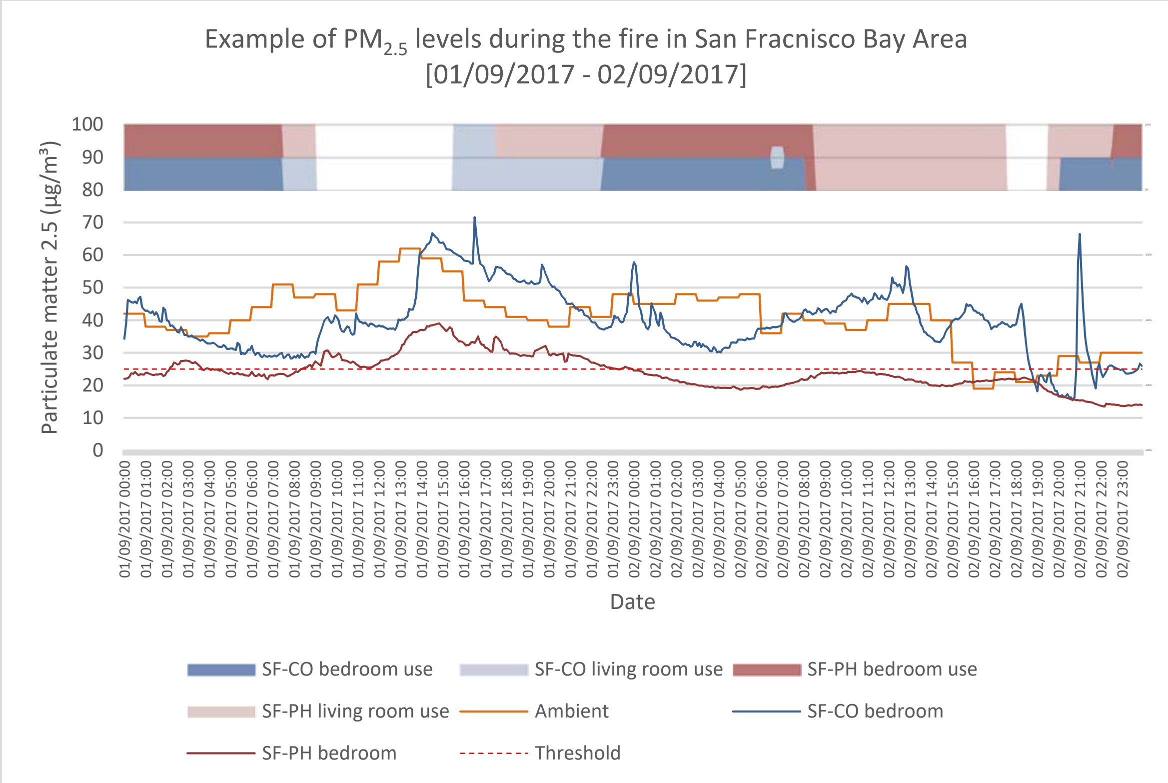


Figure 6.19 Example of indoor and outdoor PM2.5 levels during the fire in San Francisco Bay Area (30/08/2017 to 08/09/2017).

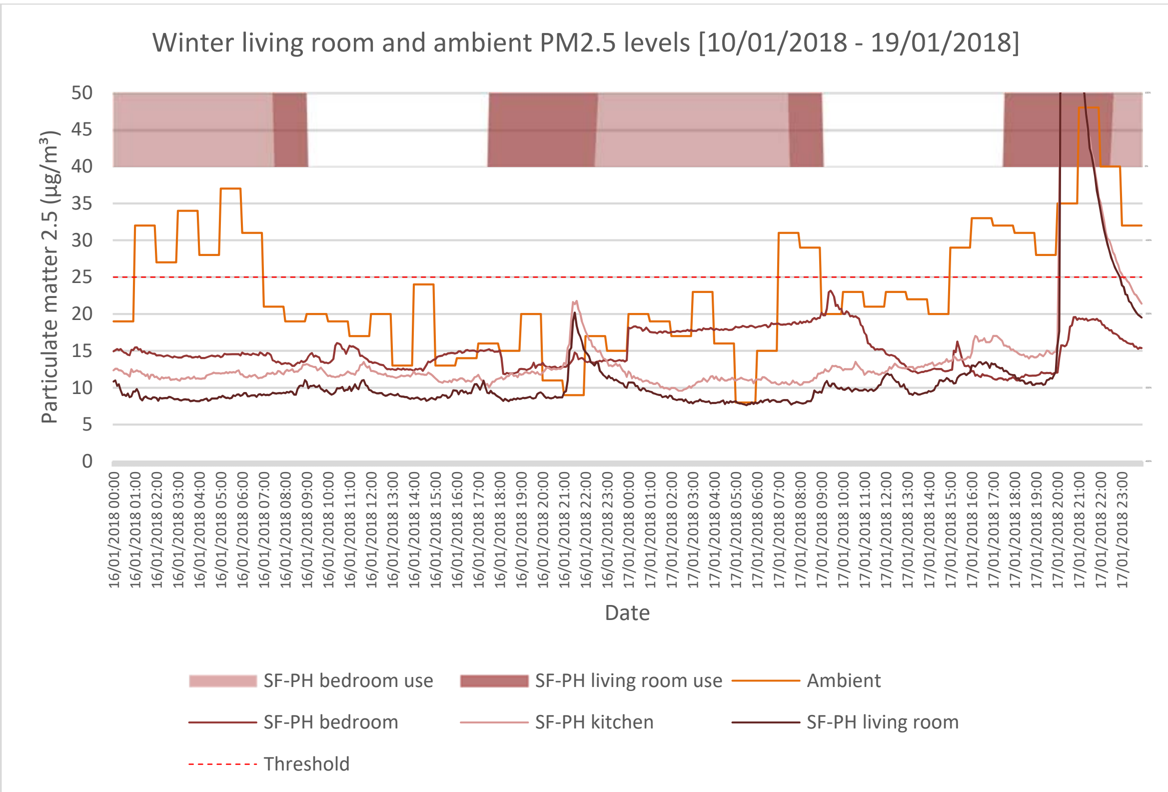


Figure 6.20 Winter SF-PH indoor and ambient PM2.5 levels.

Figure 6.21 and Figure 6.22 show the hourly concentrations per day, per month. It is clear that indoor $PM_{2.5}$ concentrations peaked consistently between 09:00 and 12:00 and 19:00 and 22:00, i.e. the same times associated with higher density in the homes, thus supporting the findings that human activities may be significant sources of pollution, as low concentrations were measured outdoors. The results of this analysis suggest that whilst SF-PH indoor $PM_{2.5}$ were lower; the differences may be related to differences in occupant behaviour and the fitlers present in the MVHR unit. Internal sources could be low, but be contained by the more airtight PH – hence elevate internal concentrations over time than in the leaky SF-CO and outdoors (due to better dispersion outdoors). MVHR in PH could also exhaust PM from indoors.

		Bedroom																									
	Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Hour	
June	SF-CO	10.6	9.1	7.5	7.3	7.0	7.1	7.1	7.2	7.3	9.6	16.9	17.8	13.9	10.9	9.6	10.7	10.3	8.9	8.6	10.7	14.0	10.4	10.3	10.0	SF-CO	June
	SF-PH	9.8	8.2	7.5	7.2	7.1	7.1	7.1	7.1	7.6	10.1	13.0	11.7	10.8	10.0	8.9	8.0	8.7	8.9	9.3	9.0	9.6	9.0	9.1	9.0	SF-PH	
	Ambient	9.3	7.7	8.8	8.4	9.1	8.8	9.8	8.6	8.3	8.9	7.4	8.2	8.4	8.1	7.5	7.5	7.7	8.2	9.2	9.4	9.0	8.5	8.4	9.8	Ambient	
July	SF-CO	8.5	8.5	8.0	7.8	7.7	7.6	7.8	7.7	7.9	8.2	9.3	11.5	11.3	11.1	9.3	12.2	15.6	11.0	11.5	10.0	10.1	12.9	11.0	9.1	SF-CO	July
	SF-PH	9.8	8.2	7.5	7.2	7.1	7.1	7.1	7.1	7.6	10.1	13.0	11.7	10.8	10.0	8.9	8.0	8.7	8.9	9.3	9.0	9.6	9.0	9.1	9.0	SF-PH	
	Ambient	9.0	8.5	7.8	8.2	7.7	7.7	7.9	7.7	8.3	8.1	6.5	6.2	6.1	6.5	6.8	6.7	8.5	8.3	9.4	8.3	9.3	8.4	7.4	8.4	Ambient	
August	SF-CO	16.0	14.0	13.3	12.4	12.0	12.0	12.1	12.1	12.2	19.4	33.1	25.3	20.6	23.3	18.5	19.6	19.2	15.8	18.8	26.9	31.6	23.5	17.4	17.6	SF-CO	August
	SF-PH	13.2	13.5	12.8	11.8	11.4	11.1	11.0	11.0	11.9	13.6	12.9	12.4	11.9	12.2	12.7	12.8	12.8	12.9	13.4	13.8	13.3	15.1	14.7	14.2	SF-PH	
	Ambient	8.0	8.1	7.9	7.0	8.2	8.5	9.3	9.0	8.5	8.8	8.5	8.6	8.3	9.6	9.3	9.4	8.3	8.3	9.5	9.7	8.8	9.0	9.4	9.3	Ambient	
September	SF-CO	18.7	17.2	15.9	14.9	15.0	15.1	15.5	15.7	16.0	22.7	27.3	28.9	22.4	17.9	17.9	17.5	17.2	20.4	19.6	20.8	21.6	25.2	22.4	18.8	SF-CO	September
	SF-PH	19.5	18.3	17.5	17.2	17.1	17.1	17.1	16.8	17.3	20.2	20.7	17.6	17.7	16.9	17.0	15.9	16.3	16.7	16.5	16.9	18.9	20.6	21.9	19.8	SF-PH	
	Ambient	13.7	13.7	14.5	14.1	14.3	15.7	14.6	15.1	15.6	15.5	14.0	14.1	14.1	14.5	13.8	14.0	12.4	13.3	14.6	15.5	15.4	14.6	13.2	13.8	Ambient	
October	SF-CO	11.6	10.9	10.2	10.1	9.9	10.2	10.9	11.4	12.3	18.2	23.6	20.0	18.0	16.1	15.7	16.9	13.9	12.9	18.7	17.7	16.2	18.2	14.9	13.3	SF-CO	October
	SF-PH	11.5	10.7	10.2	9.1	9.0	9.6	10.2	11.1	13.2	18.9	17.8	16.3	15.8	14.3	13.1	12.5	11.9	11.2	11.3	11.4	10.8	11.7	11.0	11.5	SF-PH	
	Ambient	13.6	12.6	14.4	15.9	17.4	24.0	28.1	23.3	18.0	20.0	22.2	18.7	15.4	12.4	10.8	12.3	12.3	10.5	10.8	12.4	14.6	13.2	14.2	14.8	Ambient	
November	SF-CO	10.2	8.8	8.3	8.0	8.0	7.9	8.0	8.0	8.8	14.8	18.0	15.0	12.9	12.8	10.5	11.4	12.0	15.6	12.3	13.8	11.1	14.8	13.1	10.8	SF-CO	November
	SF-PH	10.7	9.4	8.4	7.8	7.6	7.8	7.8	8.0	9.7	14.9	16.2	11.8	11.7	11.5	10.7	10.6	9.7	8.8	8.7	11.5	10.5	10.5	12.2	11.4	SF-PH	
	Ambient	10.3	10.4	9.6	10.3	10.1	10.2	12.7	10.5	9.8	9.9	7.2	7.3	6.7	6.3	5.6	7.4	7.8	9.0	9.5	11.4	11.0	11.8	10.6	10.1	Ambient	
December	SF-CO	13.2	11.8	11.1	10.4	10.3	10.1	10.2	10.2	9.9	17.5	24.2	18.8	18.2	23.1	23.7	23.2	15.1	14.7	13.5	18.4	21.3	13.6	12.0	12.2	SF-CO	December
	SF-PH	19.4	15.5	12.5	11.1	10.2	9.5	9.3	9.1	9.9	15.2	16.5	14.0	12.3	10.7	10.1	10.1	10.1	10.0	19.7	17.3	14.1	19.2	21.6	20.5	SF-PH	
	Ambient	17.6	17.5	17.9	18.3	18.5	21.2	24.0	20.7	18.4	16.1	15.0	15.2	13.7	13.5	14.1	14.9	15.8	17.6	18.5	19.0	18.0	19.2	17.9	18.3	Ambient	
January	SF-CO	15.1	14.2	14.5	13.3	12.8	12.5	12.0	11.6	11.6	14.5	18.1	15.4	18.1	21.8	16.4	16.7	19.2	16.7	18.4	28.0	30.1	20.2	15.7	14.5	SF-CO	January
	SF-PH	22.0	20.1	19.0	18.4	18.2	18.1	18.0	18.0	18.4	21.0	20.9	18.9	17.6	15.7	13.8	13.0	12.9	12.6	13.2	13.6	15.0	26.4	27.3	24.3	SF-PH	
	Ambient	13.4	13.1	12.6	14.7	13.9	16.8	15.0	13.7	13.6	13.0	10.0	10.7	10.3	11.2	11.2	9.9	12.4	13.2	12.9	13.1	12.5	12.6	12.9	12.4	Ambient	
February	SF-CO	15.7	13.8	13.2	12.5	12.1	12.1	11.7	11.5	11.6	17.5	21.5	15.1	14.2	13.2	15.3	18.5	15.6	14.5	14.2	18.6	16.7	13.9	22.1	18.4	SF-CO	February
	SF-PH	21.2	20.2	19.8	19.8	20.0	20.4	20.7	20.9	21.5	23.1	23.5	23.8	21.2	18.7	16.6	13.4	12.2	12.6	16.1	17.6	19.2	23.1	22.1	21.5	SF-PH	
	Ambient	12.9	11.7	11.3	12.7	13.7	15.9	13.9	11.4	10.5	9.5	9.1	8.9	6.4	6.1	7.6	9.1	9.7	11.2	12.3	13.7	13.7	12.5	12.4	12.0	Ambient	
	PM2.5 (µg/m³) scale	0	2.3	4.5	6.8	9.1	11	14	16	18	20	23	25		26	27	28	29	30	30	31	32	33	34	35	PM2.5 (µg/m³) scale	

Figure 6.21 SF-CO, SF-PH and ambient hourly $PM_{2.5}$ means in the bedrooms per month.

Living room																												
	Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Hour	
June	SF-CO	11.7	9.8	8.6	8.3	8.3	8.2	8.2	8.3	8.3	16.8	22.3	20.3	15.4	12.4	12.0	14.1	10.5	9.9	9.8	13.0	16.5	11.9	12.8	12.3	SF-CO	June
	SF-PH	8.0	6.9	6.5	6.4	6.6	6.6	6.6	6.6	7.1	9.0	15.4	12.7	10.1	9.4	8.8	8.1	8.3	8.4	8.7	8.6	9.7	9.5	11.1	8.9	SF-PH	
	Ambient	9.3	7.7	8.8	8.4	9.1	8.8	9.8	8.6	8.3	8.9	7.4	8.2	8.4	8.1	7.5	7.5	7.7	8.2	9.2	9.4	9.0	8.5	8.4	9.8	Ambient	
July	SF-CO	9.0	8.3	7.8	7.5	7.4	7.3	7.3	7.2	7.3	7.7	9.3	12.9	12.4	11.0	9.1	14.1	10.3	8.6	8.9	9.2	9.7	10.6	9.0	8.4	SF-CO	July
	SF-PH	8.7	8.2	7.9	7.7	7.7	7.7	7.8	7.8	7.6	9.8	10.9	9.3	8.5	13.3	14.3	10.1	8.4	7.6	7.8	8.9	9.3	9.1	8.8	8.6	SF-PH	
	Ambient	9.0	8.5	7.8	8.2	7.7	7.7	7.9	7.7	8.3	8.1	6.5	6.2	6.1	6.5	6.8	6.7	8.5	8.3	9.4	8.3	9.3	8.4	7.4	8.4	Ambient	
August	SF-CO	12.0	10.7	10.1	9.8	9.7	9.9	9.9	10.0	10.1	25.7	31.2	20.4	19.3	20.4	15.3	15.0	15.5	12.2	18.0	23.2	28.5	17.1	14.1	17.0	SF-CO	August
	SF-PH	8.7	8.2	7.9	7.7	7.7	7.7	7.8	7.8	7.6	9.8	10.9	9.3	8.5	13.3	14.3	10.1	8.4	7.6	7.8	8.9	9.3	9.1	8.8	8.6	SF-PH	
	Ambient	8.0	8.1	7.9	7.0	8.2	8.5	9.3	9.0	8.5	8.8	8.5	8.6	8.3	9.6	9.3	9.4	8.3	8.3	9.5	9.7	8.8	9.0	9.4	9.3	Ambient	
September	SF-CO	16.8	15.0	13.9	13.4	13.4	13.6	14.0	14.0	14.0	29.8	21.9	26.2	17.2	16.1	15.7	15.6	14.7	19.6	17.9	18.0	20.5	25.5	21.0	17.6	SF-CO	September
	SF-PH	16.1	14.3	13.5	13.2	13.2	13.3	13.4	13.2	13.7	16.8	16.2	15.3	14.4	14.5	15.0	14.2	14.1	13.6	14.2	14.0	16.1	19.0	20.3	17.4	SF-PH	
	Ambient	13.7	13.7	14.5	14.1	14.3	15.7	14.6	15.1	15.6	15.5	14.0	14.1	14.1	14.5	13.8	14.0	12.4	13.3	14.6	15.5	15.4	14.6	13.2	13.8	Ambient	
October	SF-CO	10.3	10.3	10.3	10.1	9.7	9.9	10.2	10.6	11.1	20.6	25.5	19.1	17.0	15.4	14.2	15.0	12.4	12.7	16.4	25.9	17.5	15.7	14.5	11.7	SF-CO	October
	SF-PH	9.9	9.0	8.6	8.3	8.2	8.5	9.2	9.9	11.6	14.8	16.5	22.9	16.3	13.5	13.2	12.3	11.5	11.1	11.2	11.1	11.8	12.6	11.9	11.1	SF-PH	
	Ambient	13.6	12.6	14.4	15.9	17.4	24.0	28.1	23.3	18.0	20.0	22.2	18.7	15.4	12.4	10.8	12.3	12.3	10.5	10.8	12.4	14.6	13.2	14.2	14.8	Ambient	
November	SF-CO	9.9	8.8	8.4	8.0	7.9	8.0	7.9	7.8	8.3	18.0	22.1	14.8	13.2	12.7	10.4	10.5	13.3	13.6	14.6	16.9	14.5	17.7	13.8	10.7	SF-CO	November
	SF-PH	8.6	7.9	7.3	7.1	7.1	7.3	7.4	7.5	9.4	13.1	12.0	11.7	13.3	10.1	8.9	9.0	7.7	7.0	7.7	12.1	10.7	10.7	10.0	8.8	SF-PH	
	Ambient	10.3	10.4	9.6	10.3	10.1	10.2	12.7	10.5	9.8	9.9	7.2	7.3	6.7	6.3	5.6	7.4	7.8	9.0	9.5	11.4	11.0	11.8	10.6	10.1	Ambient	
December	SF-CO	11.8	10.5	9.7	9.3	9.0	8.8	8.9	8.8	8.5	22.8	26.2	18.7	19.1	20.3	23.4	23.9	15.6	14.1	15.9	18.6	18.4	12.9	11.1	13.2	SF-CO	December
	SF-PH	16.1	12.4	10.3	9.4	9.2	9.0	8.8	8.8	9.1	10.0	13.4	14.2	11.3	10.7	8.8	8.1	8.0	8.4	9.7	8.2	11.3	28.2	20.5	22.5	SF-PH	
	Ambient	17.6	17.5	17.9	18.3	18.5	21.2	24.0	20.7	18.4	16.1	15.0	15.2	13.7	13.5	14.1	14.9	15.8	17.6	18.5	19.0	18.0	19.2	17.9	18.3	Ambient	
January	SF-CO	14.6	13.6	13.3	12.1	11.6	11.4	10.9	10.8	10.8	18.2	18.3	16.6	21.3	19.8	16.3	16.0	16.6	16.4	22.7	34.4	28.2	22.5	15.9	14.2	SF-CO	January
	SF-PH	13.9	11.9	10.6	10.0	9.7	9.4	9.0	8.7	10.9	11.5	10.9	10.8	10.0	9.5	8.7	8.0	7.8	7.7	7.1	7.2	12.0	28.9	21.1	16.6	SF-PH	
	Ambient	13.4	13.1	12.6	14.7	13.9	16.8	15.0	13.7	13.6	13.0	10.0	10.7	10.3	11.2	11.2	9.9	12.4	13.2	12.9	13.1	12.5	12.6	12.9	12.4	Ambient	
February	SF-CO	11.6	9.8	9.0	8.3	8.1	7.8	7.5	7.3	7.2	22.0	18.1	12.2	15.1	9.7	12.6	12.9	10.0	12.0	10.3	15.1	11.7	12.7	30.2	16.0	SF-CO	February
	SF-PH	17.4	15.0	13.6	13.0	12.6	12.5	12.5	12.5	12.9	14.5	31.5	26.0	18.8	18.9	15.7	12.5	11.6	11.3	18.4	21.0	31.2	31.6	25.3	21.0	SF-PH	
	Ambient	12.9	11.7	11.3	12.7	13.7	15.9	13.9	11.4	10.5	9.5	9.1	8.9	6.4	6.1	7.6	9.1	9.7	11.2	12.3	13.7	13.7	12.5	12.4	12.0	Ambient	
	PM2.5 (μg/m³) scale	0	2.3	4.5	6.8	9.1	11	14	16	18	20	23	25		26	27	28	29	30	30	31	32	33	34	35	PM2.5 (μg/m³) scale	

Figure 6.22 SF-CO, SF-PH and ambient hourly $PM_{2.5}$ means in the living rooms per month.

Table 6.11 $PM_{2.5}$ excess (indoor-ambient) concentration differences by month.

		June (μg/m3)	July (μg/m3)	August (μg/m3)	September (μg/m3)	October (μg/m3)	November (μg/m3)	December (μg/m3)	January (μg/m3)	February (μg/m3)
SF-CO	Bedroom	1.58	1.99	9.90	5.02	-1.26	2.05	-2.25	4.01	3.97
	Kitchen	3.64	0.75	8.19	6.21	-2.52	2.47	-1.59	4.52	1.80
	Living room	3.53	1.36	7.34	3.38	-1.49	2.75	-2.56	4.21	1.19
SF-PH	Bedroom	0.36	1.40	4.05	3.64	-3.67	0.92	-3.87	5.46	8.41
	Kitchen	-0.02	-0.84	3.67	2.36	-3.28	0.71	-4.18	2.13	5.00
	Living room	0.14	1.18	3.20	0.61	-4.05	-0.13	-5.60	-1.39	6.76

6.5.4 Total volatile organic compounds (tVOCs)

Indoor tVOC levels were measured in both homes as part of IAQ monitoring in the bedrooms, kitchens and living rooms. Outdoor measurements were not available from the local monitoring network. Mean tVOC concentrations exceeded the 300μg/m³ (ECA, 1992) in SF-CO (kitchen 325.99μg/m³, living-room 346.92μg/m³ and bedroom 380.19μg/m³) and SF-PH (kitchen 296.04μg/m³, living-room 324.17μg/m³ and bedroom 336.87μg/m³). A study that took air samples in 108 Californian homes found that indoor tVOC concentrations were on average

173.5μg/m^3, though a maximum of 1,373.1μg/m^3 was measured, however that study only took 24-hour measurements and was calculated based on a 24-hour time-average mass concentration[7] (Offerman, 2009). It also excluded coastal sites such as San Francisco and may have included suburban dwellings in the sample. Another study that looked at indoor VOCs in dwellings across the US found similar seasonal variations to those found in this study, i.e. summer (192.32μg/m^3) concentrations were higher than winter (106.78μg/m^3, Jia, Batterman and Godwin, 2008).

Although annual tVOC concentrations were lower in SF-PH than in SF-CO (Figure 6.23), there were not statistical difference between the median differences:

- Bedroom diffrences (14.16μg/m^3) between the SF-CO (284μg/m^3) and SF-PH (278.6μg/m^3), z=-27.81, p=.462.

- Kitchen diffrences (9.98μg/m^3) between the SF-CO 279μg/m^3) and SF-PH (257.03μg/m^3), z=--19.61, p=.437.

- Bedroom diffrences (6.83μg/m^3) between the SF-CO (295μg/m^3) and SF-PH (279μg/m^3), z=-12.37, p=.521.

Similarly, there were no statistical significant differences between rooms in the same dwelling although bedroom concentrations were usually higher in both homes, especially at night. Figure 6.24 shows the monthly mean per hour in the bedrooms, and it is clear that tVOC were higher during the night than at any other point of the day, or even in the living room (Figure 6.25). A possible explanation for this could be the higher temperatures that could enhance the off-gassing of such products and other building materials, keeping the windows closed, low air exchange rates and the use of personal cleaning products, among other human activities or behaviours, as explained by Rehwagen et al. (2003).

Comparison of the percentage of time above 300μg/m^3 between the occupied, as reported on the occupant diary, and complete period revealed that occupant

[7] Based on the EPA method TO-17, “Determination of Volatile Organic Compounds in Ambient Air Using Active Sampling onto Sorbent Tubes”. Samples were collected and then analysed in the laboratory to identify 20 VOCs. Therefore, the tVOC count only takes these 20 VOCs into account.

exposure is higher in the bedrooms during the occupied time (SF-CO 66.54%, SF-PH 64.40%) than those during the complete period (SF-CO 46.86%, SF-PH 46.16%, Table 6.12). It is worth noting that indoor tVOC pollution was higher from the evening to the morning (Figure 6.26), when the participants reported higher occupancy and activities. Figure 6.24 and Figure 6.25 also highlight seasonal changes, whereby, during summer, lower values were measured because occupants opened their windows more frequently than during winter or autumn.

Table 6.12 TVOC summary of analysis of time periods with exposition above 300μg/m³ in the SF-CO, and SF-PH. Negative difference values indicate that the exposition is lower during occupied periods.

		>300μg/m³				
		Complete period (a)	Occupied period (b)	Difference (b-a)	Unoccupied period (c)	Difference (c-a)
SF-CO	Bedroom	46.86%	66.54%	19.68%	33.16%	-13.70%
	Kitchen	44.79%	35.62%	-9.17%	48.20%	3.41%
	Living room	48.84%	36.30%	-12.54%	50.60%	1.76%
SF-PH	Bedroom	46.16%	64.40%	18.23%	34.61%	-11.55%
	Kitchen	38.85%	36.54%	-2.31%	40.07%	1.22%
	Living room	44.43%	36.46%	-7.96%	45.50%	1.07%

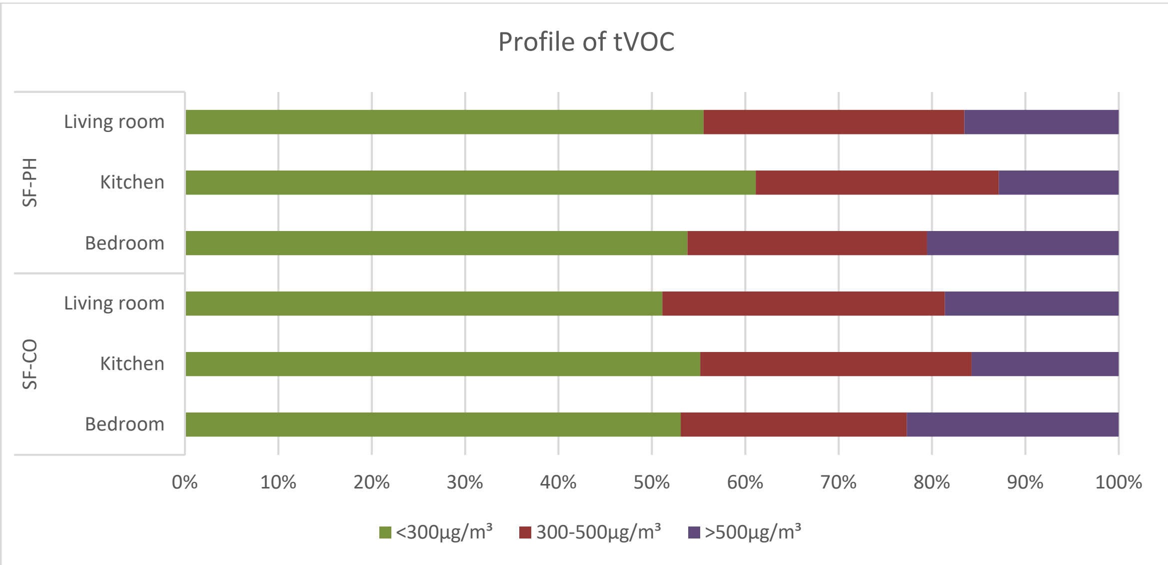


Figure 6.23 SF-CO and SF-PH indoor tVOC concentrations by exposure range during the monitored time.

	Bedroom																										
	Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Hour	
June	SF-CO	356	415	468	493	475	431	379	384	349	352	343	268	210	193	172	179	208	194	198	205	216	217	242	289	SF-CO	June
	SF-PH	286	308	280	311	326	333	307	275	263	272	244	211	202	221	205	182	184	187	198	198	201	211	233	248	SF-PH	
July	SF-CO	306	370	389	444	447	411	359	309	283	272	296	265	220	176	164	172	183	203	213	202	197	245	278	271	SF-CO	July
	SF-PH	211	244	279	273	246	235	242	240	226	212	197	178	180	184	163	152	149	152	152	158	173	171	172	187	SF-PH	
August	SF-CO	389	548	607	628	661	685	691	584	537	520	431	335	249	204	192	210	242	248	246	281	285	292	288	298	SF-CO	August
	SF-PH	352	378	378	379	381	381	348	334	348	402	323	292	254	231	254	258	257	253	262	228	222	242	262	276	SF-PH	
September	SF-CO	457	566	707	799	794	746	668	564	488	524	437	349	263	218	208	204	213	236	229	239	259	308	319	391	SF-CO	September
	SF-PH	391	411	405	419	421	403	411	407	449	482	430	360	328	296	277	261	257	253	241	247	269	321	347	348	SF-PH	
October	SF-CO	457	566	707	799	794	746	668	564	488	524	437	349	263	218	208	204	213	236	229	239	259	308	319	391	SF-CO	October
	SF-PH	437	470	468	496	494	535	571	594	661	691	577	483	417	374	316	288	274	262	265	265	275	334	368	382	SF-PH	
November	SF-CO	498	555	589	643	674	651	623	577	624	508	378	294	239	201	177	190	203	219	235	331	348	410	409	436	SF-CO	November
	SF-PH	476	496	483	499	532	571	551	524	519	470	372	307	260	208	186	177	175	184	197	226	258	307	357	428	SF-PH	
December	SF-CO	419	532	613	596	614	636	560	549	523	484	379	310	271	258	309	242	210	239	272	362	479	371	359	357	SF-CO	December
	SF-PH	413	473	491	531	551	543	534	527	548	521	381	300	253	207	193	177	189	195	206	209	247	313	339	346	SF-PH	
January	SF-CO	458	528	538	525	505	451	418	390	386	340	307	265	241	243	229	225	227	247	276	295	332	332	331	356	SF-CO	January
	SF-PH	473	544	544	557	605	605	586	564	519	453	362	275	229	205	185	171	162	153	159	189	239	312	379	421	SF-PH	
February	SF-CO	458	483	533	526	503	478	447	406	393	405	383	343	316	306	301	298	278	288	317	370	370	339	447	388	SF-CO	February
	SF-PH	423	501	514	541	621	681	699	635	657	540	428	362	332	302	283	257	231	217	221	268	302	346	356	359	SF-PH	
	tVOC (μg/m³) scale	125	141	157	173	189	205	220	236	252	268	284	300		345	391	436	482	527	573	618	664	709	755	800	tVOC (μg/m³) scale	

Figure 6.24 SF-CO and SF-PH hourly tVOC averages in the bedrooms per month.

	Living room																										
	Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Hour	
June	SF-CO	384	414	406	379	358	345	322	304	310	371	395	303	243	231	192	211	231	203	203	229	258	270	319	375	SF-CO	June
	SF-PH	339	278	235	214	204	198	192	177	183	244	265	250	229	244	218	210	210	216	227	234	259	278	327	363	SF-PH	
July	SF-CO	305	305	286	279	275	271	256	239	228	253	278	258	225	193	183	192	188	189	193	185	212	246	256	267	SF-CO	July
	SF-PH	242	251	237	222	220	223	225	229	222	236	249	224	216	213	200	192	193	192	183	194	212	210	214	232	SF-PH	
August	SF-CO	362	399	421	417	398	401	415	410	387	433	392	316	247	204	195	205	231	217	246	270	279	300	297	347	SF-CO	August
	SF-PH	310	308	301	299	296	294	289	286	297	335	314	274	265	259	275	274	277	270	267	243	259	297	324	322	SF-PH	
September	SF-CO	532	556	559	568	566	540	520	476	437	491	437	402	312	273	255	253	243	248	253	262	295	356	428	521	SF-CO	September
	SF-PH	456	460	440	428	419	406	403	409	428	485	481	447	418	389	365	367	374	361	357	332	335	388	449	408	SF-PH	
October	SF-CO	488	448	476	442	415	416	437	452	473	539	535	465	384	321	291	278	249	245	279	332	339	389	403	456	SF-CO	October
	SF-PH	503	479	466	464	455	468	492	502	528	642	650	593	536	487	440	416	371	339	336	343	401	460	509	501	SF-PH	
November	SF-CO	424	418	433	432	436	425	414	399	432	509	454	344	273	227	208	210	219	237	307	398	419	483	457	431	SF-CO	November
	SF-PH	389	342	304	291	278	279	278	278	302	382	386	353	327	291	263	244	237	235	247	295	373	441	464	409	SF-PH	
December	SF-CO	456	470	482	454	426	420	394	380	389	496	452	373	333	300	363	264	243	275	317	422	577	440	433	424	SF-CO	December
	SF-PH	424	377	330	298	286	281	273	272	289	364	378	347	330	328	297	261	266	282	263	293	391	496	486	471	SF-PH	
January	SF-CO	391	400	384	374	348	325	302	290	285	336	350	298	270	253	236	225	230	269	301	365	392	385	394	393	SF-CO	January
	SF-PH	401	360	314	291	278	273	268	261	276	327	315	285	259	245	225	202	189	183	196	230	315	404	454	444	SF-PH	
February	SF-CO	399	370	366	347	339	321	304	291	293	411	402	360	332	316	319	301	270	298	323	394	369	435	496	448	SF-CO	February
	SF-PH	390	371	330	293	281	273	280	290	310	409	446	419	388	370	349	311	270	251	254	292	365	433	410	406	SF-PH	
	tVOC (μg/m³) scale	125	141	157	173	189	205	220	236	252	268	284	300		345	391	436	482	527	573	618	664	709	755	800	tVOC (μg/m³) scale	

Figure 6.25 SF-CO and SF-PH hourly tVOC averages in the living rooms per month.

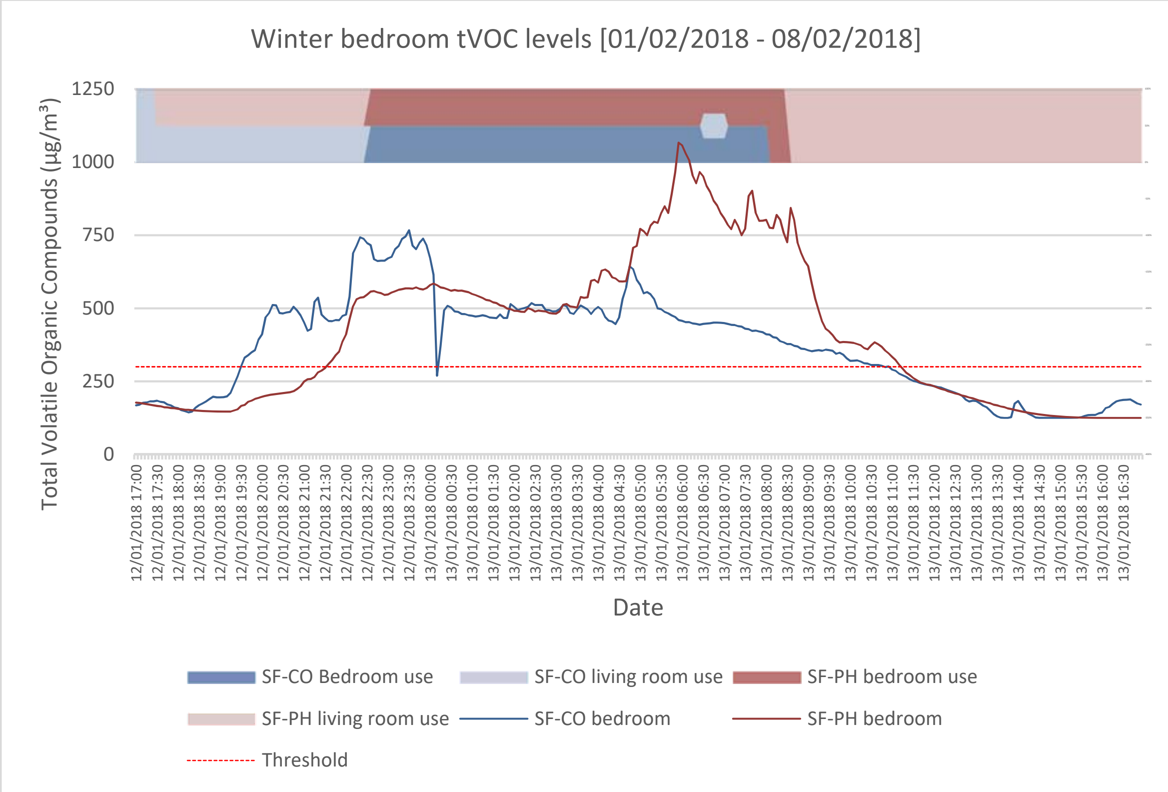


Figure 6.26 Winter night example of tVOC levels.

Figure 6.27 and Figure 6.28 show summer sample weeks of indoor tVOC concentrations in both homes, during the same periods. It is evident that tVOC levels during the night rose in both homes, albeit only in the bedrooms, and concentrations in the living rooms and kitchens rose slightly. Indoor tVOC in the living room and the kitchen rose in the morning, just before the occupants left the house, perhaps due to morning activities, following which indoor pollution then dissipated until late afternoon/early evening, when the occupants were back in their homes and the tVOC levels started to rise again. This strengthens the assertion that indoor tVOC pollution was significantly related to human behaviour and not to building materials off-gassing and the impact of the MVHR to dilute tVOC levels. For instance, Figure 6.29 and Figure 6.30 show how temperature remains stable during the day and night, but indoor concentrations of tVOC and $PM_{2.5}$ show pollution peaks due to human activities.

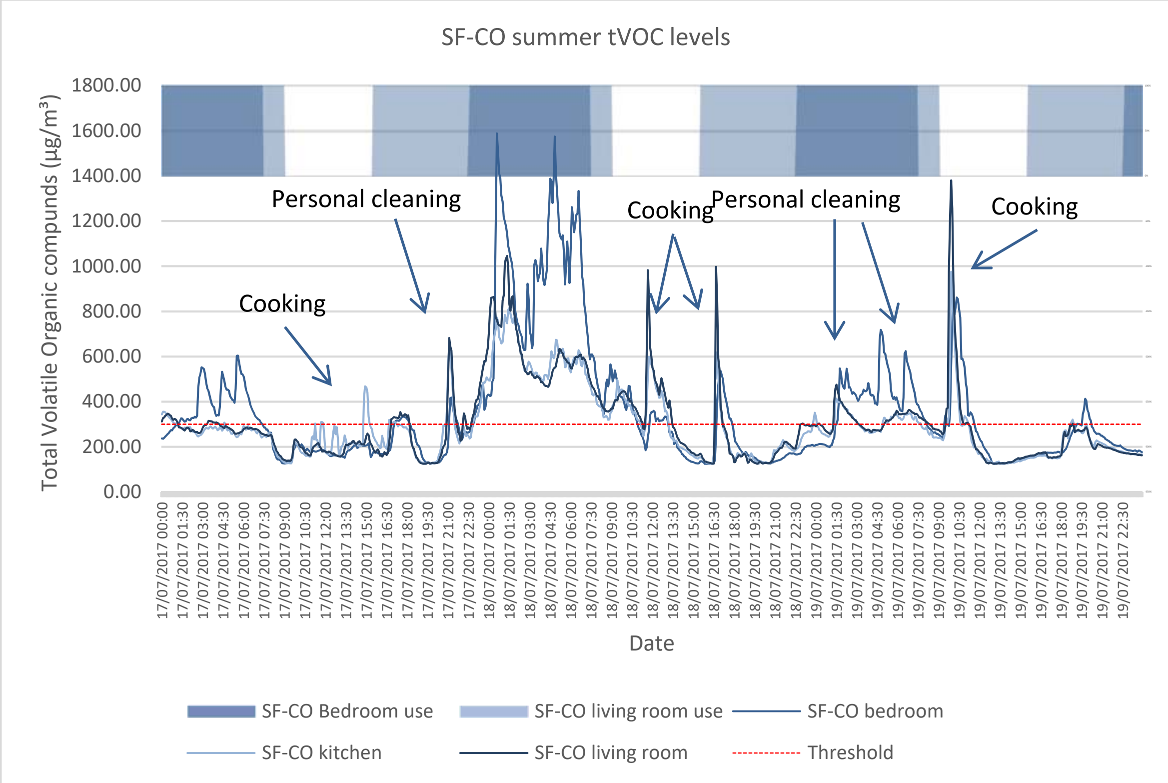


Figure 6.27 Indoor summer tVOC concentrations in SF-CO's bedroom, kitchen and living room.

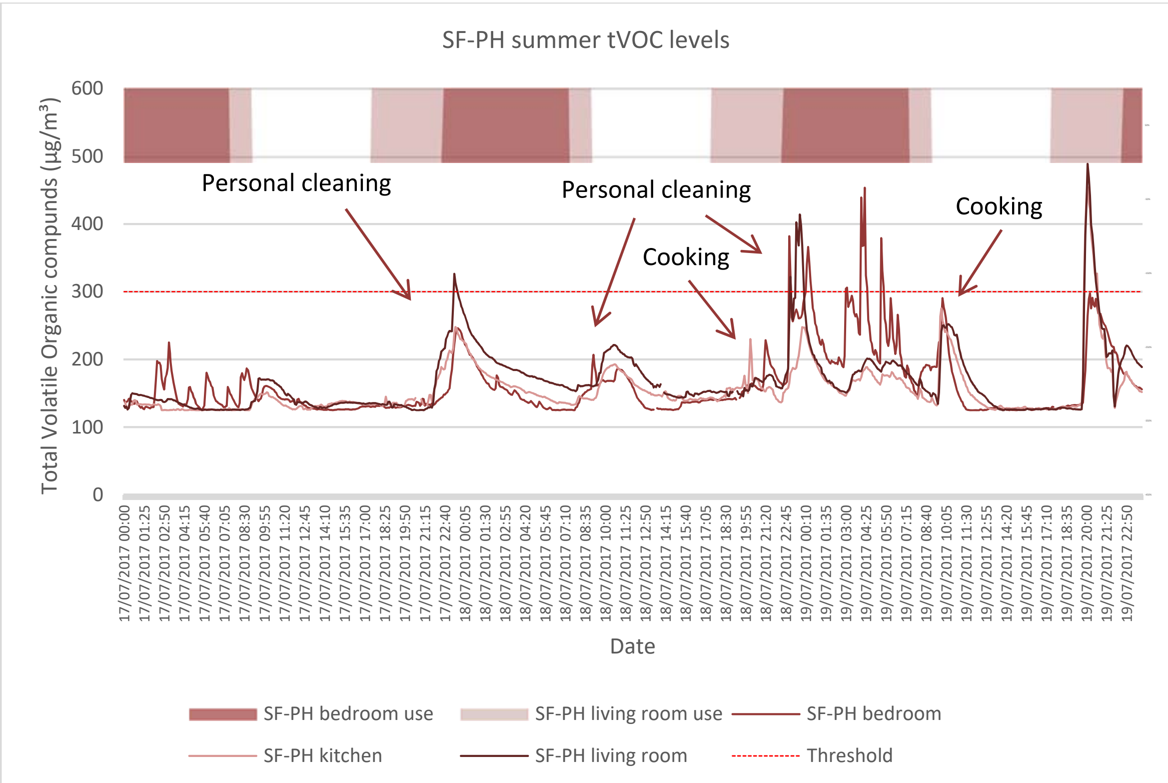


Figure 6.28 Indoor summer tVOC concentrations in SF-PH's bedroom, kitchen and living room.

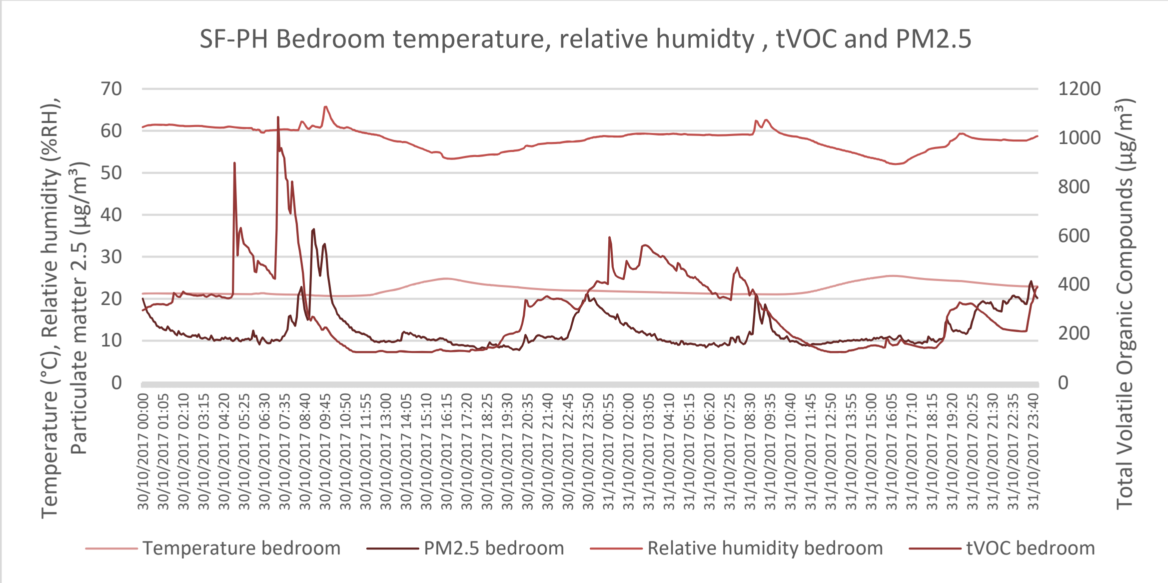


Figure 6.29 Example of the relation between temperature and indoor pollutants in the SF-PH bedroom.

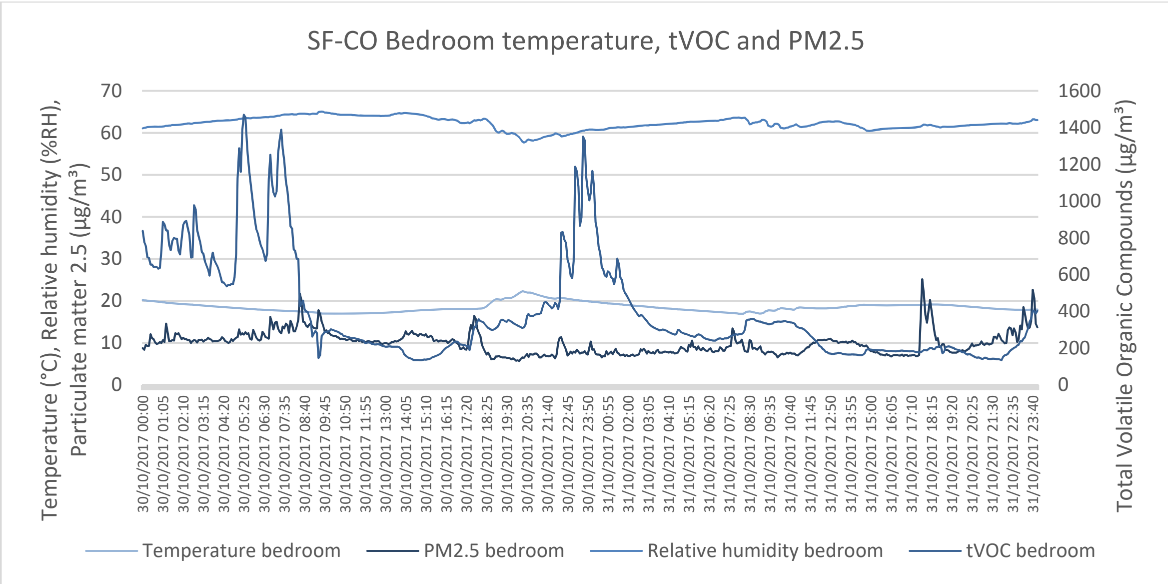


Figure 6.30 Example of the relation between temperature and indoor pollutants in the SF-CO bedroom.

Indoor tVOC concentrations may be related to outdoor temperatures depending on the type of VOC, indoor sources, building type and location, among other factors (Schlink *et al.*, 2004). In cold climates tVOC are expected to rise due to lower ventilation and air exchange rates (Rehwagen, Schlink and Herbarth, 2003). In warmer climates, it is expected that windows will remain closed due to the use of air conditioning, the desire to minimise dust, pollen and pollution or possibly for security reasons, in addition to the higher temperatures that may increase VOC emissions from some sources (Jia, Batterman and Godwin, 2008).

While indoor tVOC in the SF-PH were lower, there were no significant differences between the dwellings. The results of this analysis suggest that occupant behaviours are a critical factor on determining the indoor concentrations. In warm locations, higher ventilation rates may be desired for thermal comfort, but also they may help to dilute and dissipate indoor pollution, so dwellings may benefit from ventilation systems as they can provide continuous air exchanges, especially at night when higher concentrations were measured.

6.6 IAQ perceptions

Occupants' perceptions of SF-CO (N=2) and SF-PH (N=3) were assessed through online surveys, using the bipolar and unipolar scales described in Chapter 4. The desired scores for the bipolar scale are between 3 and 5, and less than 3 for the unipolar scales.

SF-PH surveys indicate that summer mean scores of the scale fresh-stuffy scale (M=3.33) require further investigation. Occupants felt satisfied overall with IAQ in SF-PH, even though they did not perceive the air to be significantly fresh. SF-CO occupants perceived the indoor air stuffy (fresh-stuffy scale M=4.50), humid (dry-humid scale M=5.50) and smelly (odourless-smelly scale M=3.50). This correlates with their overall satisfaction with IAQ, as they stated to be dissatisfied overall with the quality of the indoor air (M=4.50) leading, possibly, to constant dissatisfaction during summer (Table 6.13).

Winter IAQ perceptions in SF-PH were rated as satisfactory overall (M=1.33), and during these months the occupants perceived indoor air to be fresh (M=2.33), odourless (M=1.67), neither dry nor humid (M=3.67) and neither still nor draughty (M=4.33). The winter IAQ perceptions in SF-CO rated poorly, in that two of the scales were rated as a cause of concern, and the air was perceived as draughty (M=6.00), smelly (M=5.00) and stuffy (M=4.50), requiring further investigation as the overall satisfaction of IAQ (M=4.50). This suggests that the SF-CO occupants had poor perceptions of IAQ (**Error! Reference source not found.**).

Table 6.13 Statistical analysis of IAQ perceptions during summer in SF-CO (N=2) and SF-PH. (N=3). *Italics represent figures outside the range of the scale (1-7).

Summer									
IAQ perceptions scale	House	Occupant	Result	Mean	SD	Mean + SD	Mean - SD*	Max	Min
Fresh (1) - stuffy (7)	SF-CO	A	4	4.50	0.71	5.21	3.79	5	4
		B	5						
		C	--						
	SF-PH	A	3	3.33	0.58	3.91	2.76	4	3
		B	4						
		C	3						
Dry (1) - humid (7)	SF-CO	A	6	5.50	0.71	6.21	4.79	6	5
		B	5						
		C	--						
	SF-PH	A	4	4.67	0.58	5.24	4.09	5	4
		B	5						
		C	5						
Still (1) - draughty (7)	SF-CO	A	5	4.50	0.71	5.21	3.79	5	4
		B	4						
		C	--						
	SF-PH	A	4	3.33	0.58	3.91	2.76	4	3
		B	3						
		C	3						
Odourless (1) - smelly (7)	SF-CO	A	3	3.50	0.71	4.21	2.79	4	3
		B	4						
		C	--						
	SF-PH	A	2	2.33	1.53	3.86	*0.81*	4	1
		B	1						
		C	4						
Overall satisfied (1) - overall dissatisfied (7)	SF-CO	A	4	4.50	0.71	5.21	3.79	5	4
		B	5						
		C	--						
	SF-PH	A	2	1.67	0.58	2.24	1.09	2	1
		B	2						
		C	1						

Despite the high relative humidity levels, SF-PH occupants reported that they did not experience condensation on doors or windows, in fact the occupants' perception of RH were good as well as their perception of air freshness, which suggests that occupants adapted to the outdoor RH levels and that the air flows were acceptable and may have helped to remove humidity. SF-PH experienced odours coming from the toilets and outdoors, a possible explanation is that the air in the toilets may be stale, but not perceived by the occupants, or that the filters (F7 and G4) need to be replaced. SF-CO occupants did not report experiencing condensation on doors but on windows, but they did report mould and humid ceilings in the living room. These results are supported by the measured hygrothermal conditions and the occupants' perception of RH. Perceived odours in SF-CO were reported to be from the toilets, outdoors and somewhere else not identified. A possible explanation could be related to the lack of continuous ventilation as the air was rated to be stuffy and smelly.

Table 6.14 Statistical analysis of IAQ perceptions during winter in SF-CO (N=2) and SF-PH. (N=3). *Italics represent figures outside the range of the scale (1-7).

Winter									
IAQ perceptions scale	**House**	**Occupant**	**Result**	**Mean**	**SD**	**Mean + SD**	**Mean - SD***	**Max**	**Min**
Fresh (1) - stuffy (7)	SF-CO	A	5	4.50	0.71	5.21	3.79	5	4
		B	4						
		C	--						
	SF-PH	A	3	2.33	0.58	2.91	1.76	3	2
		B	2						
		C	2						
Dry (1) - humid (7)	SF-CO	A	5	4.50	0.71	5.21	3.79	5	4
		B	4						
		C	--						
	SF-PH	A	4	3.67	0.58	4.24	3.09	4	3
		B	3						
		C	4						
Still (1) - draughty (7)	SF-CO	A	6	6.00	0.00	6.00	6.00	6	6
		B	6						
		C	--						
	SF-PH	A	4	4.33	0.58	4.91	3.76	5	4
		B	5						
		C	4						
Odourless (1) - smelly (7)	SF-CO	A	4	5.00	1.41	6.41	3.59	6	4
		B	6						
		C	--						
	SF-PH	A	2	1.67	0.58	2.24	1.09	2	1
		B	1						
		C	2						
Overall satisfied (1) - overall dissatisfied (7)	SF-CO	A	3	3.50	0.71	4.21	2.79	4	3
		B	4						
		C	--						
	SF-PH	A	2	1.33	0.58	1.91	*0.76*	2	1
		B	1						
		C	1						

6.7 Thermal perceptions

Occupants' perceptions of thermal comfort were examined through online surveys using unipolar and bipolar scales, as described in Chapter 4; the rating scale proposed by Raw (1995) was used in this assessment. The results of the statistical analysis were derived from the participants of each household, namely SF-CO (N=2) and SF-PH (N=3).

Table 6.15 Statistical analysis of thermal comfort perceptions during summer in SF-CO (N=2) and SF-PH. (N=3). *Italics represent figures outside the range of the scale (1-7).

Summer									
Thermal perceptions scale	**House**	**Occupant**	**Result**	**Mean**	**SD**	**Mean + SD**	**Mean - SD***	**Max**	**Min**
Comfortable (1) - uncomfortable (7)	SF-CO	A	3	3.00	0.00	3.00	3.00	3	3
		B	3						
		C	--						
	SF-PH	A	1	1.33	0.58	1.91	*0.76*	2	1
		B	2						
		C	1						
Too hot (1) - too cold (7)	SF-CO	A	3	3.50	0.71	4.21	2.79	4	3
		B	4						
		C	--						
	SF-PH	A	4	3.67	0.58	4.24	3.09	4	3
		B	3						
		C	4						
Stable (1) - varies during the day (7)	SF-CO	A	5	5.50	0.71	6.21	4.79	6	5
		B	6						
		C	--						
	SF-PH	A	1	1.33	0.58	1.91	*0.76*	2	1
		B	1						
		C	2						
Satisfactory overall (1) - unsatisfactory overall (7)	SF-CO	A	3	3.50	0.71	4.21	2.79	4	3
		B	4						
		C	--						
	SF-PH	A	1	1.33	0.58	1.91	*0.76*	2	1
		B	1						
		C	2						

Summer thermal comfort perceptions in SF-PH were rated as satisfactory, whereas for SF-CO it was poorly rated (Table 6.15). SF-CO temperatures were considered in a range where they could not be perceived to be either comfortable or uncomfortable (M=3), but on the too hot-too cold scale (M=3.5) they were not perceived to be beyond the comfort zone. The temperature analysis suggests that the SF-CO temperatures are higher than those observed in the SF-PH. This suggests that the most significant problem that influenced the perceptions of thermal comfort in SF-CO was temperature variations during the day (M=5, rated as a cause of concern), which may lead to constant dissatisfaction. Compared to the SF-PH (mean summer daily temperature variations B 2.17°C, K 2.34°C and L 2.53°C), the daily summer variations were more significant in SF-CO (mean summer daily temperature variations B 3.49°C, K 4.12°C and L 3.94°C, with maximum variations up to 9.38°C). Although temperatures in the SF-CO living room may drop to 15°C, it is not possible to establish weather or not the living rooms was occupied at such times.

Table 6.16 Statistical analysis of thermal comfort perceptions during winter in SF-CO (N=2) and SF-PH. (N=3). *Italics represent figures outside the range of the scale (1-7).

Winter									
Thermal perceptions scale	House	Occupant	Result	Mean	SD	Mean + SD	Mean - SD*	Max	Min
Comfortable (1) - uncomfortable (7)	SF-CO	A	3	3.50	0.71	4.21	2.79	4	3
		B	4						
		C	--						
	SF-PH	A	1	1.33	0.58	1.91	0.76	2	1
		B	2						
		C	1						
Too hot (1) - too cold (7)	SF-CO	A	6	5.50	0.71	6.21	4.79	6	5
		B	5						
		C	--						
	SF-PH	A	5	4.67	0.58	5.24	4.09	5	4
		B	4						
		C	5						
Stable (1) - varies during the day (7)	SF-CO	A	3	4.00	1.41	5.41	2.59	5	3
		B	5						
		C	--						
	SF-PH	A	1	1.33	0.58	1.91	0.76	2	1
		B	1						
		C	2						
Satisfactory overall (1) - unsatisfactory overall (7)	SF-CO	A	4	4.50	0.71	5.21	3.79	5	4
		B	5						
		C	--						
	SF-PH	A	1	1.33	0.58	1.91	0.76	2	1
		B	2						
		C	1						

Perceived thermal comfort during winter (Table 6.15), similar to summer, was rated as satisfactory in SF-PH and as poor in SF-CO. Temperatures in SF-CO were perceived as cold and as a cause of concern (M=5.5) during winter, which converges with a higher frequency of temperatures below 18°C (B 77%, L 53% of the winter time). The comfort scale (M=3.5) was rated as neither comfortable nor uncomfortable, and the daily temperature was perceived to have significant variations (M=4, mean winter daily temperature variations B 4.93°C, K 5.03°C and L 5.94°C with maximum variations up to 9.66°C). These situations may be enough to assume that the participants were dissatisfied overall (M=4.5) with the thermal performance of the dwelling.

6.8 Chapter conclusion

This chapter emphasises the importance occupant behaviours to the IAQ and indoor environmental comfort. This chapter outlined and discussed the results of the measurements and assessment of indoor $PM_{2.5}$ and tVOCs as indoor pollutants, as well as hygrothermal conditions in a PassivHaus (SF-PH) and a standard building practice (SF-CO) dwelling in San Francisco.

This case study tested in detail the monitoring methdology using low-cost IAQ and online surveys as outlined in Chapter 3 and 4. The application of the monitoring protocol proved to be useful to collect data with reasonable quality and desired quantity to provide insights and shortcomings about the IAQ in the dwellings. However, the monitoring protocol presented some limitations, particularly regarding the collection of detailed construction data, physical observation of the dwellings and real occupant behaviour data. Online surveys about occupants' perceptions of IAQ, thermal comfort and self-reported health were convenient. Although, more data, especially real occupancy and behaviours, are needed to fully correlate qualitative and quantitative data.

Although, lower indoor pollution was measured in the PassivHaus dwelling, there were no statistically significant differences between both homes by exception of $PM_{2.5}$ in the kitchen and living room. Occupant behaviour and ventilation may be the most critical factors for these changes. Relative indoor background pollution ($PM_{2.5}$ and tVOC) levels were usually lower in the PassivHaus dwelling; however, indoor pollution peak levels were usually higher in this particular home. For instance, controlled ventilation rates may act as a 'double-edged sword,' in that while the continuous air flow achieved through the MVHR system may help to dilute and remove indoor pollution, pollution peaks took longer (between 2 and 6 times more compared to the SF-CO depending on the ventilation conditions) to dissipate due to the low ventilation rates (lack of purge). In contrast, indoor pollution may have dissipated faster in the control house, but natural ventilation could not always be achieved and so IAQ was poorer in general. The IAQ in the SF-PH could be improved with simple changes to human behaviour. For instance, SF-PH occupants used the boost functions of the system only on rare occasions, but if used during or after cooking or showering, this could help to improve IAQ as well as the use of the cooker extraction after cooking.

Similar to other studies, lower indoor pollution was found compared to when the building was empty for long time-periods (i.e. holidays). This suggests that indoor emissions from building materials were not very significant and that occupant behaviour may have been a key factor in indoor pollution. In addition, building material emissions can be affected by high indoor temperatures and higher relative humidity levels, which are likely to occur when any building is in use.

Although, statistically significant warmer temperatures were measured in the PassivHaus dwelling, they were modest. This implies that the PassivHaus could be associated with higher risk of overheating, although, such differences could be related to occupant behaviour rather than the building itself. Nevertheless, PassivHaus occupants were satisfied with thermal performance during summer and winter.as

Chapter 7 Dunfermline case study

7.1 Summary

This chapter discusses the results of the last of the case studies where the monitoring methodology was tested. The homes are located in Dunfermline (Scotland) a tempearte oceanic climate, included a PassivHaus and control home equal in layout, as well as a dwelling representing a midpoint between the PassivHaus and control home. This case study measured indoor air temperature, relative humidity, $PM_{2.5}$ and tVOC levels simultaneously in three rooms in each of the homes. The first part of the chapter describes the building and household characteristics of the dwellings, while the second part presents the results of the monitoring campaign. Finally, the results of the IAQ and thermal occupant' perceptions surveys are presented. The monitoring protocol followed methodology described in Chapter 4 and collected ambient levels from the local monitoring network.

7.2 Background

The Housing Innovation Showcase (HIS) was built and completed by Kingdom Housing Association (KHA) in May 2012. The HIS is located near to a motorway and a busy street, suggesting a risk of raised pollution levels. HIS main goal was to select a method to reduce CO_2 emissions from their new building stock through high performance homes. KAH built a varied and highly specified set of energy-efficient homes to select, test and adopt better procurement and affordable housing.

The HIS comprised 27 dwellings in ten blocks, using different construction methods. Each of the blocks was built using a different construction process but with similar roof and flooring systems. However, to allow comparability between performance indicators, all homes were built to the same design brief and general specification. This case study looks at three dwellings: a control house built to KHA standards, a PassivHaus and a Gold Standard dwelling. Accordingly to the Scottish building regulations, bronze, silver, gold and platinum standard are part of the Levels of Sustainability addressed in the Building Standards (2007) for domestic buildings in Scotland. The gold level aims to reduce the energy consumption to 30kWh/m^2 for houses (20kWh/m^2 for flats) and water consumption, as well as enhancing noise separation, natural light, security and outdoor space (Scottish Government, 2017). The interest on adding the gold house was to evaluate a dwelling that uses similar design strategies – airtightness, MVHR system and insulation – as a PassivHaus but with less rigorous performance. The three homes are located next to each other and the environmental monitoring point is 2.8 km from the homes.

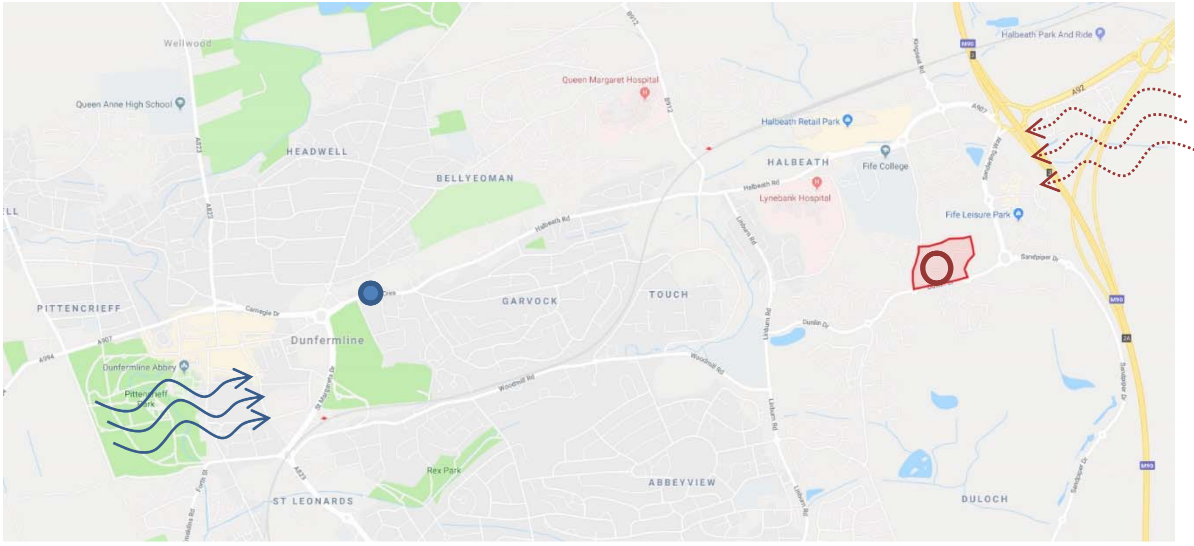


Figure 7.1 Location of the HIS. The red circle indicates the location of the homes, and the blue circle the location of the nearest pollution monitoring point. Source: Google My Maps (accessed November 2018)

THE HIS is located in the east suburbs of Dunfermline, Scotland. This neighbourhood is limited by the Motorway M90 and Fife Leisure Park to the east, to the south with a main street, to the north with another neighbourhood, the A907 and Halbeath Retail Park, finally to the west Fife College and a new residential development. The predominant winds from the west drag the pollution from the city to the HIS during the cold months, while during April and May the east wind does the same with the pollution from the motorway (Figure 7.1).

The Scottish building code established that natural ventilation could be achieved with trickle vents, windows, roof-lights or doors, recommending the use of trickle vents for background ventilation in dwellings. Mechanical ventilation required to extract air of at least 15-30 l/s (intermittent) (Scottish Government, 2017) and 8-13 l/s (continuous), similarly to the UK Approved Document F (HM Government, 2013). However, the efficiency of trickle vents in Scotland has been questioned (T. R. Sharpe *et al.*, 2014). The control house achieved ventilation using trickle vents, whereas the other two homes used MVHR systems. The PassivHaus dwelling used the Paul Novus MVHR system, whilst the maker claimed an efficiency rating of 93%, field calculations presented in the HIS report suggested that this figure was no higher than 85% (Jack *et al.*, 2013). The Gold house used a Nuaire MXMRXBOX95-WH1. Similarly, the manufacturer claimed an efficiency rate of 91%, whereas the field tests indicated 81% (Jack *et al.*, 2013).

At the time of this study, an ongoing investigation was being carried out by Edinburgh Napier University (ENU) into how dwellings' energy performance has changed over the years. As part of ENU's study, the author collaborated in some airtightness tests, including those used in this study. This was the only information shared between both studies, as the research questions were different. ENU's studies of these homes provided an invaluable source of information about the fabric performance, building specifications and building layouts in this study. Special effort was made to reference the sources correctly when explaining household characteristics. IAQ monitoring and online surveys were carried out independently from ENU's studies and were the primary research aim of this study.

7.3 Methods

The monitoring of the three homes started the 15th January 2017, but as explained in Chapter 4, data from the first two weeks were discarded to allow Foobot an "e-learning period" and to reduce the impact of the Hawthorne effect. Therefore, the information discussed in this chapter corresponds to data between 1st February 2017 to 15th August 2017 resulting in limited winter data. The Foobots were posted to the participants from Glasgow, with a printed guide and a welcome package. The online surveys were distributed to the participants in two forms, one by email and QR codes in the welcome packages.

Air temperature, relative humidity, $PM_{2.5}$ and tVOC levels were collected simultaneously in the living rooms, kitchens and main bedrooms of the dwellings, using the protocol described in Chapter 4 and analysed as described in Chapter 3. Ambient $PM_{2.5}$ concentrations were obtained from Air Quality in Scotland (http://www.scottishairquality.co.uk/), and temperature and relative humidity came from the Met Office (https://www.metoffice.gov.uk/). A site visit was arranged to perform airtightness tests, conducted before IAQ data collection, between November and December 2016, when introductions took place.

7.4 Household characteristics

The houses faced south and have parking on site but no garage (Figure 7.2 and Figure 7.3). SC-CO and SC-PH were three-bedroom houses, while the SC-GD was a two-bedroom house. They were semi-detached dwellings built with a closed panel timber frame and with a similar configuration. The ground floor accommodated the living room, kitchen, shower and utility rooms, while the first floor the bedrooms and a toilet (Figure 7.4).

The control house (SC-CO) was designed and built using SAP version 9.90 (SAP2009) to meet the 2010 Scottish Building Standards. Adjacent was the second house, designed to the PassivHaus standard (SC-PH), and next to them was the third property, designed to meet the Gold Standard (SC-GD) set by the Scottish Building Standards Section 7 Sustainability.

The SC-PH external walls have to the inside 12.5 mm plasterboard, 25 mm internal service battens, 25 mm polyurethane board, an airtight/vapour control layer (VCL), 10 mm OSB, 235 mm injected polyurethane insulation, 235 x 38 mm treated timber panelling, 10 mm OSB, and a layer of reflectashield TF insulating barrier. The attic roof to the inside has 12.5 mm plasterboard (ceiling - supported by treated timber), 350 mm mineral wool insulation (between the over rafters), 50 mm gap of proprietary eaves vent tray, 10 mm OSB, concrete roof tiles (25 x 50 mm sw tiling battens, 18 x 25 mm counter battens, proctor roof shield roofing membrane, proprietary roof cassette). The ground flooring to the indoor has 22 mm V313 chipboard on 70 x 50 mm treated timber battens @ 400 mm with 45 mm rigid insulation between 150 mm of rigid insulation on VCL, on a concrete slab and 25 mm of sand blinding.

The SC-GD external walls have to the inside 12.5 mm wallboard, 25 mm batten/service zone, VCL, 11 mm OSB, 45 x 45 mm stud filled with insulation, 65 mm insulation, 90 x 45 mm stud insulation, 9 mm OSB, thermo reflective breather membrane, 50 mm cavity, 102.5 common brick, 19 mm render coat. The attic roof has to the inside 12.5 wallboard, VCL, 3 x 90 mm insulation, 22 mm P5 chipboard, attic frame, 15 mm OSB, roof membrane, 25 x 50 mm treated counter battens, 25 x 38 mm treated battens, fibre cement tiles. The ground flooring has to the inside 22 mm chipboard, 70 mm treated batten service zone, 100 mm perimeter insulation, 150 mm RC in-situ ground bearing slab, 100 mm rigid insulation, 25 mm sand blinding.

The SC-CO external walls have to the inside 12.5 mm plasterboard, a VCL, 140 mm timber frame panels with insulation between studs, 10 mm OSB sheathing, a reflective breather membrane, 50 mm vertical treated timber battens @ 600 mm and 5 mm of proprietary render system. The attic roof to the inside has 12.5 mm plasterboard (ceiling - supported by treated timber), 350 mm mineral wool insulation (between the over rafters), 50 mm gap of proprietary eaves vent tray, 10 mm OSB, concrete roof tiles (25 x 50 mm sw tiling battens, 18 x 25 mm counter battens, type 1f roof felt, 15 mm OSB sheathing). The ground flooring to the indoor has 22 mm V313 chipboard on 70 x 50 mm treated timber battens @ 400 mm with 20 mm service void, concrete slab, 100 mm rigid insulation, 25 mm sand blinding. Table 7.1 shows the building characteristics summary of the three dwellings, as described in Jack et al. (2013) and Bros-Williamson et al. (2016).

Figure 7.2 Housing Innovation Showcase masterplan. The dwellings' locations are marked in red. Source: Google Maps (accesses November 2018).

Figure 7.3 Front façade of the SC-GD (left), SC-PH (centre) and SC-CO (right). Images taken from Jack et al. (2013).

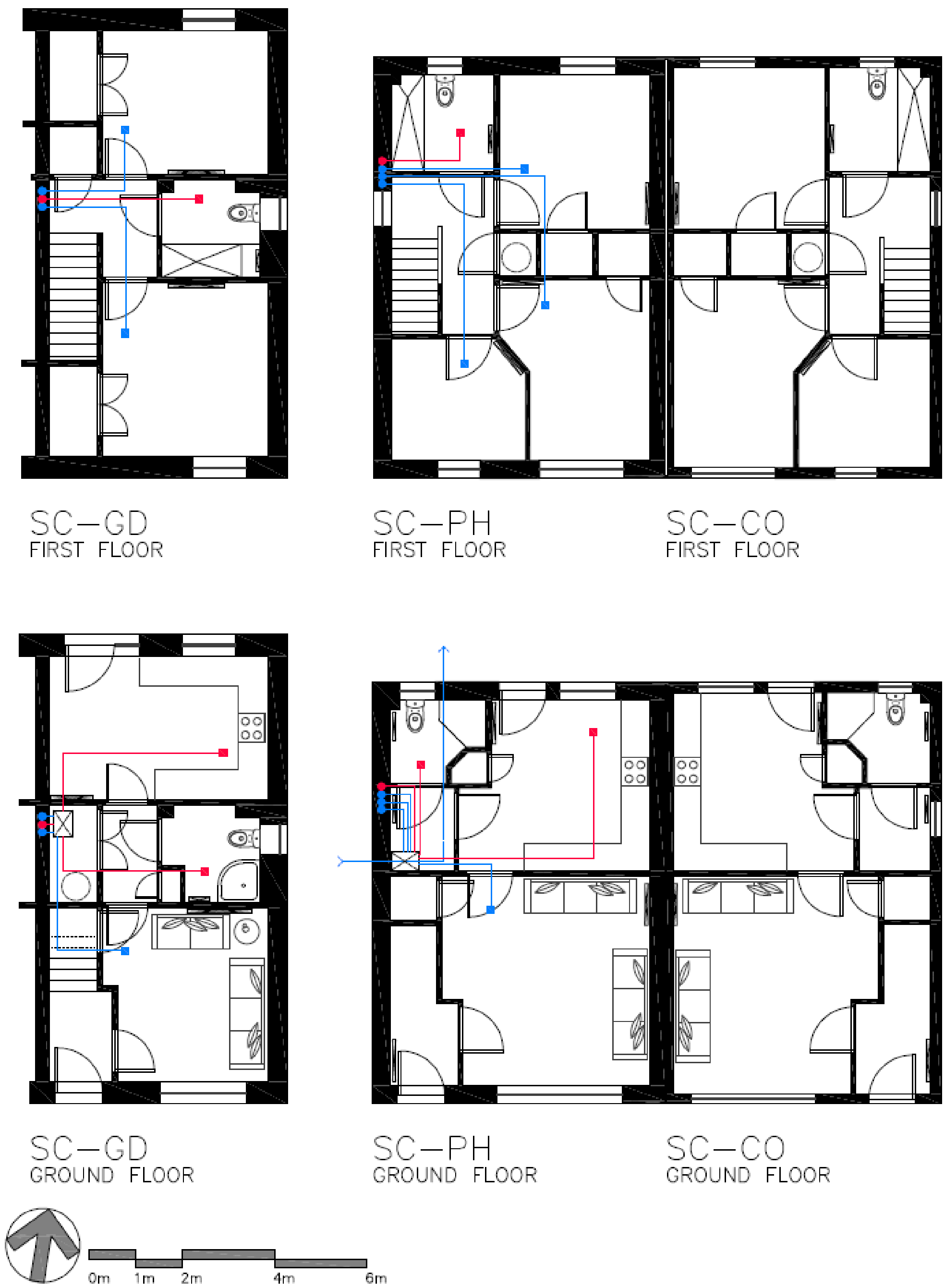


Figure 7.4 Floor plans for SC-PH, SC-GD and SC-CO. Ground floor plans for SC-PH (left-bottom), ground floor MX-CO (right-bottom), first floor.

The SC-CO achieved natural ventilation using trickle vents and an extractor fan in the bathroom and kitchen. Trickle vents were located in the top of the windows and manually operated by the occupants, but they always had them closed. Purge ventilation was possible when opening the windows. SC-PH and SC-GD relied on the MVHR system to provide ventilation and window opening when the air inside of the house was stuffy, thereby acting as purge ventilation. SC-PH occupants stated that they were not satisfied with the MVHR system: “*We think that it is a* *good system, but it seems that is not working properly, as some of the vents pass more air than others".* SC-GD occupants stated, "*We feel healthier, and the MVHR might be a cause of it*" and "*I feel happy to have a warm and secure home*".

Table 7.1 Building characteristics of SC-PH, SC-GD and SC-CO.

Building characteristic	**SC-PH**	**SC-GD**	**SC-CO**
Airtightness as-designed @50Pa	0.60 $m^3/h*m^3$	3.00 $m^3/h*m^3$	5.00 $m^3/h*m^3$
Airtightness as-built @ 50Pa	0.53 $m^3/h*m^3$	3.90 $m^3/h*m^3$	3.60 $m^3/h*m^3$
Floor area	94 m^2	96 m^2	96 m^2
U_g-value (window)	0.8 W/(m^2K)	0.8 W/(m^2K)	0.8 W/(m^2K)
U-value (floor slab)	0.15 W/(m^2K)	0.15 W/(m^2K)	0.15 W/(m^2K)
U-value (roof)	0.10 W/(m^2K)	0.09 W/(m^2K)	0.10 W/(m^2K)
U-value (external wall)	0.10 W/(m^2K)	0.15 W/(m^2K)	0.23 W/(m^2K)
Ventilation	Mechanical with MVHR	Mechanical with MVHR	Natural with window trickle vents, extract fans
Window type	Triple glazing, low-e, uPVC		
Building Standard	PassivHaus (certified)	GOLD Standard 2016 SBS	2010 SBS
Contractor	Campion Homes	Springfield Properties	Campion Homes

The houses were occupied by families that had been living in the properties for four to five years, as stated in the building information surveys. Household occupancy was four persons in the SC-CO and SC-PH, and two persons in the SC-GD (Table 7.2). None of the participants smoked. On average, the SC-CO and SC-PH dwellings were occupied 20 hours a day during the week (usually not occupied between 13:00 to 16:00). The SC-GD was 14 hours on average during the weekdays as occupants left the house around 08:00 and came back just after 17:00 and 12 hours during weekends when they usually left at 10:00 and came back at 21:00.

Table 7.2 Households profiles.

Household profile	**SC-PH**	**SC-GD**	**SC-CO**
No. occupants	4 adults	2 adults	2 adults, 2 child
Cooking fuel	Electricity	Electricity	Gas
Heating fuel	Gas	Electricity	Gas
No. smokers indoors	0	0	0
No. smokers outdoors	0	0	0
Average of occupied hours during weekdays	20	14	20
Average of occupied hours during weekend days	20	12	20

7.5 Results

7.5.1 Ventilation and heating

SC-PH and SC-GD dwellings relied on MVHR systemsand SC-CO on natural ventilation as main ventilation strategies. SC-PH occupants stated that they were not satisfied with the MVHR system, in contrast to SC-GD occupants' perception. However, they did not state the level of satisfaction towards the MVHR system. SC-CO occupants did not have any issues with ventilation. KHA advised the occupants on how to operate the MVHR system before this study and filter replacement in the MVHR was performed before the study accordingly to scheduled work. Occupants in both MVHR dwellings stated that they had not had to change the flow rates since taking up residence. Occupants in the SC-PH used the ventilation boost rarely and stated only to use it when cooking. SC-GD occupants used it constantly, especially during and after cooking, as well as after showering. The three households stated using the cooking hood constantly or regularly during cooking, but rarely or never thereafter. Cooking hoods recirculate the air filtering suspended particles without removing humidity or heat. One of the SF-GD occupants stated that the kitchen hood was noisy while on after cooking and moreover felt that its use after cooking was not important, as the pollution event had passed.

Occupants stated that the filters from the MVHR system were well maintained, corresponding with the findings of previous ENU studies (Jack *et al.*, 2013). They were also asked if they had ever had other problems with the ventilation system (such as noise, thermal comfort, draughts or others). Despite the comments on the MVHR system from the SC-PH occupants, they said they had not suffered from noise and were happy with the ventilation. The SC-PH residents believed that air quality in their homes was better than their previous house and that the MVHR system had a positive health impact. Comments included: "*You get constant fresh air, so you are bound to feel healthier! My son used to suffer from a blocked nose, but not anymore*". Both households, SC-PH and SC-GD, felt healthier after they moved in.

Some of the occupants were more sensitive to draughts than others. For instance, an occupant in SC-PH stated to need to close the door from the living room to the hall, as they could feel some draughts coming in. Neither occupant in SC-GD was bothered by draughts. SC-PH also had problems with thermal comfort: "*There are times when the bedrooms are too hot – and that causes discomfort while sleeping*", which may suggest overheating problems.

Window opening patterns during summer and winter are illustrated in Figure 7.5. SC-PH occupants explained that it was too warm indoors and therefore they needed to open the windows regularly and leave them open during the night, to aid sleep. The window opening pattern of SC-CO shows that the house was likely to be too warm during the afternoon, while this applied to the evening for SC-GD.

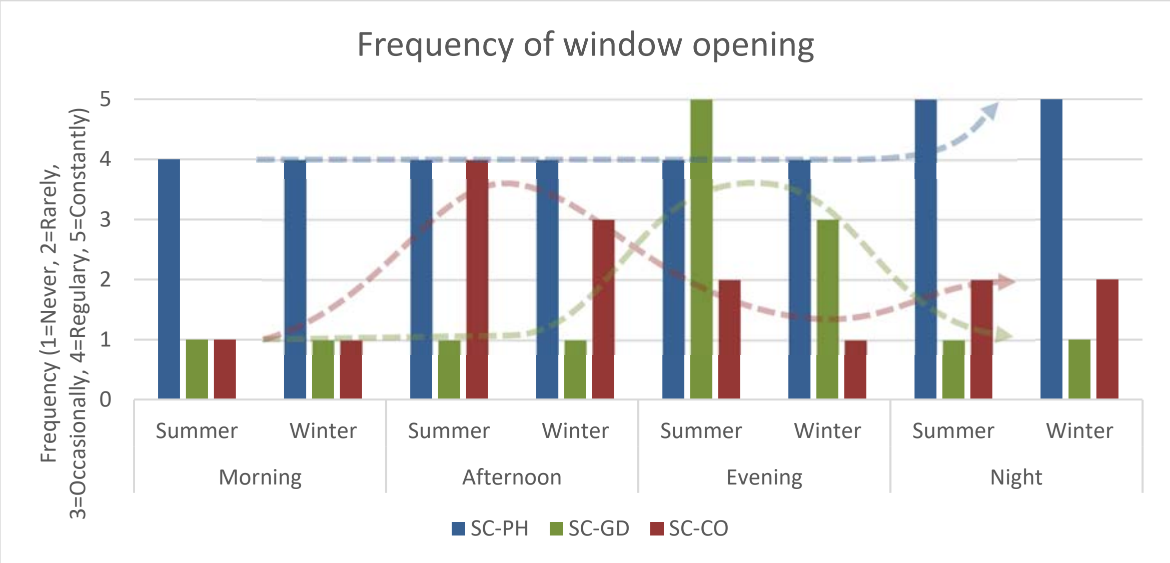


Figure 7.5 Reported frequency of window opening during summer and winter.

All homes had the option to be heated by radiators in the monitored rooms and bathrooms, controlled by a thermostat located in the living room. Table 7.3 illustrates the reported heating schedule for each season. While the SC-CO and SC-GD used the heating, SC-PH occupants stated that the MVHR system was enough, but occupants were content to have radiators in case they needed them. Thermostat temperatures varied from house to house. For instance, SC-CO occupants reported setting the thermostat to 25°C, SC-GD from 20-24°C and SC-PH stated not using any heating, so they did not set any temperature on the thermostat.

Table 7.3 Heating schedules for SC-PH, SC-GD and SC-CO.

Heating Schedule	SC-PH	SC-GD	SC-CO
Spring	---	17:00-20:00	08:00-09:00, 16:00-18:00
Summer	---	---	08:00-09:00, 16:00-18:00
Autumn	---	17:00-20:00	08:00-09:00, 16:00-18:00
Winter	---	17:00-20:00	08:00-10:00, 15:00-19:00

Households were asked about the levels of satisfaction of the heating operation. SC-GD occupants were neither satisfied nor dissatisfied with instructions on how to operate the central heating programmer, and they would like to have more training to understand the system and therefore take control of their indoor environment. SC-CO and SC-PH occupants did not have any problems controlling their heating and mentioned operating the central heating programmer. These findings converge with those from ENU (Jack *et al.*, 2013).

7.5.2 Hygrothermal conditions

A summary of the statistical analyses of temperature, relative humidity and moisture content in the three dwellings is presented in Table 7.4.

7.5.2.1 Temperature

As observed in Table 7.5, problems with cold temperatures were identified in the kitchen and living room of SC-GD and overheating was observed in SC-PH – especially in the bedroom. Air temperatures in SC-CO's living room were above the PassivHaus, CIBSE A and Adaptive thresholds, thereby suggesting problems with overheating.

7.5.2.2 Overheating and cold temperatures

Air temperatures associated to overheating were observed in all dwellings. The most affected room was the living room in SC-CO, as a higher risk of overheating was observed for all seasons. This suggests that occupants may misuse the heating system or prefer warmer temperatures, leading to overheating. The SC-PH dwelling also experienced overheatingin the bedroom and kitchen . SC-GD exhibited the higher frequency of low air temperatures.

In Scotland, temperatures below 18°C have been related to high blood pressure (Shiue and Shiue, 2014). Air temperatures below 18°C were measured in the kitchen and living room of SC-GD. Air temperatures below 21°C, the ideal recommended temperature in the UK (PHE, 2014), were also measured in all homes as illustrated in Figure 7.6. The occurrence of air temperatures between 21°C to 25°C were more frequent in the SC-PH dwelling than in SC-GD and SC-CO. The bedrooms were the most comfortable rooms in all dwellings.

Table 7.4 Statistical analysis of temperature, relative humidity and absolute humidity for SC-CO, SC-*GD and SC-PH.

House	Parameter	Statistical analysis	Winter			Spring			Summer			All		
			Bedroom	Kitchen	Living room	Bedroom	Kitchen	Living room	Bedroom	Kitchen	Living room	Bedroom	Kitchen	Living room
SC-CO	Temperature	Min	16.0	16.1	16.2	13.2	16.8	15.6	18.0	18.4	18.3	13.2	16.1	15.6
		Max	23.2	26.0	33.4	26.8	26.5	33.5	26.2	27.1	32.7	26.8	27.1	33.5
		Mean	20.3	21.6	24.7	21.4	21.8	24.7	22.4	22.5	26.3	21.7	22.0	25.3
		SD	1.4	1.9	2.5	1.4	1.6	2.8	1.3	1.3	2.2	1.5	1.6	2.6
	Relative Humidity	Min	42.7	33.0	27.3	37.6	33.0	24.7	44.5	40.1	32.1	37.6	33.0	24.7
		Max	60.5	61.1	55.2	64.3	65.1	63.8	71.0	73.1	60.0	71.0	73.1	63.8
		Mean	51.8	46.5	43.0	49.9	46.5	42.8	55.2	54.1	47.0	52.3	49.4	44.5
		SD	2.8	3.9	3.7	3.5	4.3	6.5	3.5	3.9	4.4	4.2	5.5	5.8
	Absolute Humidity	Min	6.6	5.7	6.2	5.9	5.6	6.3	8.5	8.0	8.4	5.9	5.6	6.2
		Max	11.6	13.2	13.9	13.9	14.2	14.8	15.4	17.1	16.4	15.4	17.1	16.4
		Mean	9.2	8.9	9.8	9.4	9.0	9.7	11.0	10.8	11.7	10.0	9.7	10.5
		SD	1.0	1.3	1.3	1.2	1.4	1.3	1.2	1.1	1.2	1.4	1.6	1.6
SC-GD	Temperature	Min	17.4	9.3	15.8	16.0	11.4	16.0	18.8	14.3	18.4	16.0	9.3	15.8
		Max	22.8	24.4	19.8	24.8	27.1	21.9	24.6	27.4	22.2	24.8	27.4	22.2
		Mean	21.3	19.9	18.1	21.3	20.3	18.9	21.8	21.4	20.1	21.5	20.7	19.3
		SD	0.8	2.4	0.7	1.1	2.4	0.9	0.8	2.4	0.6	1.0	2.5	1.0
	Relative Humidity	Min	38.0	34.3	41.6	35.4	27.7	37.0	40.9	37.3	44.9	35.4	27.7	37.0
		Max	52.5	58.9	61.1	61.1	69.8	67.0	64.8	70.7	68.3	64.8	70.7	68.3
		Mean	45.0	45.7	51.5	45.5	46.9	50.8	53.4	54.4	57.7	48.5	49.7	53.6
		SD	2.5	2.9	3.3	4.4	5.7	4.7	3.2	5.6	3.4	5.4	6.6	5.2
	Absolute Humidity	Min	6.3	4.3	6.1	5.9	4.2	5.9	7.0	6.8	7.4	5.9	4.2	5.9
		Max	10.5	11.9	10.2	13.0	13.5	12.5	13.0	14.1	12.5	13.0	14.1	12.5
		Mean	8.4	7.9	8.0	8.5	8.3	8.3	10.3	10.2	10.0	9.2	9.0	8.9
		SD	0.7	1.2	0.7	1.1	1.5	1.1	0.9	1.2	0.8	1.3	1.6	1.3
SC-PH	Temperature	Min	18.1	19.8	17.9	18.2	19.3	17.6	17.7	22.6	19.3	17.7	19.3	17.6
		Max	25.8	28.3	25.0	28.6	29.1	27.5	26.7	28.3	26.1	28.6	29.1	27.5
		Mean	22.1	23.2	21.0	22.4	23.5	21.5	22.1	25.2	22.7	22.2	24.1	21.9
		SD	1.1	1.3	1.2	1.5	1.5	1.4	1.4	1.0	1.3	1.4	1.6	1.5
	Relative Humidity	Min	33.4	33.7	36.4	30.7	28.9	33.0	38.8	38.0	43.4	30.7	28.9	33.0
		Max	54.6	58.7	62.6	63.6	62.8	65.7	68.8	63.6	67.4	68.8	63.6	67.4
		Mean	41.9	40.5	43.6	42.9	41.3	44.6	52.9	46.1	52.9	46.7	43.1	47.7
		SD	3.2	3.4	3.8	5.1	3.9	4.8	4.0	3.2	3.3	6.7	4.4	5.9
	Absolute Humidity	Min	6.6	6.4	6.1	6.1	5.3	5.7	7.3	8.3	8.3	6.1	5.3	5.7
		Max	9.9	14.9	12.1	14.4	16.4	16.1	14.1	16.4	15.7	14.4	16.4	16.1
		Mean	8.2	8.4	8.0	8.6	8.8	8.5	10.3	10.8	10.7	9.2	9.5	9.3
		SD	0.7	1.1	0.9	1.2	1.4	1.4	1.1	1.2	1.1	1.4	1.6	1.7

Table 7.5 Overheating and freezing analysis.

Room	Criterion	SC-CO				SC-GD				SC-PH			
		Winter	Spring	Summer	All	Winter	Spring	Summer	All	Winter	Spring	Summer	All
Bedroom	PassivHaus												
	CIBSE A			•	•			•		•	•	•	•
	CIBSE B	•	•	•	•						•	•	•
	Adaptive approach Criterion 1	N/A	N/A			N/A	N/A			N/A	N/A	•	•
	Adaptive approach Criterion 2									•	•		•
	Adaptive approach Criterion 3	•	•	•	•	•		•	•	•		•	•
	18°C to 21°C <10% of winter	x	x	N/A	X	x	x	N/A	X	x	x	N/A	X
	<18°C <10% of winter			N/A				N/A				N/A	
Kitchen	PassivHaus			•							•	•	•
	CIBSE A			•	•					•	•	•	•
	CIBSE B			•	•							•	•
	Adaptive approach Criterion 1	N/A	N/A	•	•	N/A	N/A			N/A	N/A	•	•
	Adaptive approach Criterion 2									•			•
	Adaptive approach Criterion 3	•		•	•			•	•	•		•	•
	18°C to 21°C <10% of winter	x	x	N/A	X	x	x	N/A	X			N/A	
	<18°C <10% of winter			N/A		x	x	N/A	X			N/A	
Living room	PassivHaus	•	•	•	•								
	CIBSE A	•	•	•	•								
	CIBSE B	•		•	•		•					•	
	Adaptive approach Criterion 1	N/A	N/A	•	•	N/A	N/A			N/A	N/A	•	•
	Adaptive approach Criterion 2	•	•	•	•								
	Adaptive approach Criterion 3	•	•	•	•		•	•	•	•		•	•
	18°C to 21°C <10% of winter			N/A		x	x	N/A	X	x	x	N/A	X
	<18°C <10% of winter			N/A		x	x	N/A	X			N/A	

Daily temperature variation analysis shows that the temperatures in SC-PH were more estable with less variations between rooms (mean daily variations 2.75°C (bedroom), 2.68°C (kitchen), 2.86°C (living-room)), whereas variations between the rooms in SC-CO were higher (mean daily variations 2.11°C (bedroom), 3.57°C (kitchen), 8.21°C (living-room),, Table 7.6). Higher variations were observed in the living room in SC-CO during the three seasons, and the lowest variation was in the living room in SC-GD over the same time period. Whereas the SC-PH dwelling may not have had lower variations in a single room, variation between the rooms was very similar (Figure 7.7), which suggests that the MVHR system was effective in providing a desired stable temperature throughout the whole house, as stated in the PassivHaus principles.

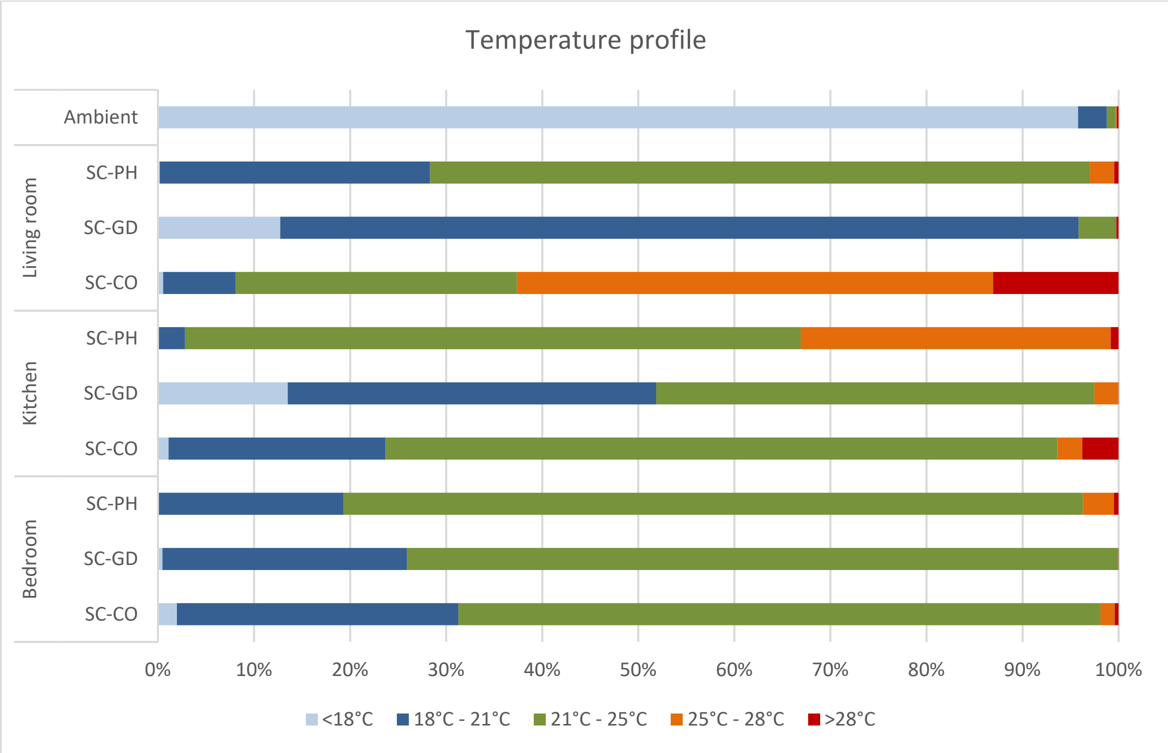


Figure 7.6 Annual thermal profile of SC-CO, SC-GD and SC-PH.

The statistical analysis showed that there was a statistical difference ($p<.001$) in the medians between bedroom-bedroom, kitchen-kitchen and living-living of all the homes. However, it is believed that such differences may be related to occupant behaviours. Compared to SC-CO, the occurrences of temperatures between 21-25°C were 1.09 times more frequent in the SC-GD and 1.07 in SC-PH bedrooms, and SC-PH living room temperatures were 3.06 times more frequent. The occurrence of temperatures between 21 and 25°C were 0.76 times less frequent in SC-GD and 0.80 in SC-PH than those in the SC-CO kitchen, and 0.82 in SC-CO's living room.

Table 7.6 Seasonal daily variations in the Scottish case study. The blue background represents SC-CO, the orange SC-GD, the red SC-PH and the green ambient.

Season	Dwelling	Room	Daily variation mean (˚C)	Extreme daily variation (˚C)	
				Min	Max
Winter	SC-CO	Bedroom	2.55	1.38	4.56
		Kitchen	4.88	3.01	7.97
		Living room	8.30	4.97	12.14
	SC-GD	Bedroom	1.62	0.77	3.94
		Kitchen	6.93	2.12	12.80
		Living room	1.53	0.95	3.76
	SC-PH	Bedroom	2.55	1.16	7.21
		Kitchen	3.70	1.64	7.21
		Living room	3.31	1.60	5.77
		Ambient	4.55	1.60	9.70
Spring	SC-CO	Bedroom	2.40	0.63	10.40
		Kitchen	3.64	1.04	6.66
		Living room	8.37	2.60	14.22
	SC-GD	Bedroom	2.17	0.40	5.73
		Kitchen	6.66	1.10	14.19
		Living room	1.57	0.47	2.95
	SC-PH	Bedroom	2.79	0.89	5.57
		Kitchen	2.69	0.92	5.74
		Living room	2.79	1.10	5.44
		Ambient	7.52	2.10	16.40
Summer	SC-CO	Bedroom	1.59	0.47	5.75
		Kitchen	2.97	1.11	5.45
		Living room	7.98	5.37	12.67
	SC-GD	Bedroom	1.48	0.19	3.69
		Kitchen	5.22	0.47	10.77
		Living room	1.15	0.42	2.11
	SC-PH	Bedroom	2.78	1.15	5.18
		Kitchen	2.21	1.00	4.52
		Living room	2.79	1.35	4.38
		Ambient	6.88	2.00	15.10
All	SC-CO	Bedroom	2.11	0.47	10.40
		Kitchen	3.57	1.04	7.97
		Living room	8.21	2.60	14.22
	SC-GD	Bedroom	1.82	0.19	5.73
		Kitchen	6.14	0.47	14.19
		Living room	1.40	0.42	3.76
	SC-PH	Bedroom	2.75	0.89	5.60
		Kitchen	2.68	0.92	7.21
		Living room	2.86	1.10	5.77
		Ambient	6.85	1.60	16.40

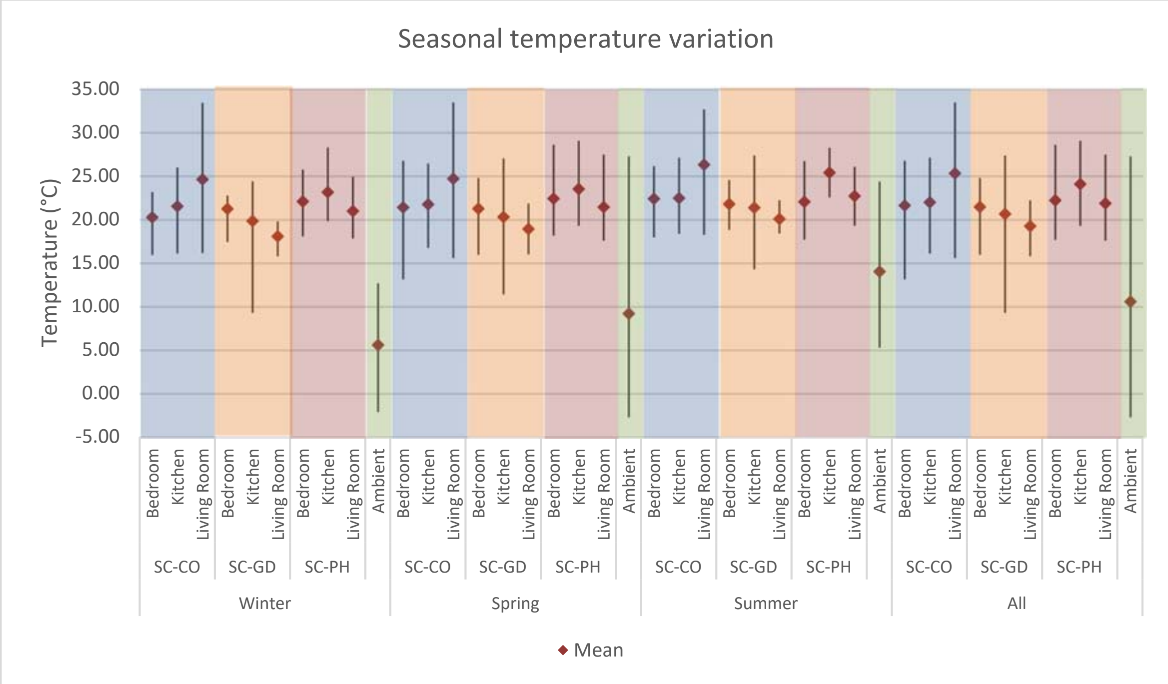


Figure 7.7 Seasonal variations in SC-CO, SC-GD, SC-PH and ambient temperatures. The blue background represents data from SC-CO, the orange from SC-GD, the red from SC-PH and the green from ambient.

7.5.2.3 Humidity

RH levels above the recommended 60%RH were measured in the three dwellings for less than 10% of the time, except for the SC-GD living room (11.2% of the time). A possible explanation could be related to one of the complaints of the occupants, in that the whole house was very dry and therefore they frequently placed bowls of water over the radiators in the living room. The kitchen had a higher occurrence of concentrations of RH levels above 60%RH in SC-CO (6.28% of the time) and SC-PH (7.92% of the time). The occurrence of RH levels between 40%RH and 60%RH was more frequent in SC-CO, followed by SC-GD and SC-PH, whereas levels below 40%RH were more frequent in SC-PH. Seasonal variations were also observed in the three homes, and RH below 40%RH were measured in each home during winter. A higher occurrence characterised relative humidity levels for summer above 60%RH in the three dwellings.

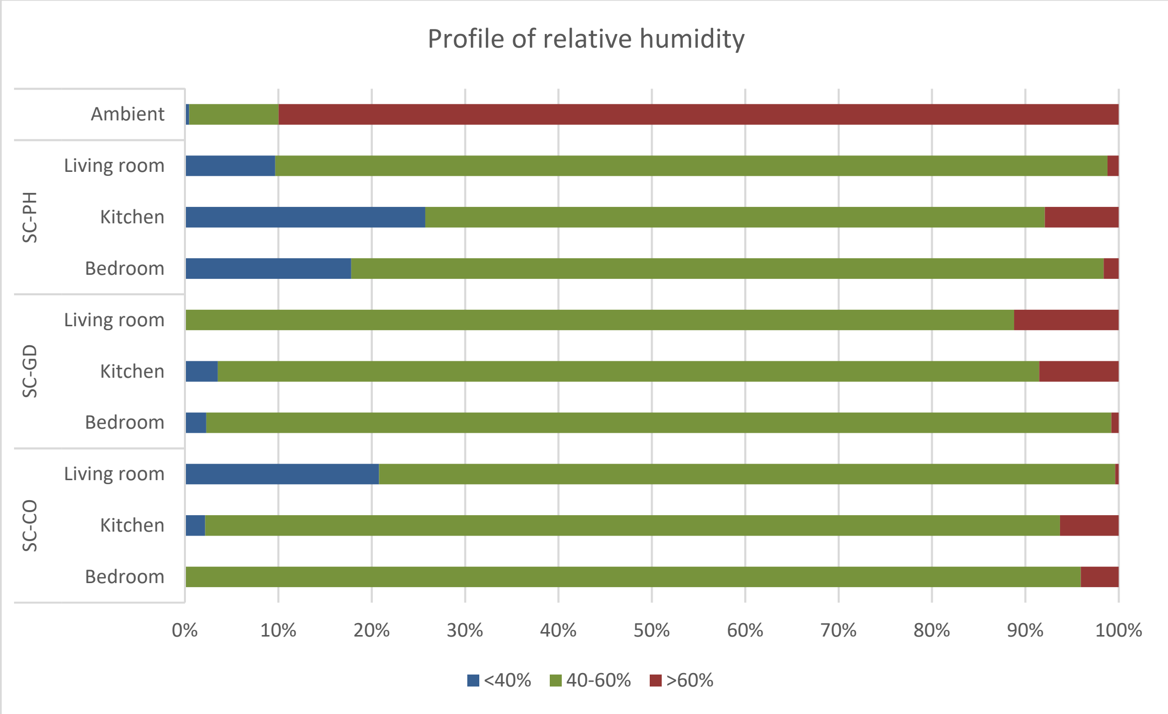


Figure 7.8 Profile of relative humidity levels in SC-CO, SC-GD and SC-PH.

Figure 7.8 compares RH range of each room in each house and ambient levels during the monitored period. RH levels between 40%RH and 60%RH were measured with a high frequency in the rooms with a few exceptions. The warm temperatures measured in the SC-CO living room and in the SC-PH, especially in the kitchen and bedroom could be a reason for a higher frequency of relative humidity levels below 40%RH. Nevertheless, vapour excess (indoor-ambient difference) showed that all rooms had a higher content of moisture than ambient concentrations. However, when comparing vapour pressure levels above 12g/kg, the SC-GD had less occurrence than the outdoors (Table 7.7). The psychrometric evaluation showed that summer levels were the most critical in the bedrooms (Figure 7.9) and living rooms (Figure 7.10) as they have the higher occurrence of warm and humid conditions, whereas bedroom winter were the most comfortable (Figure 7.11).

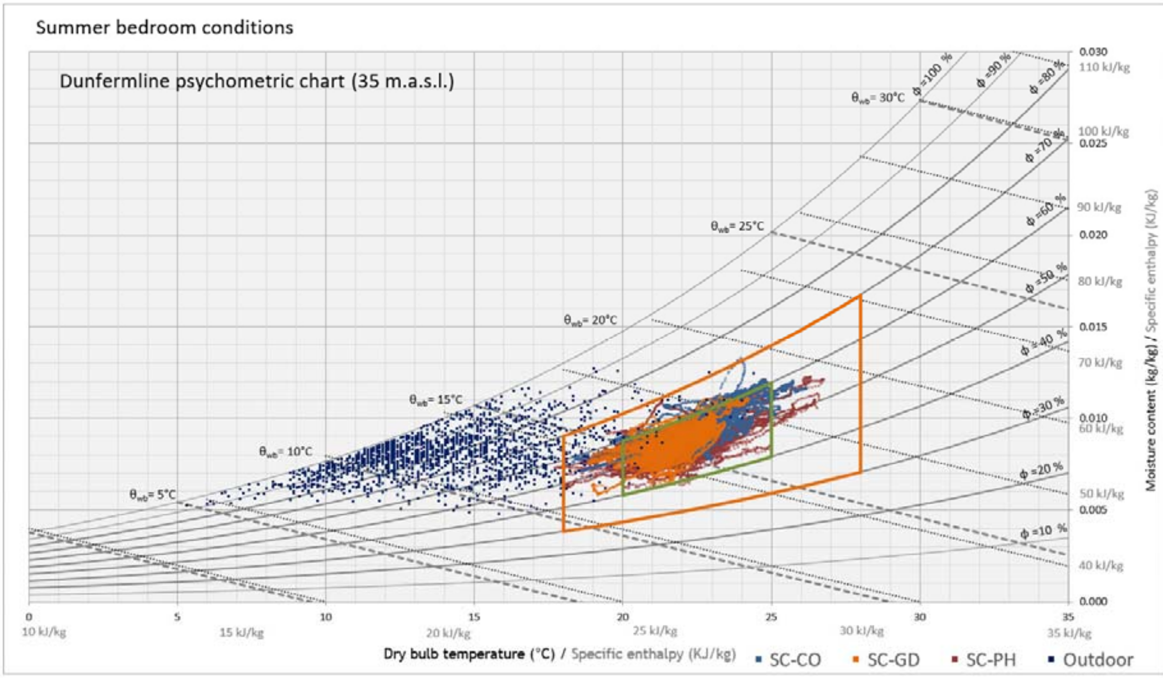


Figure 7.9 Summer bedroom psychrometric evaluation of the conditions indoors. The green rectangle delimitates the ideal range and the orange the extended range.

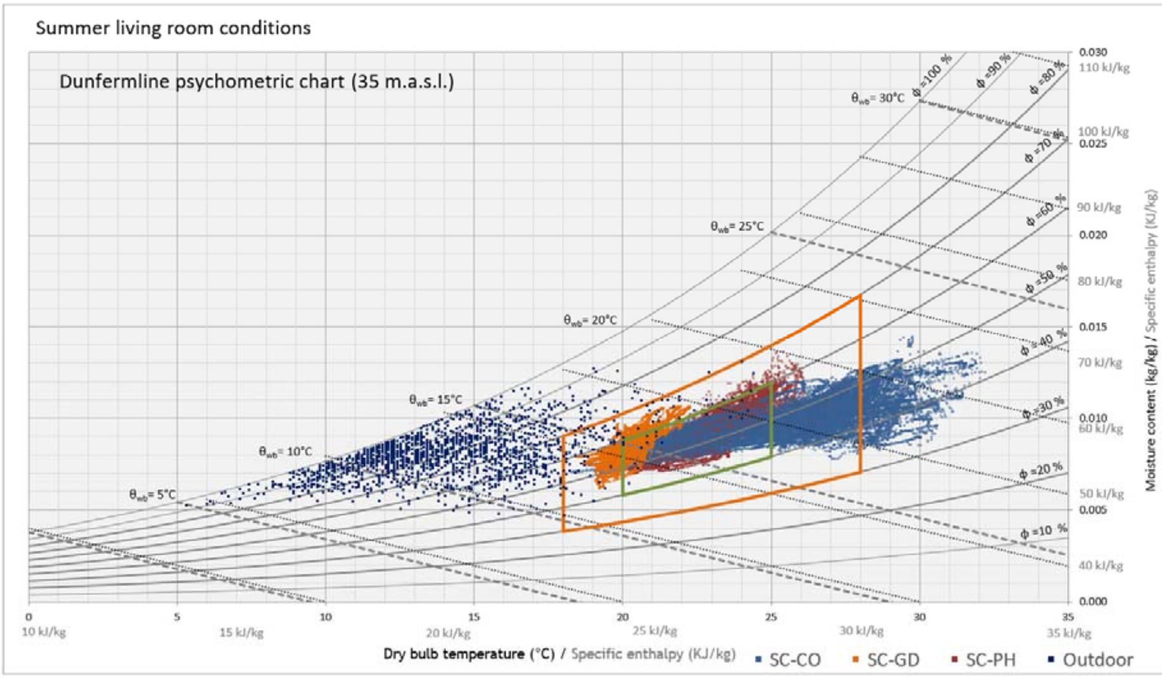


Figure 7.10 Summer living room psychrometric evaluation of the conditions indoors. The green rectangle delimitates the ideal range and the orange the extended range.

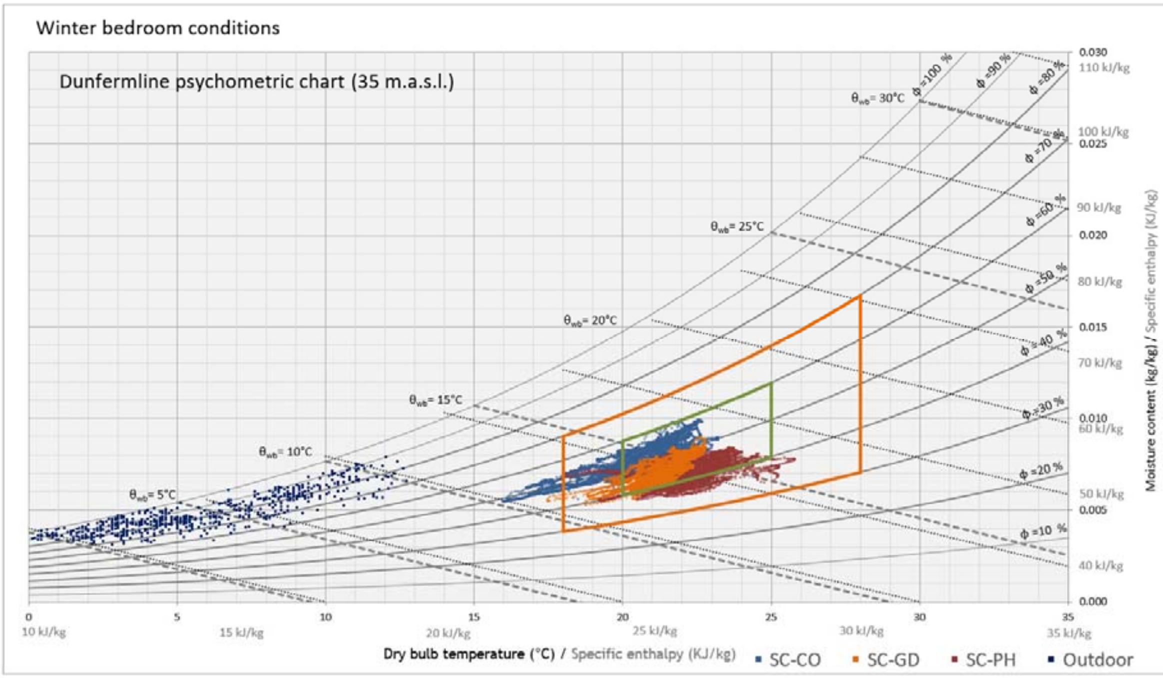


Figure 7.11 Winter bedroom psychrometric evaluation of the conditions indoors. The green rectangle delimitates the ideal range and the orange the extended range.

Table 7.7 Vapour excess measurements. A positive vapour excess shows that the indoor concentration was higher than the ambient, whereas the negative value indicates that it was lower than the ambient.

		Winter			Spring			Summer			All		
		Vapour excess (%)		>12 g/kg only occupied hours (%)	Vapour excess (%)		>12 g/kg only occupied hours (%)	Vapour excess (%)		>12 g/kg only occupied hours (%)	Vapour excess (%)		>12 g/kg only occupied hours (%)
		>7 g/kg	>12 g/kg		>7 g/kg	>12 g/kg		>7 g/kg	>12 g/kg		>7 g/kg	>12 g/kg	
SC-CO	Bedroom	75.0	2.3	1.2	59.3	2.4	4.0	2.6	13.8	27.5	39.5	6.8	12.8
	Kitchen	68.3	2.5	5.6	55.1	2.5	4.2	2.6	16.6	23.5	36.6	8.0	11.9
	Living room	74.5	4.9	3.5	59.3	2.8	4.8	2.6	30.8	40.9	39.4	14.0	18.7
SC-GD	Bedroom	74.4	0.0	0.1	55.3	0.5	2.2	2.6	-4.4	3.8	37.5	-1.5	2.6
	Kitchen	57.6	0.0	0.0	44.1	1.1	2.9	2.6	-0.4	8.9	29.8	0.4	4.8
	Living room	68.0	0.0	0.0	60.2	98.4	100	2.6	-5.6	3.5	34.9	-2.2	2.4
SC-PH	Bedroom	72.1	0.1	0.1	55.0	1.4	2.9	2.6	0.4	7.7	37.0	0.8	4.4
	Kitchen	70.5	0.6	1.7	55.3	2.7	5.4	2.6	27.0	40.7	37.0	11.9	18.6
	Living room	63.7	0.1	0.0	50.3	2.0	3.2	2.6	7.3	14.1	33.6	3.8	7.0

Examination of humidity, as defined by the PassivHaus standard of 12g/kg over 20% of the occupied time, showed that this threshold was not exceeded in any of the homes. The analysis of the vapour pressure identified levels of concern regarding the threshold levels for dust mite control (7g/kg) since levels above 7g/kg were measured for more than 89% of the time in all dwellings. Levels exceeded the recommended 7g/kg in SC-CO during 96.51% (kitchen), 99.37%

(living-room) and 99.42% (bedroom) of the time, and in SC-GD this was 89.79% (kitchen), 97.86% (living-room) and 97.45% (bedroom) of the time and in SC-PH during 93.59% (living-room), 96.91% (kitchen) and 96.98% (bedroom) of the time. The low occurrence of relative humidity above 60%RH masked the moisture content as a result of higher indoor temperatures in SC-CO, as vapour pressure above 7g/kg had a higher occurrence in this home.

Different studies have assessed the prevalence and proliferation of different species of house dust mite in Scotland (Colloff, 1987), especially in beds (Seasay and Dobson, 1972). For instance, Colloff (1987) looked at a sample of 23 homes, in which he found the presence of *Dp* as well as a small mixed population of *Euroglymphus maynei* and *Df.* Similar results were found by Seasay & Dobson (1972), who studied 60 beds in Glasgow and Edinburgh and found *Dp* and *Df* populations. A literature review of house dust mites in the built environment (Crowther *et al.*, 2000) supports their findings. Therefore, it was decided to assess the proliferation of *Dp* and *Df* with the use of CEH for house dust mite populations (de Boer and Kuller, 1997). The CEH for *Df* was assessed as suggested by Cunningham (1996), Arlian (1981) and Arlian (1992), and for *Dp* as suggested by de Boer & Kuller (1997) and Ucci et al. (2011). The population equilibrium humidity (PEH) was also used to evaluate the *Dp* population (Crowther *et al.*, 2006). The PEH and CEH were plotted for all seasons. The CEH and PEH for *Df* and *Dp* were exceeded during summer, while winter conditions were more favourable (Figure 7.12 to Figure 7.15).

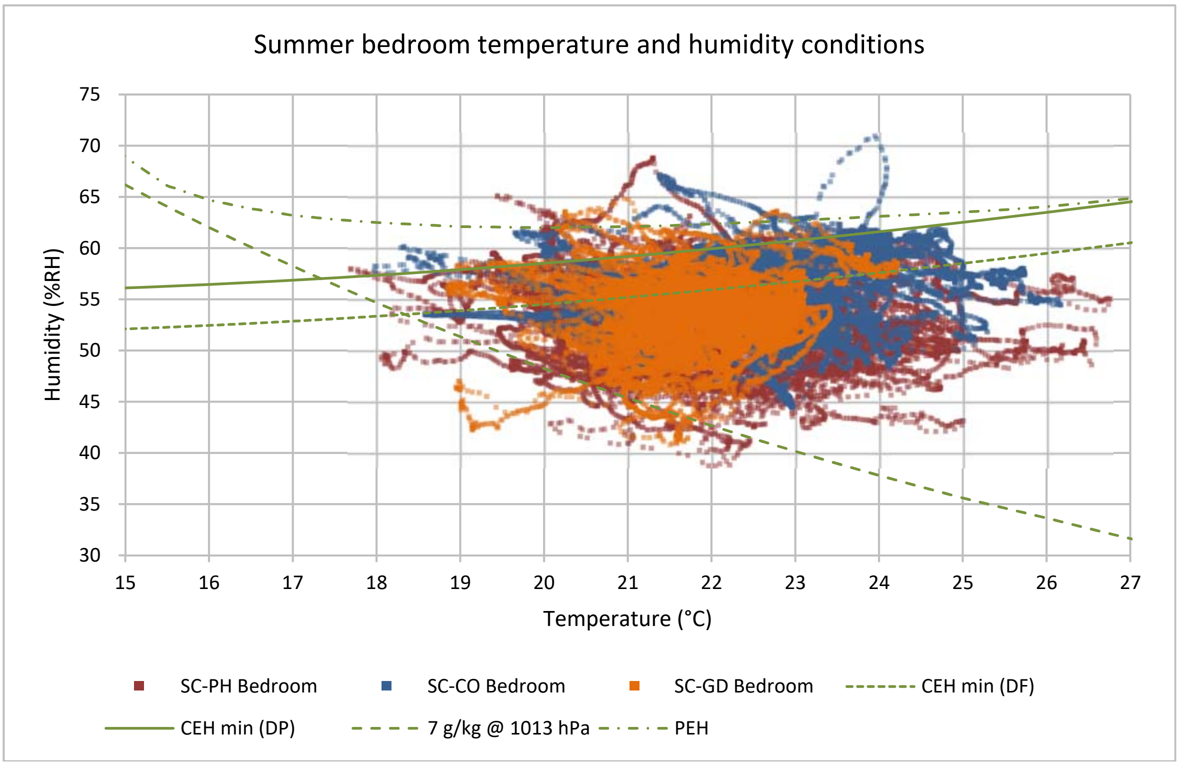


Figure 7.12 Summer bedroom temperature and humidity conditions. The figure shows the analysis of the dust mites population threshold conditions according to the CEH *Df* and *Dp*.

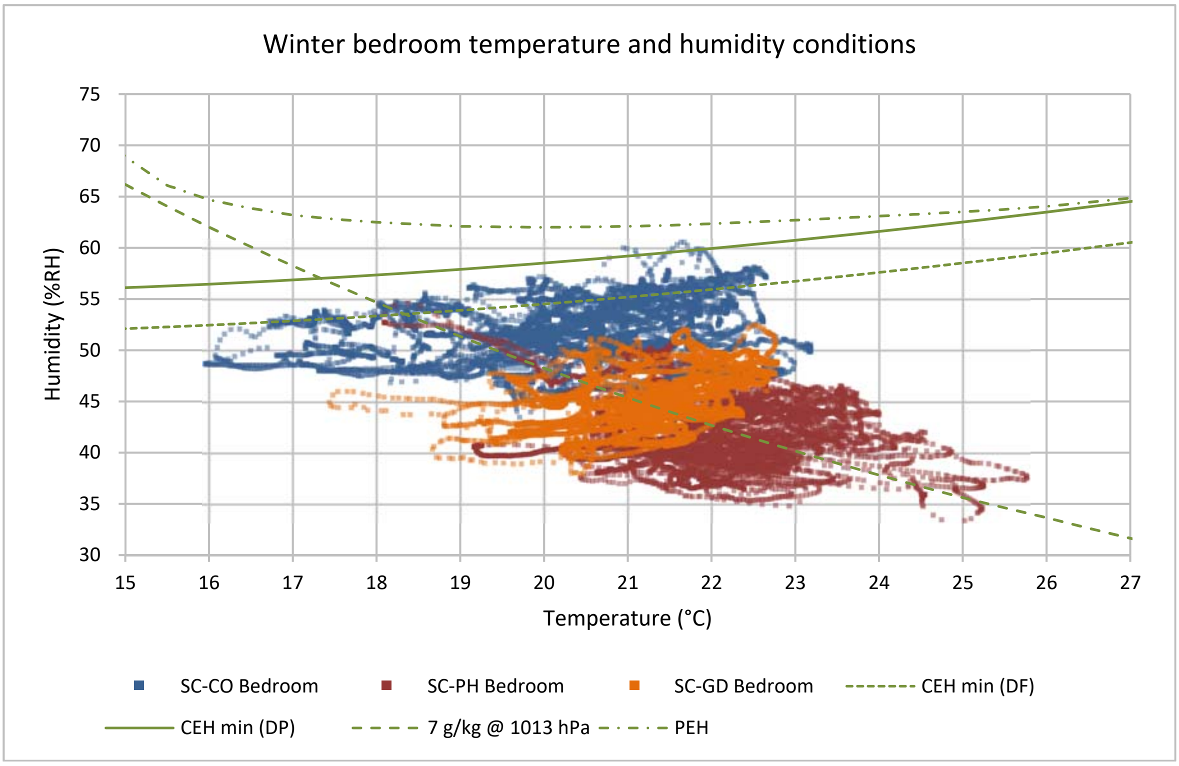


Figure 7.13 Winter bedroom temperature and humidity conditions. The figure shows the analysis of the dust mites population threshold conditions according to the CEH *Df* and *Dp*.

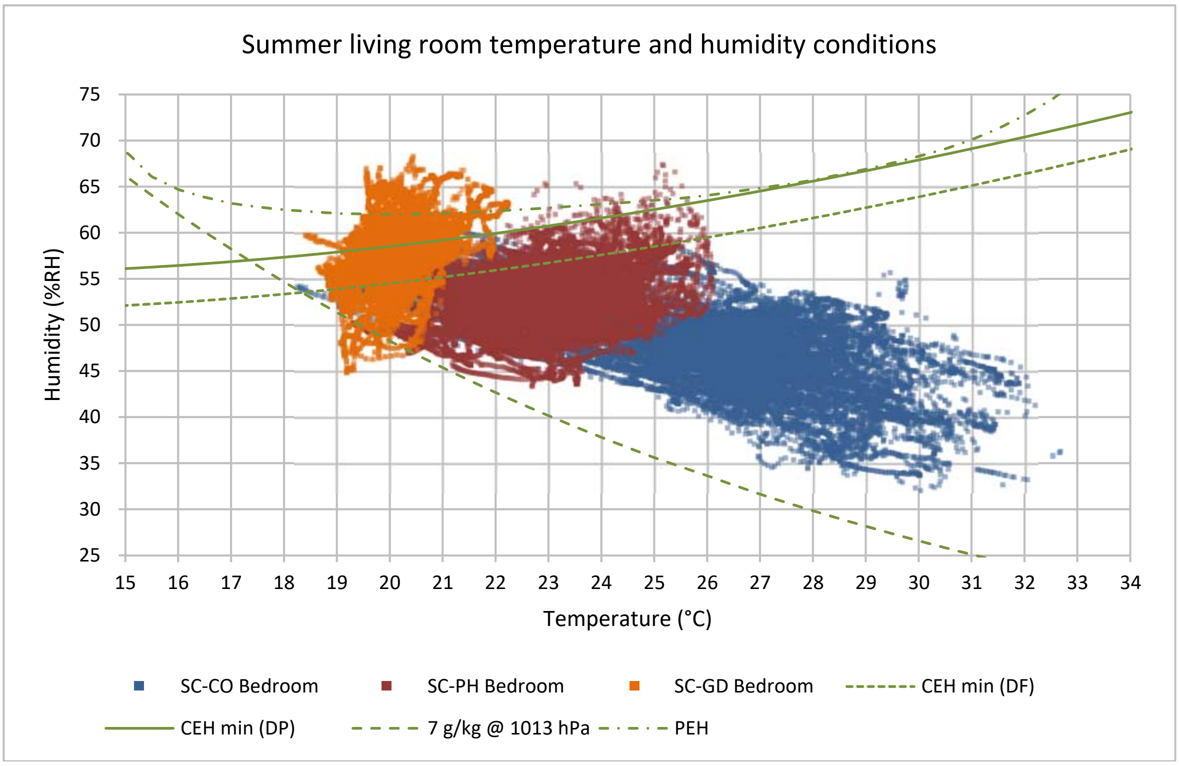


Figure 7.14 Summer living room temperature and humidity conditions. The figure shows the analysis of the dust mites population threshold conditions according to the CEH *Df* and *Dp*.

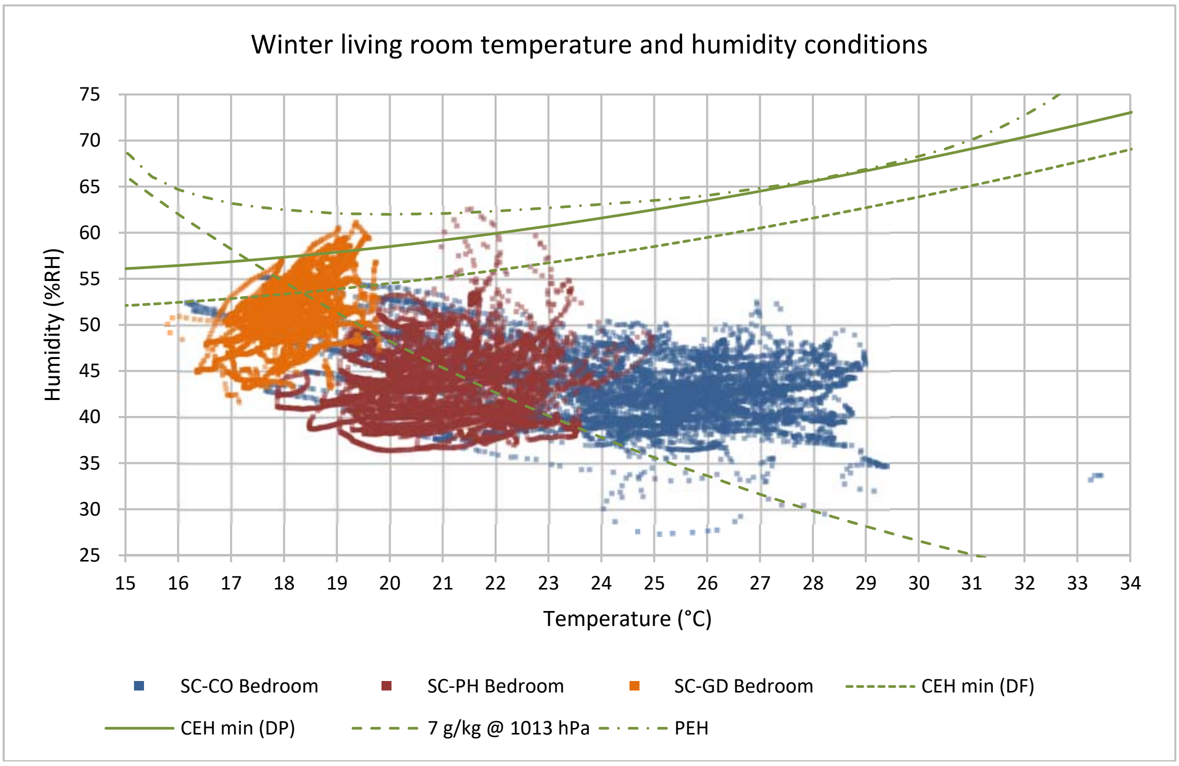


Figure 7.15 Winter living room temperature and humidity conditions. The figure shows the analysis of the dust mites population threshold conditions according to the CEH *Df* and *Dp*.

7.5.3 Particulate Matter 2.5µm

Annual mean levels of $PM_{2.5}$ concentrations above 10µg/m^3 the maximum annual concentration, as suggested by WHO (2000), were exceeded indoors in the three dwellings and outdoor levels. The Air Quality Strategy for the UK suggests the annual mean of $PM_{2.5}$ should not exceed 25µg/m^3 (DEFRA, 2007). However, within the UK, air quality is a devolved matter, so the Scottish government is responsible for developing its air quality policies. The local air quality management plan for Scotland states that the annual mean should not exceed 10µg/m^3 (DEFRA, 2016), similar to WHO guidelines.

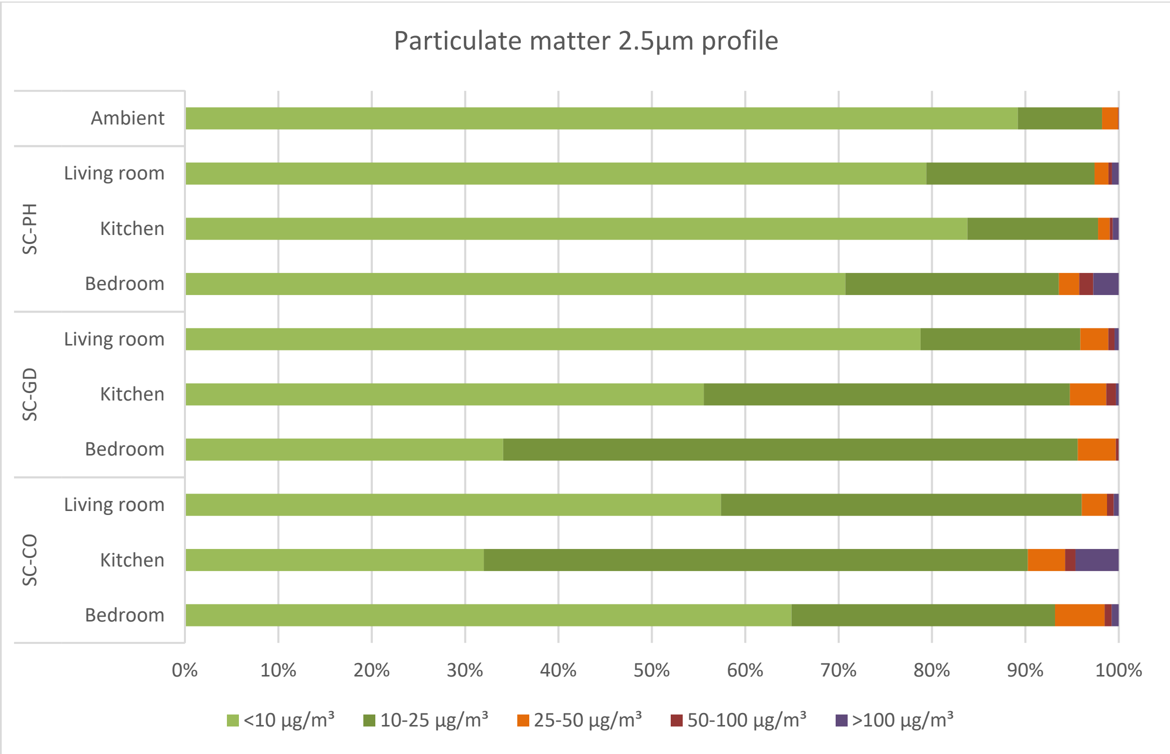


Figure 7.16 $PM_{2.5}$ profile by exposure ranges during the monitored time.

The mean indoor concentrations in SC-CO (bedroom 10.88µg/m^3, living-room 11.68µg/m^3 and kitchen 15.70µg/m^3) were higher than those in SC-GD (living-room 8.90µg/m^3, kitchen 11.73µg/m^3 and bedroom 14.00 µg/m^3) and SC-PH (kitchen 8.26µg/m^3-, living-room 9.15µg/m^3 and bedroom 15.14 µg/m^3). The occurrence of $PM_{2.5}$ concentrations below the 10µg/m^3 threshold was more frequent in SC-PH than in the other dwellings, as observed in Figure 7.16. Correlational analysis between the indoor and outdoor concentrations showed a weak association and even in some cases negative correlations (SC-PH: bedroom $r_s=0.167$ ($p<.001$), kitchen $r_s=0.306$ ($p<.001$) and living-room $r_s=0.163$ ($p<.001$); SC-GD: bedroom $r_s=-0.157$ ($p<.001$), kitchen $r_s=0.322$ ($p<.001$) and living-room $r_s=0.340$ ($p<.001$): SC-

CO: bedroom r_s=-0.111 (p<.001), kitchen r_s=0.235 (p<.001) and living-room r_s=0.235 (p<.001)), suggesting that the principal sources of indoor pollution are related to human activities.

The recommended daily mean of 25µg/m^3 set out by the WHO was exceeded in all dwellings at certain times. The occurrence of daily means above 25µg/m^3 was higher in SC-CO (Table 7.9). Concentrations above 100µg/m^3 were observed frequently in SC-CO's (Figure 7.17) and SC-GD's (Figure 7.18) kitchens and SC-PH's bedroom (Figure 7.19). A possible explanation for SC-CO and SC-GD pollution in the kitchen was cooking, whereas the concentration in the SC-PH bedroom could be related to the use of sprays and personal cleaning products, as the pollution peaks occurred during early mornings (Figure 7.21), but they could also be related to cooking if the doors were open.

There was a statistically significant (p <.001) median difference between the SC-CO (7.85µg/m^3), SC-GD (12.68µg/m^3) and SC-PH (7.80µg/m^3) bedrooms; SC-CO (13.09µg/m^3), SC-GD (9.48µg/m^3) and SC-PH (6.39µg/m^3) kitchens; as well as SC-CO (9.34µg/m^3), SC-GD (6.39µg/m^3) and SC-PH (6.89µg/m^3) living rooms. Further examination suggests that the significance of these differences is related to the timing of the pollution events in the homes and internal door opening between rooms. The analysis of the $PM_{2.5}$ levels in the living room suggests that the kitchen and bedroom doors may be kept open most of the time, as it was clearly identifiable that pollution peaks could be traced from the bedroom to the living room and kitchen (Figure 7.20). However, pollution events in the bedroom did not have a significant impact on the other rooms. The combination of $PM_{2.5}$ levels, heat (Wan *et al.*, 2011), air flows, cooking methods and type and source of heat energy (Amouei Torkmahalleh *et al.*, 2017), as well as partitions and wall openings, impact the $PM_{2.5}$ dissipation.

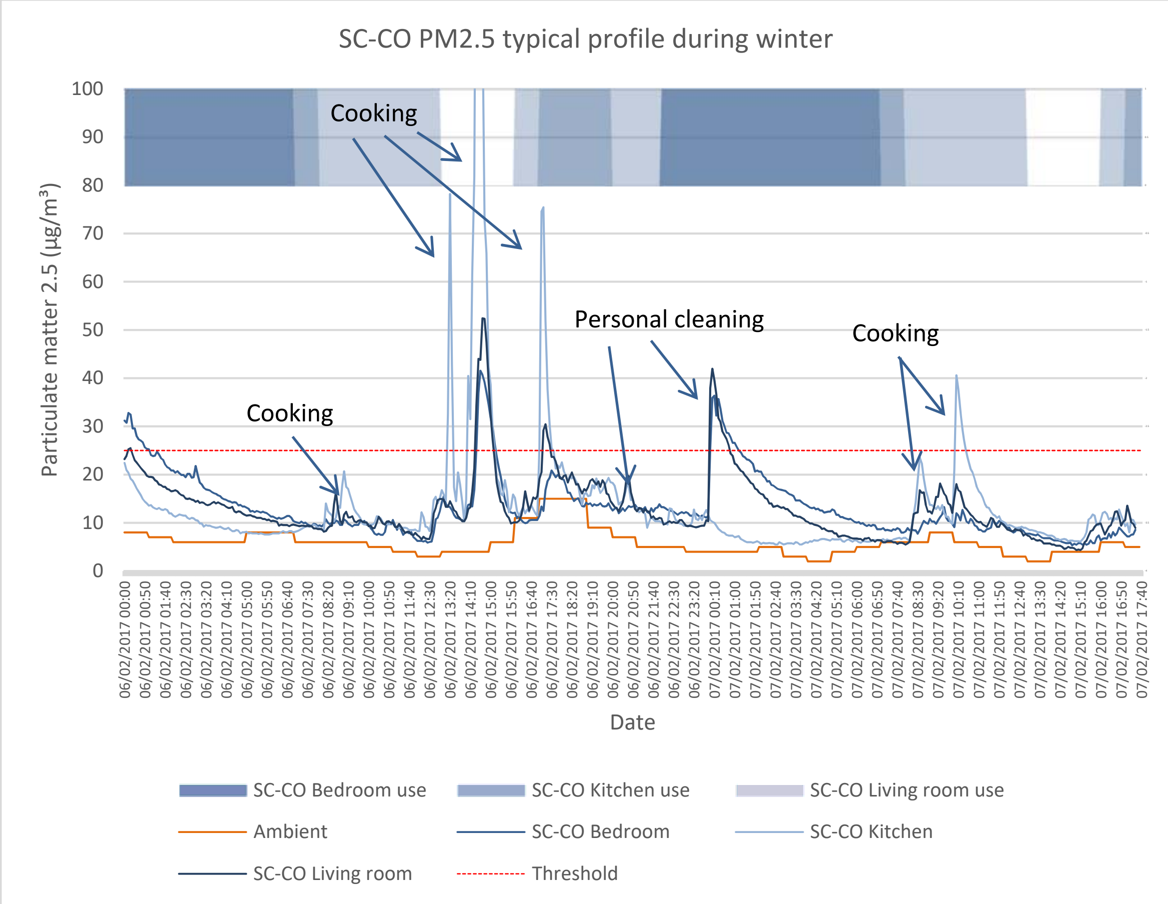


Figure 7.17 Example of typical $PM_{2.5}$ behaviour in the SC-CO (06/02/2017-07/02/2017).

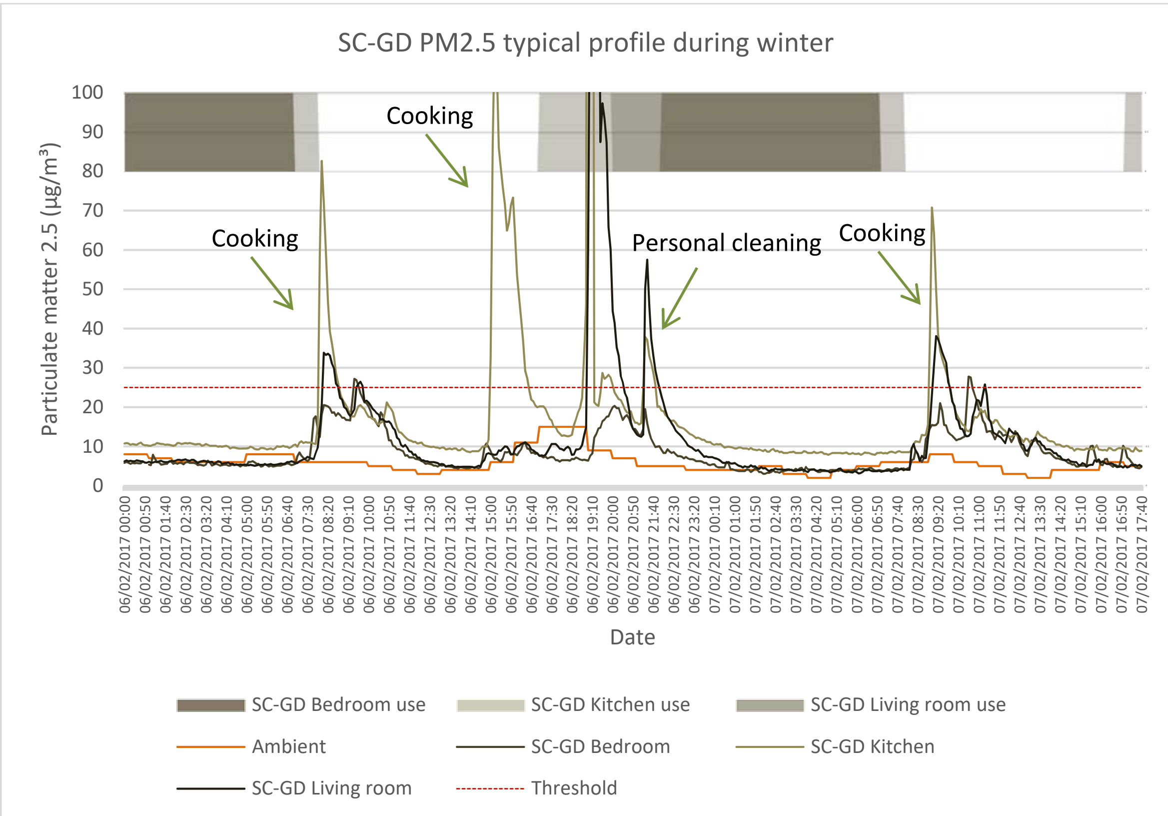


Figure 7.18 Example of typical $PM_{2.5}$ behaviour in the SC-GD (06/02/2017-07/02/2017).

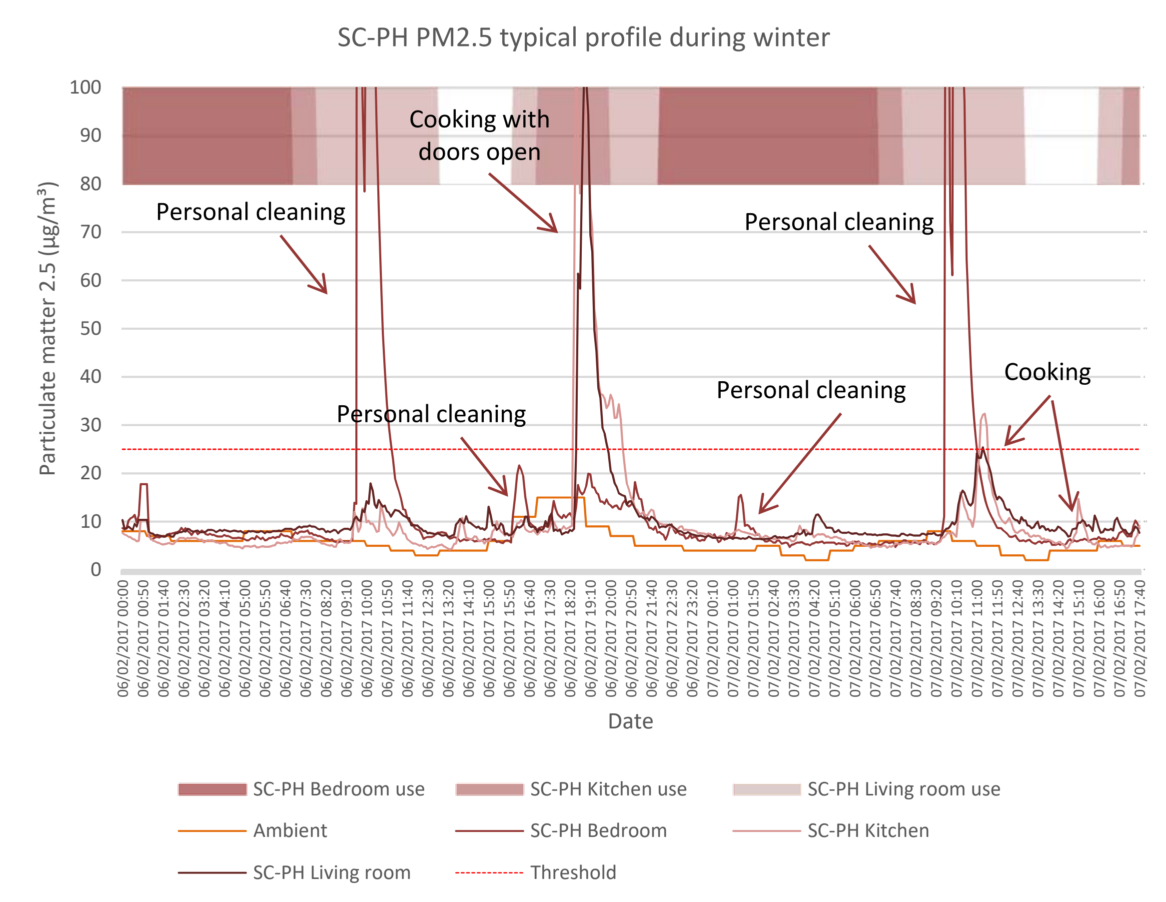


Figure 7.19 Example of typical $PM_{2.5}$ behaviour in the SC-PH (06/02/2017-07/02/2017).

Table 7.8 Summary of analysis of time periods with exposition above 25µg/m³ in the SC-CO, SC-GD and SC-PH.

		>25µg/m³				
		Total period (a)	Occupied time (b)	Difference (b-a)	Unoccupied time (c)	Difference (c-a)
SC-CO	Bedroom	6.82%	5.75%	-1.08%	7.54%	0.71%
	Kitchen	9.73%	10.49%	0.76%	9.58%	-0.15%
	Living room	3.95%	5.62%	1.67%	3.20%	-0.75%
SC-GD	Bedroom	4.38%	1.28%	-3.11%	6.44%	2.06%
	Kitchen	5.23%	5.02%	-0.21%	5.26%	0.03%
	Living room	4.12%	7.58%	3.47%	3.85%	-0.27%
SC-PH	Bedroom	6.41%	2.41%	-4.00%	9.06%	2.65%
	Kitchen	2.20%	6.69%	4.49%	1.31%	-0.90%
	Living room	2.58%	2.35%	-0.23%	2.68%	0.10%

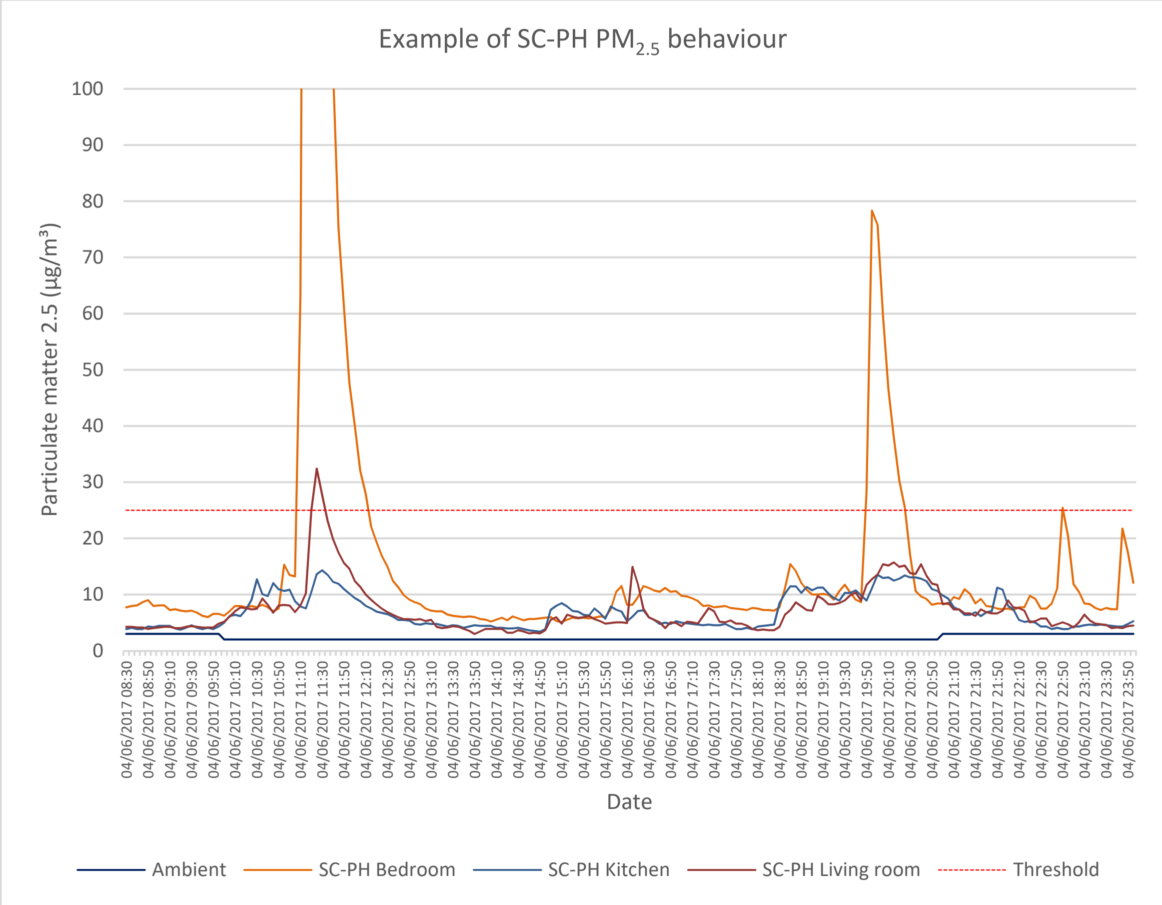


Figure 7.20 Example of $PM_{2.5}$ behaviour in the SC-PH. Pollution peaks in the bedroom may have influenced the pollution in other rooms.

Table 7.9 Analysis of $PM_{2.5}$ concentrations in the Scottish case study.

		6.5 month mean (μg/m³)	Standard Deviation	% of time above 10μg/m³	No. of days with daily mean above 25μg/m³	% of the year of days above 25μg/m³
SC-CO	Bedroom	10.89	14.16	35.04%	13	6.67%
	Kitchen	15.70	26.46	67.98%	10	5.26%
	Living room	11.69	16.45	42.61%	5	2.56%
SC-GD	Bedroom	14.01	7.40	65.92%	4	2.05%
	Kitchen	11.73	18.45	44.43%	8	4.10%
	Living room	8.91	17.80	21.23%	4	2.05%
SC-PH	Bedroom	15.15	42.02	29.27%	12	6.15%
	Kitchen	8.26	19.25	16.21%	3	1.67%
	Living room	9.15	23.46	20.61%	4	2.05%
	Ambient	5.55	5.47	13.17%	2	1.03%

		Bedroom																									
	Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Hour	
February	SC-CO	14.2	12.8	10.6	9.2	8.5	8.0	7.4	7.1	8.7	10.2	11.5	11.0	11.8	12.2	12.7	9.4	10.8	31.6	37.2	24.8	20.1	20.3	15.5	12.6	SC-CO	February
	SC-GD	8.3	7.7	7.2	7.0	6.9	6.7	6.7	7.6	10.9	16.6	16.0	13.7	10.7	8.5	8.0	8.3	10.4	10.6	9.1	9.7	12.0	12.2	9.5	9.1	SC-GD	
	SC-PH	12.2	8.4	7.5	7.1	6.9	7.1	6.9	20.2	20.0	64.5	77.5	18.8	12.6	8.8	7.6	11.8	23.4	34.6	16.6	14.0	11.1	10.6	8.9	9.0	SC-PH	
	Ambient	7.2	7.1	7.3	7.3	7.6	7.9	8.1	8.0	7.3	7.1	7.6	7.2	7.7	7.5	8.0	7.9	8.7	9.6	9.2	8.0	7.6	7.8	7.9	7.5	Ambient	
March	SC-CO	12.8	11.5	10.2	9.2	8.4	8.0	7.6	7.6	10.3	13.7	13.4	13.8	13.3	11.8	11.0	11.5	10.5	11.9	21.8	25.4	19.5	19.5	16.5	14.2	SC-CO	March
	SC-GD	9.3	8.9	8.9	8.6	8.3	8.1	8.0	8.8	12.7	16.0	14.5	13.2	11.9	10.1	9.2	9.6	10.1	11.0	12.1	10.4	9.6	10.9	11.7	10.5	SC-GD	
	SC-PH	10.2	6.4	5.5	5.2	5.0	6.4	8.9	5.3	5.2	63.0	73.9	11.5	6.0	8.5	6.3	19.1	13.2	22.3	10.9	15.3	10.5	7.6	8.5	15.8	SC-PH	
	Ambient	6.5	6.0	5.7	5.5	5.7	7.1	7.5	7.5	7.1	6.7	6.3	6.4	6.1	6.1	6.6	7.1	7.7	8.3	9.2	8.3	8.0	7.5	7.1	6.8	Ambient	
April	SC-CO	6.4	5.5	5.0	4.7	4.6	4.5	4.5	4.6	5.1	6.6	7.0	8.6	7.8	8.3	7.6	6.6	6.1	6.7	6.9	7.4	6.8	7.1	7.5	7.2	SC-CO	April
	SC-GD	10.1	9.6	9.5	9.5	9.5	9.6	9.6	10.5	13.0	16.9	18.5	16.9	15.0	14.0	13.6	12.5	12.0	12.3	12.2	11.7	11.3	11.2	10.6	10.4	SC-GD	
	SC-PH	12.4	5.4	4.2	3.9	3.8	5.7	19.9	7.7	8.2	26.8	61.6	18.1	8.4	8.0	12.5	15.1	15.4	14.4	9.4	11.3	10.7	11.6	6.3	17.8	SC-PH	
	Ambient	3.7	3.7	3.9	4.3	4.8	5.2	5.5	5.5	5.0	5.0	5.0	4.9	4.5	4.5	4.6	4.3	4.3	4.1	4.6	4.8	4.6	5.2	4.9	4.1	Ambient	
May	SC-CO	9.0	8.1	7.5	7.3	7.3	7.4	7.4	7.2	8.9	13.4	12.2	13.9	12.5	14.2	9.6	9.6	8.3	8.2	11.9	11.8	10.6	10.8	11.0	10.1	SC-CO	May
	SC-GD	9.9	9.7	9.5	9.6	9.9	10.1	10.2	10.4	12.9	15.0	15.5	15.5	12.1	11.0	11.0	11.3	11.5	11.7	13.3	11.3	10.2	10.4	10.2	10.1	SC-GD	
	SC-PH	12.2	9.7	9.0	9.7	10.9	15.4	22.7	10.8	15.4	45.5	39.9	22.4	11.5	15.5	15.4	15.2	12.6	22.3	16.9	18.8	13.6	10.7	10.0	11.8	SC-PH	
	Ambient	7.3	7.5	7.7	8.0	8.3	8.6	8.6	8.2	7.9	7.8	7.4	7.6	7.6	7.3	7.4	7.3	7.4	7.5	7.5	7.5	7.6	7.4	7.3	7.0	Ambient	
June	SC-CO	8.3	6.9	6.3	6.0	5.9	5.7	5.5	5.4	5.8	7.2	7.7	8.1	7.4	7.8	6.0	5.7	5.7	6.0	6.3	6.2	6.2	7.0	7.5	8.2	SC-CO	June
	SC-GD	14.0	13.9	14.0	13.8	13.7	13.8	13.8	13.8	16.3	21.2	20.4	19.8	16.6	15.8	14.5	14.4	14.6	15.4	14.4	14.0	14.0	13.8	14.0	14.4	SC-GD	
	SC-PH	11.3	9.5	9.4	9.3	9.8	11.1	13.0	12.5	13.8	33.5	71.3	15.6	10.7	9.6	14.2	8.7	15.5	10.5	17.5	14.2	10.9	10.4	9.8	11.8	SC-PH	
	Ambient	4.1	4.1	3.8	3.9	3.8	3.7	3.7	3.7	3.5	3.2	3.2	3.4	3.0	2.9	3.0	3.0	3.2	3.3	3.2	3.5	4.1	4.0	3.9	4.1	Ambient	
July	SC-CO	12.5	12.6	11.4	10.8	10.2	9.9	9.7	9.9	10.0	10.1	10.2	10.8	11.4	11.9	11.0	10.6	10.0	9.7	10.5	10.7	11.1	11.0	12.0	12.3	SC-CO	July
	SC-GD	20.3	20.4	20.5	20.5	20.5	20.6	20.5	20.8	21.7	22.8	23.4	22.6	23.1	22.5	21.6	21.3	21.0	20.9	20.9	20.5	20.5	20.4	20.4	20.3	SC-GD	
	SC-PH	10.1	9.5	9.5	9.6	10.0	12.8	18.1	21.8	13.4	25.6	34.7	12.9	10.5	13.9	12.3	10.2	12.4	16.4	11.2	16.0	11.0	12.4	14.1	15.7	SC-PH	
	Ambient	4.4	4.3	4.8	4.6	4.6	4.5	4.4	3.9	3.9	3.9	3.9	4.0	4.2	4.3	4.1	4.1	4.1	4.3	4.1	4.0	4.1	4.1	4.0	4.1	Ambient	
August	SC-CO	19.0	18.5	19.3	19.2	19.0	19.0	19.5	19.7	19.7	19.8	20.2	20.6	22.9	22.3	21.0	19.9	19.5	19.5	20.9	20.5	19.5	20.1	20.6	20.1	SC-CO	August
	SC-GD	19.7	20.1	20.0	19.9	20.0	20.3	20.4	20.8	21.4	24.1	25.3	25.5	24.4	24.9	21.6	20.6	19.9	19.9	19.7	19.8	19.9	20.5	20.1	20.3	SC-GD	
	SC-PH	8.1	8.3	7.7	7.4	7.7	8.8	21.3	9.7	8.7	10.4	63.4	33.5	13.3	24.8	11.9	7.2	7.0	8.1	10.8	10.9	13.7	12.6	8.8	9.2	SC-PH	
	Ambient	3.2	3.4	3.3	3.0	2.9	2.6	2.5	2.7	2.5	2.4	2.2	2.7	3.0	2.8	2.9	2.9	2.8	2.8	2.9	2.9	2.8	3.1	2.9	3.1	Ambient	
	PM2.5 (μg/m^3) scale	0	3	7	10	14	17	21	24	28	31	35	38	42	45	49	52	56	59	63	66	70	73	77	80	PM2.5 (μg/m^3) scale	

Figure 7.21 Hourly $PM_{2.5}$ means divided in months in bedrooms.

A UK study (Lai *et al.*, 2004) over two years found that indoor $PM_{2.5}$ exposure in residential environments was around 11.4μg/m^3 with moderate variations during the day, and indoor $PM_{2.5}$ and smoking were the most significant factors to affect personal $PM_{2.5}$ exposure. Measured $PM_{2.5}$ in SC-CO and SC-GD was higher than this value and lower in SC-PH (Table 7.8). An indoor $PM_{2.5}$ 24-h mean of 12.6 μg/m^3 in 100 Scottish and Irish dwellings was reported by Semple et al. (2012), this value was considerably higher for smoking dwellings (99.3 μg/m^3). Lower 24-h mean were found in dwellings that burned wood (5.7 μg/m^3), gas (7.1 μg/m^3) and coal (7.4 μg/m^3). The daily mean of $PM_{2.5}$ concentrations recommended by the WHO (25μg/m^3) were exceeded by between 5 and 13 days at SC-CO, for SC-GD it was from 4 to 8 days, while at SC-PH from 3 to 12 days.

$PM_{2.5}$ concentrations varied significantly between the ground floor and the first floor in the three dwellings, while for the bedrooms (first floor) they were usually higher than those measured on the ground. This supports that $PM_{2.5}$ are distributed through the homes depending on the source, its location, and the door openings. SC-PH and SC-GD were more efficient than SC-CO in removing and diluting indoor concentrations. However, pollution peaks took a prolonged time to dissipate in

SC-GD and SC-PH, perhaps due to the low ventilation rates and higher airtightness, especially in SC-PH (Figure 7.22).

The analysis of the $PM_{2.5}$ excess (indoor-ambient) showed that the three dwellings had higher concentrations indoors than outdoors. The median $PM_{2.5}$ difference from ambient (4.0μg/m^3) to SC-CO (7.85μg/m^3), SC-GD (12.68μg/m^3) and SC-PH (7.8μg/m^3) bedrooms were:

- The difference (-3.37μg/m^3) between ambient and SC-CO was significant, z=147.22, p<.001.
- The difference (-7.84μg/m^3) between ambient and SC-GD was significant, z=177.22, p<.001.
- The difference (-3.57μg/m^3) between ambient and SC-PH was significant, z=145.23, p<.001.

The median $PM_{2.5}$ difference from ambient (4.0μg/m^3) to SC-CO (13.09μg/m^3), SC-GD (9.48μg/m^3) and SC-PH (6.39μg/m^3) kitchens were:

- The difference (-7.94μg/m^3) between ambient and SC-CO was significant, z=196.21, p<.001.
- The difference (-5.02μg/m^3) between ambient and SC-GD was significant, z=165.29, p<.001.
- The difference (-1.84μg/m^3) between ambient and SC-PH was significant, z=103.56, p<.001.

The median $PM_{2.5}$ difference from ambient (4.0μg/m^3) to SC-CO (9.34μg/m^3), SC-GD (6.39μg/m^3) and SC-PH (6.89μg/m^3) living rooms were:

- The difference (-5.19μg/m^3) between ambient and SC-CO was significant, z=174.61, p<.001.
- The difference (-1.98μg/m^3) between ambient and SC-GD was significant, z=107.91, p<.001.

- The difference (-2.74μg/m^3) between ambient and SC-PH was significant, z=128.47, p<.001.

Even though indoor concentrations in the bedroom of SC-PH were among the higher mean concentrations, SC-PH bedroom recorded longer periods with levels below 10μg/m^3 compared to the bedrooms in SC-GD and SC-CO. This suggests a higher frequency of $PM_{2.5}$ pollution peaks combined with low background levels in the SC-PH bedroom compared to the other homes (Figure 7.23). Indoor excesses in the living room and the kitchen of SC-PH were constantly lower when compared to the other homes (Table 7.10). Occurrence of levels above 25μg/m^3 were 0.41% lower in the SC-PH bedroom, 1.37% lower in the living room and 7.53% in the kitchen than those found at the control house; whereas those in the SC-GD were 2.44% lower in the bedroom, 4.50% lower in the kitchen and 0.17% higher in the living room compared to those in the SC-CO.

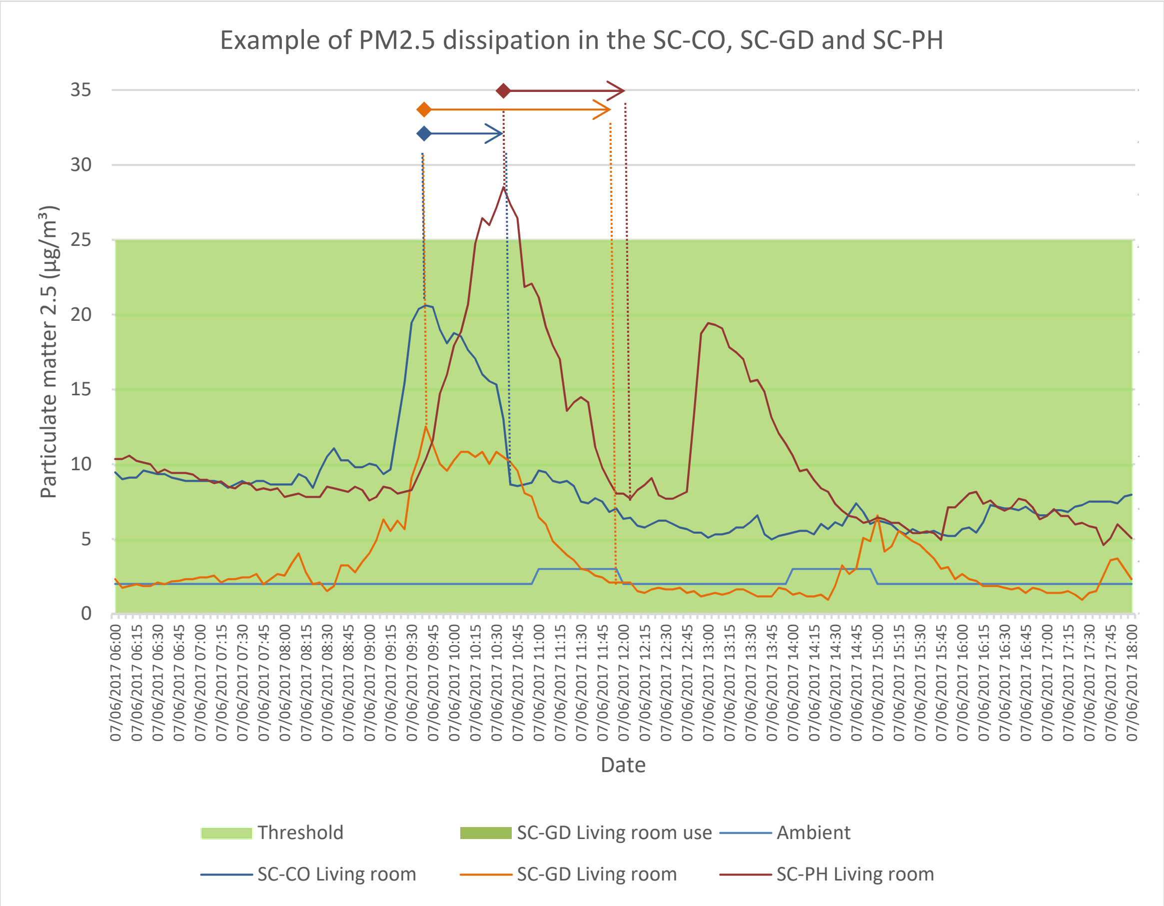


Figure 7.22 Example of $PM_{2.5}$ dissipation in the SC-CO, SC-GD and SC-PH homes.

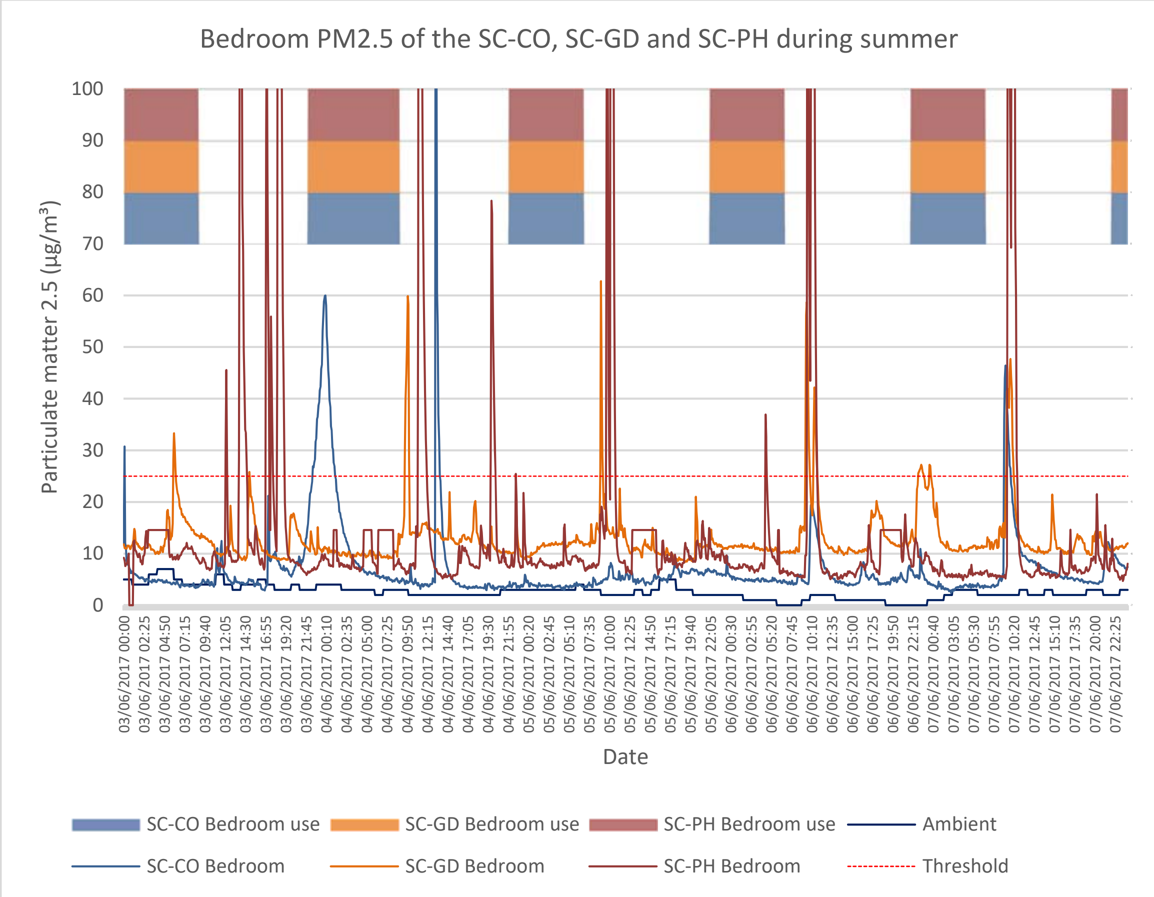


Figure 7.23 Bedroom winter profiles of $PM_{2.5}$ pollution levels in the SC-CO, SC-GD and SC-PH homes.

Table 7.10 Monthly $PM_{2.5}$ excess (indoor-ambient) concentration differences.

		February	March	April	May	June	July	August	Total
SC-CO	Bedroom	6.28	6.11	1.76	2.27	3.07	6.65	17.16	5.34
	Kitchen	9.58	8.79	6.20	7.39	14.78	12.95	12.51	10.16
	Living room	7.05	4.17	5.02	5.87	7.23	6.84	7.68	6.14
SC-GD	Bedroom	1.92	3.57	7.46	3.69	11.63	16.98	18.37	8.46
	Kitchen	8.96	7.34	7.43	3.77	7.16	2.86	5.93	6.19
	Living room	5.45	3.57	3.36	0.60	2.94	3.10	5.94	3.36
SC-PH	Bedroom	9.96	7.67	8.65	8.92	11.61	10.15	11.03	9.60
	Kitchen	2.42	2.86	1.67	1.75	3.89	2.40	5.31	2.72
	Living room	2.57	3.11	2.65	1.79	6.41	4.56	4.56	3.60

	Living room																										
	Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Hour	
February	SC-CO	12.8	10.4	8.9	8.3	7.9	7.3	6.8	6.7	9.6	12.4	13.5	11.4	11.8	10.9	13.4	11.1	21.2	46.4	34.1	23.5	19.9	19.0	15.9	13.1	SC-CO	February
	SC-GD	12.7	10.3	9.0	8.3	7.9	7.7	7.5	8.2	12.6	21.7	18.0	13.9	10.8	8.9	8.6	9.0	11.0	12.3	10.8	19.9	44.3	15.1	14.4	15.2	SC-GD	
	SC-PH	8.1	7.7	7.6	7.8	8.3	8.2	8.0	8.1	8.5	9.8	14.2	13.3	10.8	9.3	8.9	9.0	10.4	12.1	17.9	21.6	12.7	9.7	8.6	8.4	SC-PH	
	Ambient	7.2	7.1	7.3	7.3	7.6	7.9	8.1	8.0	7.3	7.1	7.6	7.2	7.7	7.5	8.0	7.9	8.7	9.6	9.2	8.0	7.6	7.8	7.9	7.5	Ambient	
March	SC-CO	8.7	7.2	6.5	6.2	5.8	5.8	5.4	5.3	10.2	13.2	12.9	11.1	12.4	10.3	11.4	10.4	10.5	12.7	25.0	20.3	14.4	17.1	12.7	11.2	SC-CO	March
	SC-GD	11.5	9.6	7.8	7.0	6.4	6.1	5.9	6.4	11.2	16.4	13.0	11.5	9.7	7.9	6.9	6.9	7.9	8.3	9.1	8.8	15.9	29.2	16.3	12.8	SC-GD	
	SC-PH	6.3	5.9	5.6	5.6	5.7	6.3	6.0	5.9	6.1	7.4	13.6	10.5	8.0	14.1	9.9	8.6	8.1	7.5	19.0	43.8	14.2	8.5	7.7	6.8	SC-PH	
	Ambient	6.5	6.0	5.7	5.5	5.7	7.1	7.5	7.5	7.1	6.7	6.3	6.4	6.1	6.1	6.6	7.1	7.7	8.3	9.2	8.3	8.0	7.5	7.1	6.8	Ambient	
April	SC-CO	8.3	7.8	7.6	7.5	7.5	7.7	7.6	7.4	9.4	10.9	12.1	12.6	11.0	11.8	9.7	9.8	9.2	10.2	12.6	10.6	10.0	10.7	10.5	9.3	SC-CO	April
	SC-GD	7.7	5.4	4.7	4.4	4.4	4.5	4.6	7.3	8.1	16.3	13.7	10.3	8.9	7.6	8.7	7.7	6.9	6.7	6.7	7.2	9.6	10.3	9.5	10.3	SC-GD	
	SC-PH	4.2	3.9	3.7	3.8	4.6	5.8	5.2	5.1	5.5	6.5	9.0	8.6	7.8	5.7	5.7	5.7	6.4	5.8	10.3	33.3	11.7	6.6	5.2	4.3	SC-PH	
	Ambient	3.7	3.7	3.9	4.3	4.8	5.2	5.5	5.5	5.0	5.0	5.0	4.9	4.5	4.5	4.6	4.3	4.3	4.1	4.6	4.8	4.6	5.2	4.9	4.1	Ambient	
May	SC-CO	13.1	11.9	11.1	11.0	11.1	11.4	11.2	10.9	12.8	14.1	16.9	14.6	13.8	11.5	11.9	12.2	12.4	13.4	19.0	15.8	17.0	17.8	15.7	14.6	SC-CO	May
	SC-GD	9.0	6.5	5.8	5.5	5.5	5.6	5.7	6.2	10.1	10.6	11.6	10.7	8.1	6.9	6.7	7.9	7.7	7.8	8.4	8.7	13.6	10.6	9.0	9.9	SC-GD	
	SC-PH	5.8	4.8	4.3	4.6	7.8	7.7	6.2	5.7	5.4	7.9	12.2	11.4	7.2	6.8	9.4	12.4	29.5	10.0	17.2	18.2	10.6	7.8	6.4	7.1	SC-PH	
	Ambient	7.3	7.5	7.7	8.0	8.3	8.6	8.6	8.2	7.9	7.8	7.4	7.6	7.6	7.3	7.4	7.3	7.4	7.5	7.5	7.5	7.6	7.4	7.3	7.0	Ambient	
June	SC-CO	10.3	9.6	9.2	9.3	9.5	9.7	9.7	9.4	10.9	12.3	13.8	13.8	14.5	10.2	9.0	9.5	9.8	10.7	10.7	10.5	11.2	12.5	11.7	11.0	SC-CO	June
	SC-GD	6.1	4.5	4.2	4.1	4.1	5.0	4.3	4.1	8.6	13.2	8.3	7.2	7.1	7.2	5.4	4.8	5.2	5.5	5.5	5.6	8.3	5.2	9.1	13.0	SC-GD	
	SC-PH	7.3	6.9	6.6	6.8	7.2	8.0	7.8	7.4	7.4	8.3	14.2	12.3	9.4	9.7	10.3	8.7	10.2	9.2	22.7	20.0	11.4	9.8	9.2	7.9	SC-PH	
	Ambient	4.1	4.1	3.8	3.9	3.8	3.7	3.7	3.7	3.5	3.2	3.2	3.4	3.0	2.9	3.0	3.0	3.2	3.3	3.2	3.5	4.1	4.0	3.9	4.1	Ambient	
July	SC-CO	11.7	10.5	9.7	10.0	10.4	10.3	9.9	9.7	10.2	10.2	9.8	11.6	14.4	15.6	11.8	10.4	9.6	9.7	11.5	11.2	12.0	11.2	12.0	11.6	SC-CO	July
	SC-GD	6.2	6.3	6.3	6.4	6.4	6.5	6.5	6.7	7.2	9.6	9.2	9.0	10.3	8.2	7.5	7.2	7.3	7.6	7.2	6.9	7.0	6.9	6.5	6.2	SC-GD	
	SC-PH	7.2	6.5	6.2	6.1	6.8	6.7	7.1	7.8	7.8	8.5	11.8	9.2	7.5	7.8	8.3	10.3	8.7	9.2	14.5	16.7	10.2	8.6	8.5	7.9	SC-PH	
	Ambient	4.4	4.3	4.8	4.6	4.6	4.5	4.4	3.9	3.9	3.9	3.9	4.0	4.2	4.3	4.1	4.1	4.1	4.3	4.1	4.0	4.1	4.1	4.0	4.1	Ambient	
August	SC-CO	9.2	8.1	7.9	8.8	9.2	9.3	12.6	11.4	9.6	8.9	10.5	13.2	14.4	12.0	11.6	9.5	9.2	10.0	13.9	10.7	10.0	11.3	11.3	10.0	SC-CO	August
	SC-GD	7.2	7.8	8.0	7.9	8.1	8.2	8.5	9.9	9.4	12.9	11.6	9.6	9.3	10.3	8.6	9.0	7.9	8.0	8.0	8.3	9.8	7.9	7.2	7.3	SC-GD	
	SC-PH	5.7	5.3	5.3	5.2	5.2	5.7	6.6	6.4	6.4	7.2	9.8	10.8	7.3	7.9	12.8	6.9	7.2	7.6	9.4	9.7	8.3	7.6	7.1	6.4	SC-PH	
	Ambient	3.2	3.4	3.3	3.0	2.9	2.6	2.5	2.7	2.5	2.4	2.2	2.7	3.0	2.8	2.9	2.9	2.8	2.8	2.9	2.9	2.8	3.1	2.9	3.1	Ambient	
PM2.5 (μg/m³) scale		0	2	4	6	8	10	12	14	16	18	20	22	23	25	27	29	31	33	35	37	39	41	43	45	PM2.5 (μg/m³) scale	

Figure 7.24 Hourly $PM_{2.5}$ means divided by month in the living rooms.

Figure 7.21 and

	Living room																										
	Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Hour	
February	SC-CO	12.8	10.4	8.9	8.3	7.9	7.3	6.8	6.7	9.6	12.4	13.5	11.4	11.8	10.9	13.4	11.1	21.2	46.4	34.1	23.5	19.9	19.0	15.9	13.1	SC-CO	February
	SC-GD	12.7	10.3	9.0	8.3	7.9	7.7	7.5	8.2	12.6	21.7	18.0	13.9	10.8	8.9	8.6	9.0	11.0	12.3	10.8	19.9	44.3	15.1	14.4	15.2	SC-GD	
	SC-PH	8.1	7.7	7.6	7.8	8.3	8.2	8.0	8.1	8.5	9.8	14.2	13.3	10.8	9.3	8.9	9.0	10.4	12.1	17.9	21.6	12.7	9.7	8.6	8.4	SC-PH	
	Ambient	7.2	7.1	7.3	7.3	7.6	7.9	8.1	8.0	7.3	7.1	7.6	7.2	7.7	7.5	8.0	7.9	8.7	9.6	9.2	8.0	7.6	7.8	7.9	7.5	Ambient	
March	SC-CO	8.7	7.2	6.5	6.2	5.8	5.8	5.4	5.3	10.2	13.2	12.9	11.1	12.4	10.3	11.4	10.4	10.5	12.7	25.0	20.3	14.4	17.1	12.7	11.2	SC-CO	March
	SC-GD	11.5	9.6	7.8	7.0	6.4	6.1	5.9	6.4	11.2	16.4	13.0	11.5	9.7	7.9	6.9	6.9	7.9	8.3	9.1	8.8	15.9	29.2	16.3	12.8	SC-GD	
	SC-PH	6.3	5.9	5.6	5.6	5.7	6.3	6.0	5.9	6.1	7.4	13.6	10.5	8.0	14.1	9.9	8.6	8.1	7.5	19.0	43.8	14.2	8.5	7.7	6.8	SC-PH	
	Ambient	6.5	6.0	5.7	5.5	5.7	7.1	7.5	7.5	7.1	6.7	6.3	6.4	6.1	6.1	6.6	7.1	7.7	8.3	9.2	8.3	8.0	7.5	7.1	6.8	Ambient	
April	SC-CO	8.3	7.8	7.6	7.5	7.5	7.7	7.6	7.4	9.4	10.9	12.1	12.6	11.0	11.8	9.7	9.8	9.2	10.2	12.6	10.6	10.0	10.7	10.5	9.3	SC-CO	April
	SC-GD	7.7	5.4	4.7	4.4	4.4	4.5	4.6	7.3	8.1	16.3	13.7	10.3	8.9	7.6	8.7	7.7	6.9	6.7	6.7	7.2	9.6	10.3	9.5	10.3	SC-GD	
	SC-PH	4.2	3.9	3.7	3.8	4.6	5.8	5.2	5.1	5.5	6.5	9.0	8.6	7.8	5.7	5.7	5.7	6.4	5.8	10.3	33.3	11.7	6.6	5.2	4.3	SC-PH	
	Ambient	3.7	3.7	3.9	4.3	4.8	5.2	5.5	5.5	5.0	5.0	5.0	4.9	4.5	4.5	4.6	4.3	4.3	4.1	4.6	4.8	4.6	5.2	4.9	4.1	Ambient	
May	SC-CO	13.1	11.9	11.1	11.0	11.1	11.4	11.2	10.9	12.8	14.1	16.9	14.6	13.8	11.5	11.9	12.2	12.4	13.4	19.0	15.8	17.0	17.8	15.7	14.6	SC-CO	May
	SC-GD	9.0	6.5	5.8	5.5	5.5	5.6	5.7	6.2	10.1	10.6	11.6	10.7	8.1	6.9	6.7	7.9	7.7	7.8	8.4	8.7	13.6	10.6	9.0	9.9	SC-GD	
	SC-PH	5.8	4.8	4.3	4.6	7.8	7.7	6.2	5.7	5.4	7.9	12.2	11.4	7.2	6.8	9.4	12.4	29.5	10.0	17.2	18.2	10.6	7.8	6.4	7.1	SC-PH	
	Ambient	7.3	7.5	7.7	8.0	8.3	8.6	8.6	8.2	7.9	7.8	7.4	7.6	7.6	7.3	7.4	7.3	7.4	7.5	7.5	7.5	7.6	7.4	7.3	7.0	Ambient	
June	SC-CO	10.3	9.6	9.2	9.3	9.5	9.7	9.7	9.4	10.9	12.3	13.8	13.8	14.5	10.2	9.0	9.5	9.8	10.7	10.7	10.5	11.2	12.5	11.7	11.0	SC-CO	June
	SC-GD	6.1	4.5	4.2	4.1	4.1	5.0	4.3	4.1	8.6	13.2	8.3	7.2	7.1	7.2	5.4	4.8	5.2	5.5	5.5	5.6	8.3	5.2	9.1	13.0	SC-GD	
	SC-PH	7.3	6.9	6.6	6.8	7.2	8.0	7.8	7.4	7.4	8.3	14.2	12.3	9.4	9.7	10.3	8.7	10.2	9.2	22.7	20.0	11.4	9.8	9.2	7.9	SC-PH	
	Ambient	4.1	4.1	3.8	3.9	3.8	3.7	3.7	3.7	3.5	3.2	3.2	3.4	3.0	2.9	3.0	3.0	3.2	3.3	3.2	3.5	4.1	4.0	3.9	4.1	Ambient	
July	SC-CO	11.7	10.5	9.7	10.0	10.4	10.3	9.9	9.7	10.2	10.2	9.8	11.6	14.4	15.6	11.8	10.4	9.6	9.7	11.5	11.2	12.0	11.2	12.0	11.6	SC-CO	July
	SC-GD	6.2	6.3	6.3	6.4	6.4	6.5	6.5	6.7	7.2	9.6	9.2	9.0	10.3	8.2	7.5	7.2	7.3	7.6	7.2	6.9	7.0	6.9	6.5	6.2	SC-GD	
	SC-PH	7.2	6.5	6.2	6.1	6.8	6.7	7.1	7.8	7.8	8.5	11.8	9.2	7.5	7.8	8.3	10.3	8.7	9.2	14.5	16.7	10.2	8.6	8.5	7.9	SC-PH	
	Ambient	4.4	4.3	4.8	4.6	4.6	4.5	4.4	3.9	3.9	3.9	3.9	4.0	4.2	4.3	4.1	4.1	4.1	4.3	4.1	4.0	4.1	4.1	4.0	4.1	Ambient	
August	SC-CO	9.2	8.1	7.9	8.8	9.2	9.3	12.6	11.4	9.6	8.9	10.5	13.2	14.4	12.0	11.6	9.5	9.2	10.0	13.9	10.7	10.0	11.3	11.3	10.0	SC-CO	August
	SC-GD	7.2	7.8	8.0	7.9	8.1	8.2	8.5	9.9	9.4	12.9	11.6	9.6	9.3	10.3	8.6	9.0	7.9	8.0	8.0	8.3	9.8	7.9	7.2	7.3	SC-GD	
	SC-PH	5.7	5.3	5.3	5.2	5.2	5.7	6.6	6.4	6.4	7.2	9.8	10.8	7.3	7.9	12.8	6.9	7.2	7.6	9.4	9.7	8.3	7.6	7.1	6.4	SC-PH	
	Ambient	3.2	3.4	3.3	3.0	2.9	2.6	2.5	2.7	2.5	2.4	2.2	2.7	3.0	2.8	2.9	2.9	2.8	2.8	2.9	2.9	2.8	3.1	2.9	3.1	Ambient	
PM2.5 (μg/m³) scale		0	2	4	6	8	10	12	14	16	18	20	22	23	25	27	29	31	33	35	37	39	41	43	45	PM2.5 (μg/m³) scale	

Figure 7.24 show the hourly $PM_{2.5}$ mean for each month in the bedroom and living rooms. It is evident that indoor pollution events in the bedroom happened between 09:00 to 11:00, especially in SC-PH. Evening pollution in the bedrooms could be related to the living room, as indoor concentrations in the living room during the evening were higher.

7.5.4 Total volatile organic compounds (tVOC)

As part of indoor environmental monitoring, tVOC measurements were conducted in the main bedroom, kitchen and living room. TVOC concentrations varied significantly from one house to another, with higher concentrations measured in SC-CO, followed by SC-GD and then SC-PH.

The median differences between the SC-CO (252μg/m^3), SC-GD (229μg/m^3) and SC-PH (206μg/m^3) bedrooms:

- The 23μg/m^3 difference between SC-CO and SC-GD was significant, z=-37.9, p<.001.

- The 37μg/m^3 difference between SC-CO and SC-PH was significant, z=-60.37, p<.001.

- The 17μg/m^3 difference between SC-GD and SC-PH was significant, z=-40.62, p<.001.

The median differences between the SC-CO (258μg/m^3), SC-GD (229μg/m^3) and SC-PH (257μg/m^3) kitchens:

- The 20μg/m^3 difference between SC-CO and SC-GD was significant, z=-38.14, p<.001.

- The 2.71μg/m^3 difference between SC-CO and SC-PH was significant, z=-6.20, p<.001.

- The 20μg/m^3 difference between SC-GD and SC-PH was significant, z=-29, p<.001.

The median differences between the SC-CO (323μg/m^3), SC-GD (213μg/m^3) and SC-PH (175μg/m^3) living rooms:

- The 98μg/m^3 difference between SC-CO and SC-GD was significant, z=-130.91, p<.001.
- The 132μg/m^3 difference between SC-CO and SC-PH was significant, z=-165.75, p<.001.
- The 28μg/m^3 difference between SC-GD and SC-PH was significant, z=72.08, p<.001.

Poor statistical associations (r_s>0.35) were observed between the rooms in each house. They indicate that indoor sources of tVOC vary significantly in each of the rooms; this was noted especially in the SC-GD and SC-PH.

Concentrations above the 300μg/m^3 recommended by the WHO were observed in all the rooms in the three dwellings. The frequency of concentrations above 300μg/m^3 of each home was higher in the SC-CO living room (56.26%of the monitored time) and the SC-GD (25.25%) and SC-PH (28.44%) kitchens; whereas the lower occurrence was in the SC-CO kitchen (36.98%) and the SC-GD (20.67%) and SC-PH (11%) living rooms (Figure 7.25).

Winter mean tVOC concentrations in SC-CO (bedroom 267μg/m^3, kitchen 288μg/m^3 and living-room 303μg/m^3), SC-GD (living-room 193μg/m^3, kitchen 239μg/m^3 and bedroom 221μg/m^3) and SC-PH (bedroom 205μg/m^3, living-room 219μg/m^3 and kitchen 241μg/m^3), and spring SC-CO (kitchen 289μg/m^3, bedroom 351μg/m^3 and living-room 374μg/m^3), SC-GD (living-room 257μg/m^3, bedroom 267μg/m^3 and kitchen 285μg/m^3) and in SC-PH (living-room 215μg/m^3, bedroom 220μg/m^3 and kitchen 286μg/m^3) were similar to those found by Lai et al. (2004) in the UK. They measured indoor tVOC between 194μg/m^3 and 288μg/m^3 in dwellings and outdoor levels of 77.2μg/m^3 in residential neighbourhoods.

When comparing bedroom (Figure 7.26) tVOC levels to those in the kitchen (Figure 7.27) and the living room (Figure 7.28), it was clear that higher concentrations were continuously measured in the bedrooms. This may represent a health risk to occupants, as higher tVOC levels in the bedroom were measured for occupied hours (Table 7.11). In fact, bedroom tVOC levels above 300µg/m³ were measured during 41.78% of the monitored time in the SC-CO compared to 71.45% of the occupied time, 24.99% (unoccupied) to 34.48% (occupied) in the SC-GD and 16.44% (unoccupied) to 21.67% (occupied) in the SC-PH.

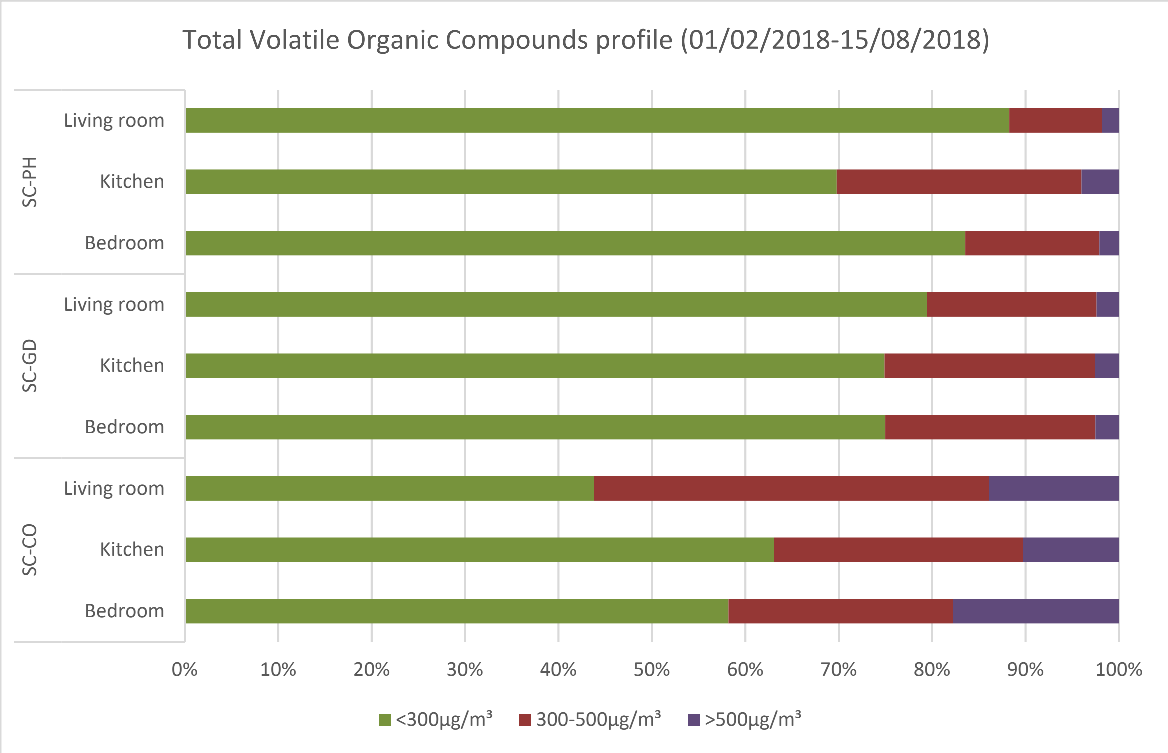


Figure 7.25 Profile of the total volatile organic compounds.

Bedroom	Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Hour	
February	SC-CO	353	386	373	365	348	335	312	296	283	241	212	180	160	150	172	162	167	218	264	283	271	276	288	322	SC-CO	February
	SC-GD	269	275	306	305	280	260	236	221	221	206	180	171	159	154	153	167	184	195	192	196	211	244	259	266	SC-GD	
	SC-PH	250	256	229	209	205	207	208	217	221	226	262	174	151	144	136	140	170	198	211	230	210	213	226	231	SC-PH	
March	SC-CO	559	614	612	628	602	610	583	566	554	407	307	240	198	177	159	155	168	186	226	251	272	312	367	459	SC-CO	March
	SC-GD	321	307	319	320	314	299	282	265	241	199	177	173	179	180	177	196	196	202	240	248	255	273	323	337	SC-GD	
	SC-PH	237	238	218	210	214	220	229	213	226	224	203	155	139	133	133	137	139	166	191	211	212	219	221	230	SC-PH	
April	SC-CO	486	508	506	500	510	492	486	475	472	410	299	220	182	163	155	154	155	157	173	195	218	250	305	384	SC-CO	April
	SC-GD	357	360	396	395	385	360	341	325	297	237	203	204	208	216	232	238	255	279	289	296	314	336	362	357	SC-GD	
	SC-PH	247	242	236	222	230	225	231	248	230	221	205	181	154	147	146	145	150	157	173	194	229	234	227	239	SC-PH	
May	SC-CO	465	499	519	533	549	542	551	575	561	412	272	220	182	171	162	165	168	173	181	194	207	244	305	347	SC-CO	May
	SC-GD	269	260	267	262	255	241	238	242	237	224	216	212	203	203	214	227	235	257	262	286	289	293	304	288	SC-GD	
	SC-PH	304	277	271	267	273	260	292	282	277	253	246	224	215	206	204	204	202	220	238	269	308	329	327	314	SC-PH	
June	SC-CO	384	398	405	426	446	439	446	434	413	327	226	175	156	148	145	146	156	182	195	190	206	229	266	325	SC-CO	June
	SC-GD	261	250	269	277	276	270	273	270	291	282	234	227	227	234	246	246	250	263	283	286	305	302	299	270	SC-GD	
	SC-PH	289	278	257	252	259	256	262	259	256	249	245	216	218	210	207	212	222	264	267	253	283	276	281	279	SC-PH	
July	SC-CO	344	398	416	436	458	473	494	444	440	401	317	249	204	182	183	174	172	181	195	205	209	225	268	302	SC-CO	July
	SC-GD	194	186	204	200	187	184	181	183	174	165	176	179	177	181	184	183	194	192	204	204	205	216	228	214	SC-GD	
	SC-PH	236	224	209	207	209	219	220	226	218	214	222	206	197	195	186	193	195	215	236	234	250	251	265	246	SC-PH	
August	SC-CO	358	403	439	485	554	561	612	613	657	613	474	350	289	245	195	175	172	182	188	213	233	247	285	306	SC-CO	August
	SC-GD	263	251	270	267	248	243	228	223	208	217	195	211	200	211	223	233	250	267	265	275	278	281	277	284	SC-GD	
	SC-PH	295	259	237	228	226	232	247	247	260	271	261	235	202	202	209	202	212	233	244	271	299	288	311	328	SC-PH	
	tVOC (µg/m³) scale	125	148	172	195	218	241	265	288	311	334	358	381	404	427	451	474	497	520	544	567	590	613	637	660	tVOC (µg/m³) scale	

Figure 7.26 Hourly bedroom tVOC mean divided by month in the Scottish case study.

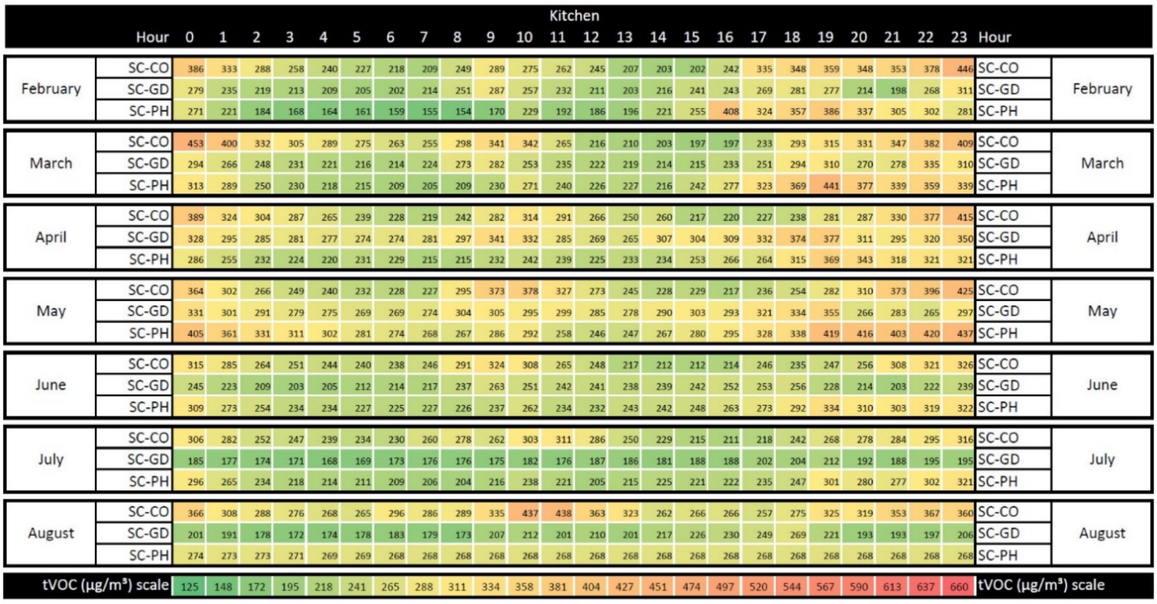


Figure 7.27 Hourly kitchen tVOC mean divided by month in the Scottish case study.

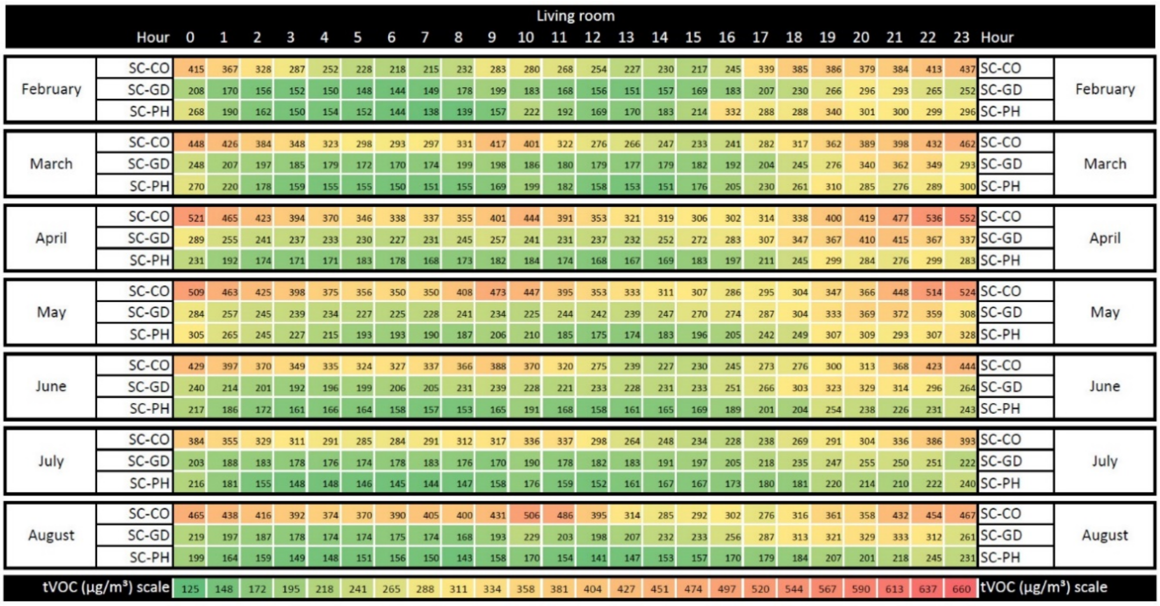


Figure 7.28 Hourly living room tVOC mean divided by month in the Scottish case study.

Table 7.11 Summary of analysis of time periods with exposition above 300µg/m³.

		>300µg/m³				
		Total period (a)	Occupied time (b)	Difference (b-a)	Unoccupied time (c)	Difference (c-a)
SC-CO	Bedroom	41.76%	71.45%	29.70%	22.11%	-19.65%
	Kitchen	36.88%	30.20%	-6.67%	38.24%	1.36%
	Living room	56.11%	57.84%	1.73%	55.41%	-0.71%
SC-GD	Bedroom	24.99%	34.48%	9.49%	18.71%	-6.27%
	Kitchen	25.05%	23.99%	-1.06%	23.40%	-1.65%
	Living room	20.54%	57.53%	37.00%	17.70%	-2.84%
SC-PH	Bedroom	16.44%	21.67%	5.24%	12.98%	-3.46%
	Kitchen	30.98%	37.78%	6.80%	26.46%	-4.52%
	Living room	11.82%	9.89%	-1.93%	11.43%	-0.39%

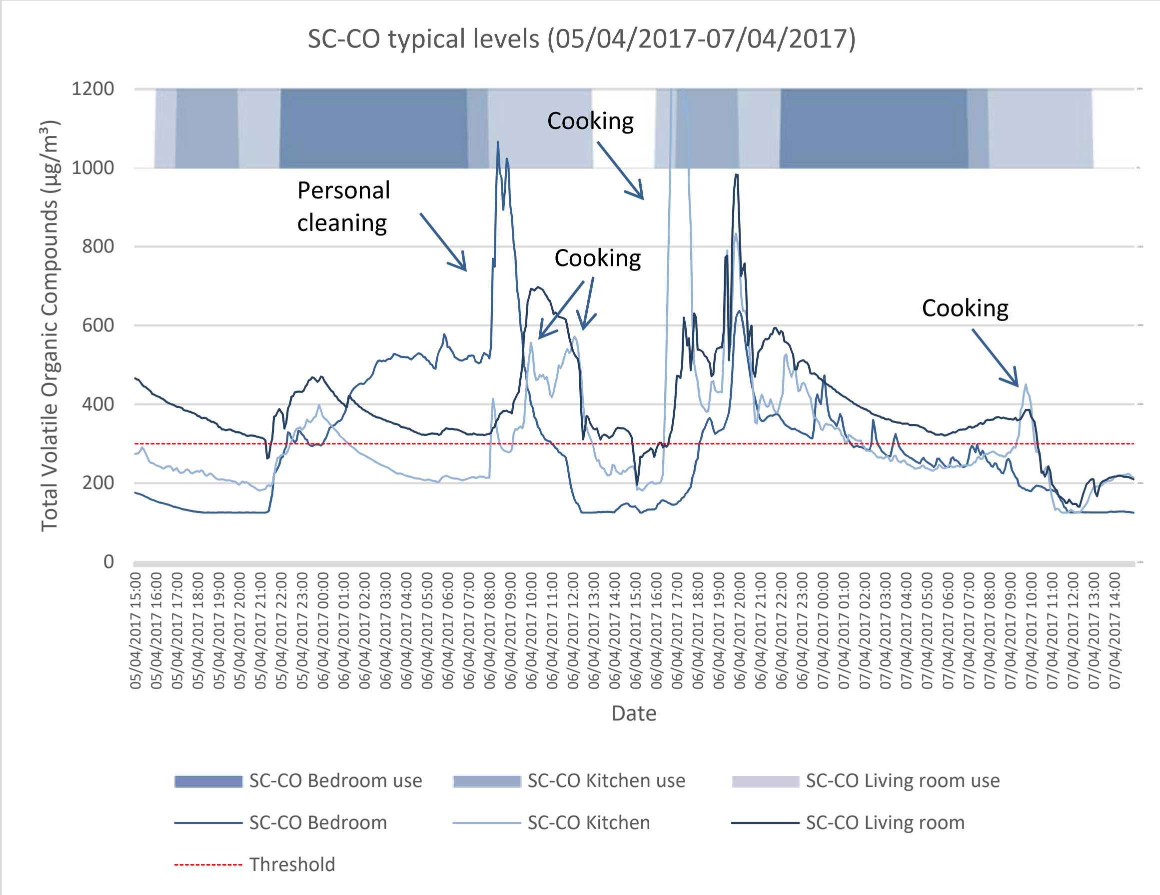


Figure 7.29 Example of the SC-CO tVOC typical levels (05/04/2017-07/04/2017).

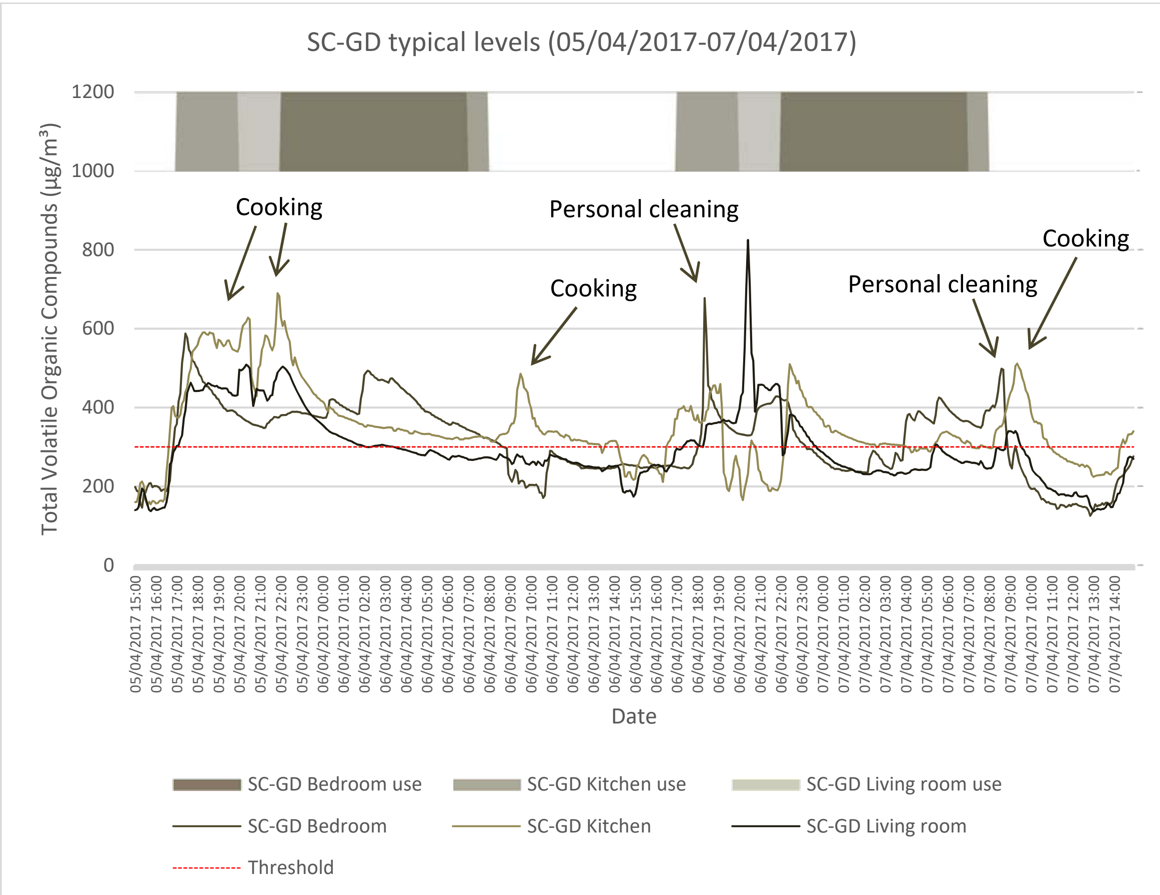


Figure 7.30 Example of the SC-GD tVOC typical levels (05/04/2017-07/04/2017).

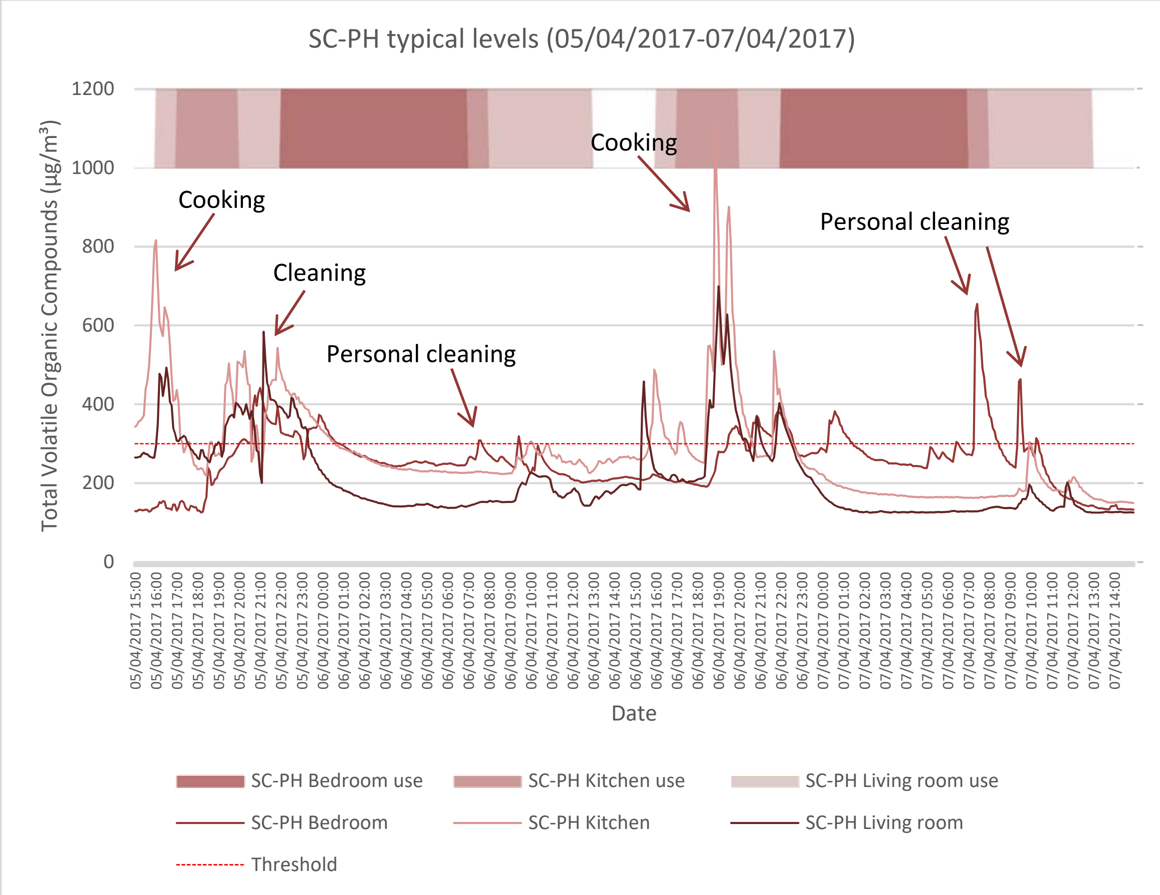


Figure 7.31 Example of the SC-PH tVOC typical levels (05/04/2017-07/04/2017).

TVOC pollution were observed to start early night and keep constant until early morning, especially in the bedrooms (Figure 7.29). Whereas night levels in the living room could be related to those measured in the bedroom, early morning levels may well be related to morning activities and cooking. In fact, breakfast and dinner cooking were possibly the more common pollution events in the kitchen and may well have been related to those in the living room. The SC-CO occupants relied on natural ventilation but opened their windows less frequently than the other dwellings relying on trickle vents installed in the top of the windows, which they stated to close. Indoor tVOC concentrations above 300µg/m^3 in SC-CO were the highest for the three dwellings, with levels above 500µg/m^3 seen for more than 10% of the time.

The frequency of tVOC concentrations above the recommended 300µg/m^3 was lower in the SC-GD and SC-PH. Nevertheless, such differences are related to human behaviour (Figure 7.30 and Figure 7.31). This is a critical factor as tVOC concentrations above the thresholds were more frequently measured at reported occupancy.

7.6 IAQ perceptions

Occupants' perceptions of the quality of indoor air were assessed through the online surveys as explained in Chapter 4 using bipolar and unipolar scales to analyse IAQ perception. The desired scores for the bipolar scale are between 3 and 5, and less than 3 for the unipolar scales. Table 7.12 shows a summary of the summer results (SC-CO (N=3), SC-GD (N=2) and SC-PH (N=3)).

SC-CO's mean scores for the fresh-stuffy scale (M=4.67) and odour scale (M=4.00) require further investigation, as well as the still-draughty scale (M=5.00), though the occupants stated being satisfied with overall IAQ (M=2.67). This suggests that even if they felt uncomfortable about draughts and stuffy air, they did not rate them as essential in terms of overall satisfaction. SC-GD's occupants had a very similar score for the satisfaction scale (M=2.5), but problems with humidity (dry, M=2.00) and air movement (still, M=2.00) were identified as requiring further investigation.

The SC-GD occupants felt that the air was very dry, so they placed bowls of water on the radiators to try to solve this problem. The examination of the humidity and temperatures in the psychrometric chart indicated, that the indoor environment in the living room measured consistently lower humidity and colder than the rest of the homes. However, this was still between the extended comfort levels. So, this appreciation could be related to air movement. This increased indoor humidity and may have affected their overall perceptions of IAQ, which they rated satisfactory.

Occupants in SC-PH felt highly satisfied with the quality of indoor air (M=1.0) and felt the air was humid (M=5.5). However, the analysis of the humidity levels revealed that less than 7% of the monitored time were above 60%RH. This suggests that they did not consider humidity in terms of IAQ satisfaction, perhaps due to the outdoor conditions.

Table 7.12 Statistical analysis of IAQ perceptions for summer in the Scottish dwellings.

IAQ perceptions	House	Participant	Result	Mean	SD	Mean + SD	Mean -SD	Max	Min
Fresh (1) - Stuffy (7)	SC-CO	A	4	4.67	0.58	5.24	4.09	5	4
		B	5						
		C	5						
	SC-GD	A	1	2	1.41	3.41	0.59	3	1
		B	3						
		C	--						
	SC-PH	A	2	2	0	2	2	2	2
		B	2						
		C	2						
Dry (1) - humid (7)	SC-CO	A	4	4.67	0.58	5.24	4.09	5	4
		B	5						
		C	5						
	SC-GD	A	2	2	0	2	2	2	2
		B	2						
		C	--						
	SC-PH	A	6	5.33	0.58	5.91	4.76	6	5
		B	5						
		C	5						
Still (1) - draughty (7)	SC-CO	A	5	5.33	0.58	5.91	4.76	6	5
		B	5						
		C	6						
	SC-GD	A	2	2	0	2	2	2	2
		B	2						
		C	--						
	SC-PH	A	4	4	0	4	4	4	4
		B	4						
		C	4						
Odourless (1) - smelly (7)	SC-CO	A	4	4	0	4	4	4	4
		B	4						
		C	4						
	SC-GD	A	2	2.5	0.71	3.21	1.79	3	2
		B	3						
		C	--						
	SC-PH	A	1	1.67	0.58	2.24	1.09	2	1
		B	2						
		C	2						
Satisfactory (1) - unsatisfactory (7)	SC-CO	A	2	2.67	0.58	3.24	2.09	3	2
		B	3						
		C	3						
	SC-GD	A	2	2.5	0.71	3.21	1.79	3	2
		B	3						
		C	--						
	SC-PH	A	1	1	0	1	1	1	1
		B	1						
		C	1						

SC-CO occupants perceived the air as stuffy (M=5), smelly (M=4) and still (M=5.33) for winter, which could be considered causes of concern. Overall winter IAQ satisfaction was rated as satisfactory (M=3), though some individual scores were classed as causes of concern. This suggests that the occupants were satisfied with IAQ for winter, but their perceptions may change. SC-GD occupants felt the air was dry (M=2) and still (M=2), but they rated overall IAQ as acceptable (M=2.5). As previously described, this score could be affected by the actions taken to humidify the air. Similarly, in summer, SC-PH occupants felt that the air was too humid (M=5.33), but they rated overall IAQ as satisfactory (M=1) (Table 7.13).

Participants at SC-PH reported that they had experienced condensation on the windows and doors, however, lower occurrence of RH above 60%RH and a higher occurrence of RH below 40%RH were observed; the analysis of the vapour levels revealed that they were between the ideal comfort range with some exceptions measured in the extended range. This contrasts with the occupants' perception as they rated the air to be humid. SC-PH reported that they had not experienced any odours, which may be related to some of the findings of ENU as they suggested that ventilation systems and filters were well maintained (Jack *et al.*, 2013).

SC-GD occupants stated they had not experienced condensation on windows or doors, this contrasted with the high occurrence of levels above 60%RH, in the living room, but may converge with the occupants' perception as they rated the air to be dry. At least one of the SC-CO occupants had experienced condensation on the windows and doors and that may be related to the humidity perceived in the air. High levels of RH were not measured, however high temperatures in the SC-CO masked real humidity problems as SC-CO had as observed in the psychrometric charts. SC-CO occupants also perceived smells coming from outdoors as the ventilation strategy lacked any filtration. However, indoor air was also rated as a stuffy so air flows may not be efficient to dissipate odours and indoor pollution.

Table 7.13 Statistical analysis of IAQ perceptions during winter in the Scottish dwellings.

IAQ perceptions	House	Participant	Result	Mean	SD	Mean + SD	Mean -SD	Max	Min
Fresh (1) - Stuffy (7)	SC-CO	A	4	5	1	6	4	6	4
		B	5						
		C	6						
	SC-GD	A	1	2	1.41	3.41	0.59	3	1
		B	3						
		C							
	SC-PH	A	2	1.67	0.58	2.24	1.09	2	1
		B	1						
		C	2						
Dry (1) - humid (7)	SC-CO	A	4	4.67	0.58	5.24	4.09	5	4
		B	5						
		C	5						
	SC-GD	A	2	2	0	2	2	2	2
		B	2						
		C	--						
	SC-PH	A	6	5.33	0.58	5.91	4.76	6	5
		B	5						
		C	5						
Still (1) - draughty (7)	SC-CO	A	5	5.33	0.58	5.91	4.76	6	5
		B	5						
		C	6						
	SC-GD	A	2	2	0	2	2	2	2
		B	2						
		C	--						
	SC-PH	A	4	4	0	4	4	4	4
		B	4						
		C	4						
Odourless (1) - smelly (7)	SC-CO	A	4	4	0	4	4	4	4
		B	4						
		C	4						
	SC-GD	A	2	2.5	0.71	3.21	1.79	3	2
		B	3						
		C	--						
	SC-PH	A	1	1.67	0.58	2.24	1.09	2	1
		B	2						
		C	2						
Satisfactory (1) - unsatisfactory (7)	SC-CO	A	2	3	1	4	2	4	2
		B	3						
		C	4						
	SC-GD	A	2	2.5	0.71	3.21	1.79	3	2
		B	3						
		C	--						
	SC-PH	A	1	1	0	1	1	1	1
		B	1						
		C	1						

7.7 Thermal perceptions

Occupants' perceptions of thermal comfort were examined through online surveys, using the unipolar and bipolar scales described in Chapter 4; the rating scale proposed by Raw (1995) was used in this assessment. The results of the statistical analysis were derived from the participants of each household, i.e. SC-CO (N=3), SC-GD (N=2) and SC-PH (N=3).

Overall summer thermal comfort was rated as satisfactory in SC-CO (M=2.0), SC-GD (M=1.50) and SC-PH (M=2.33). However, occupants of SC-PH stated that the temperatures were uncomfortable rating the comfort scale as a cause of concern (M=6). Indeed temperatures in the SC-PH were associated to a higher probability of overheating where temperatures above 25°C were frequently measured in the bedroom.

Occupants in SC-GD stated that the temperature in their home had significant variations over the day, as they rated the stable scale as a cause of concern (M=5.50), this may be related to the temperature variation measured in the kitchen (M=5.22°C), but may differ from those measured in the living room (M=1.15°C) or bedroom (M=1.48°C). This scale, however, was also rated as unsatisfactory by SC-CO (M=3.33, mean summer daily temperature variations B 1.59°C, K 2.97°C and L 7.98°C) and SC-PH (M=5, mean summer daily temperature variations B 2.78°C, K 2.21°C and L 2.79°C), thereby indicating that temperature variations may require further investigation.

SC-PH occupants also felt that the temperatures were warm (M=2) for summer. This suggests that they had different perceptions of thermal comfort as a whole compared to each component evaluated in this survey, whereas SC-GD occupants may not consider temperature variations as significant (
Table 7.14).

Table 7.14 Statistical analysis of thermal comfort perceptions for summer.

Thermal perceptions	House	Participant	Result	Mean	SD	Mean + SD	Mean -SD	Max	Min
Comfortable (1) - uncomfortable (7)	SC-CO	A	2	2.67	0.58	3.24	2.09	3	2
		B	3						
		C	3						
	SC-GD	A	2	2	0	2	2	2	2
		B	2						
		C	--						
	SC-PH	A	5	6	1	7	5	7	5
		B	6						
		C	7						
Too hot (1) - too cold (7)	SC-CO	A	4	4	0	4	4	4	4
		B	4						
		C	4						
	SC-GD	A	4	4	0	4	4	4	4
		B	4						
		C	--						
	SC-PH	A	2	2	1	3	1	3	1
		B	3						
		C	1						
Stable (1) - varies for the day (7)	SC-CO	A	3	3.33	0.58	3.91	2.76	4	3
		B	3						
		C	4						
	SC-GD	A	5	5.50	0.71	6.21	4.79	6	5
		B	6						
		C	--						
	SC-PH	A	5	5	1	6	4	6	4
		B	4						
		C	6						
Satisfactory overall (1) - unsatisfactory overall (7)	SC-CO	A	2	2	0	2	2	2	2
		B	2						
		C	2						
	SC-GD	A	2	1.50	0.71	2.21	0.79	2	1
		B	1						
		C	--						
	SC-PH	A	2	2.33	0.58	2.91	1.76	3	2
		B	3						
		C	2						

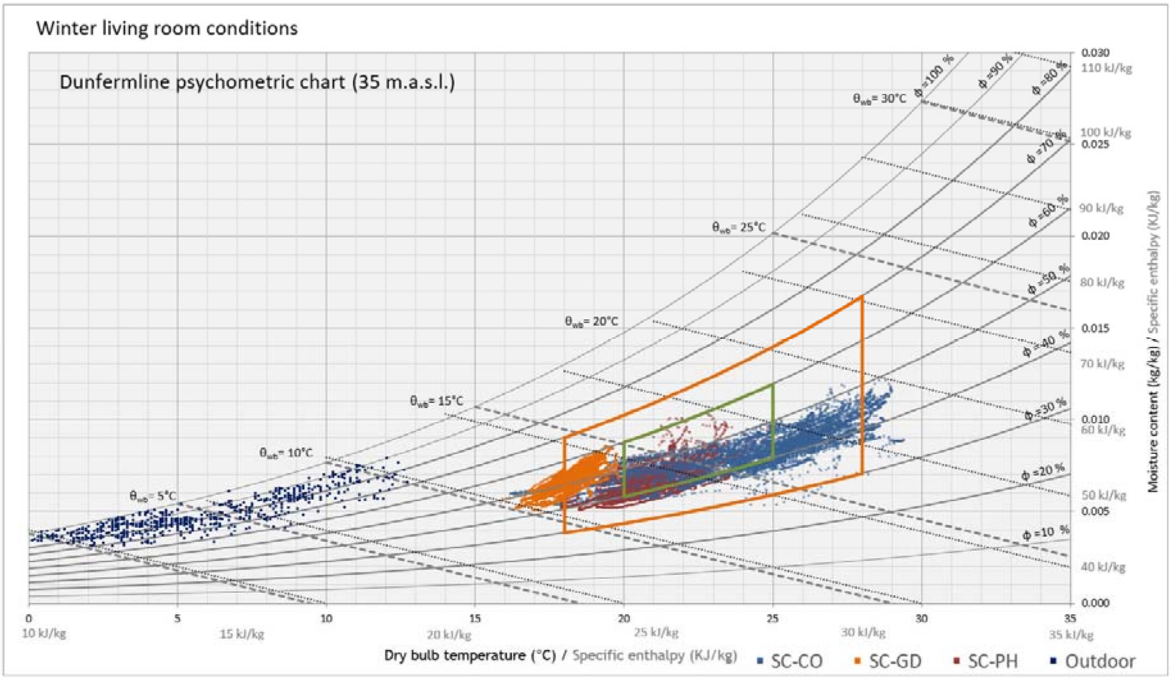


Figure 7.32 Winter living room psychrometric evaluation of the conditions indoors. The green rectangle delimitates the ideal range and the orange the extended range.

Overall thermal comfort in the homes in winter was rated satisfactory in the MVHR dwellings, but SC-CO felt dissatisfied (M=3.67). Occupants in SC-CO (M=5.33) and SC-GD (M=5.50) felt that the temperatures were cold, though SC-GD occupants felt even more uncomfortable, as they rated the scale as a cause of concern (M=6). In fact, SC-GD measured winter living room air temperatures were below the extended range accordingly to the psychrometric chart (Figure 7.32) and had the higher occurrence of temperatures below 18˚C (47% of the winter time) among the three houses.

The three dwellings' occupants felt unhappy with temperature variations during the day. Occupants in SC-CO (mean winter daily temperature variations bedroom 2.55˚C, kitchen 4.88˚C and living-room 8.30˚C) and SC-PH (mean winter daily temperature variations bedroom 2.55˚C, kitchen 3.70˚C and living-room 3.31˚C) had a similar rating (M=5.33), whereas SC-GD (mean winter daily temperature variations (bedroom 1.62˚C, kitchen 6.93˚C and living-room 1.53˚C) felt more uncomfortable (M=6). This suggests that each household assigned a good deal of importance to temperature variations when rating overall thermal comfort and factors like feeling cold and uncomfortable were critical (Table 7.15).

Table 7.15 Statistical analysis of thermal comfort perceptions for winter.

Thermal perceptions	House	Participant	Result	Mean	SD	Mean + SD	Mean -SD	Max	Min
Comfortable (1) - uncomfortable (7)	SC-CO	A	4	4.67	0.58	5.24	4.09	5	4
		B	5						
		C	5						
	SC-GD	A	6	6	0	6	6	6	6
		B	6						
		C	--						
	SC-PH	A	2	1.67	0.58	2.24	1.09	2	1
		B	1						
		C	2						
Too hot (1) -too cold (7)	SC-CO	A	5	5.33	0.58	5.91	4.76	6	5
		B	5						
		C	6						
	SC-GD	A	5	5.5	0.71	6.21	4.79	6	5
		B	6						
		C	--						
	SC-PH	A	4	4.33	0.58	4.91	3.76	5	4
		B	5						
		C	4						
Stable (1) -varies for the day (7)	SC-CO	A	5	5.33	0.58	5.91	4.76	6	5
		B	5						
		C	6						
	SC-GD	A	6	6	0	6	6	6	6
		B	6						
		C	--						
	SC-PH	A	6	5.33	1.15	6.49	4.18	6	4
		B	4						
		C	6						
Satisfactory overall (1) - unsatisfactory overall (7)	SC-CO	A	3	3.67	0.58	4.24	3.09	4	3
		B	4						
		C	4						
	SC-GD	A	1	1.5	0.71	2.21	0.79	2	1
		B	2						
		C	--						
	SC-PH	A	2	1.67	0.58	2.24	1.09	2	1
		B	1						
		C	2						

7.8 Chapter conclusion

This chapter presented and discussed the results of the indoor measurements and assessment of indoor hygrothermal conditions, as well as indoor $PM_{2.5}$ and tVOC in a PassivHaus (SC-PH), a Gold Standard (Scottish building regulations, SC-GD) and a control home using standard building practices (SC-CO), in Dunfermline, Scotland. Data was collected using the monitoring methodology developed for this research. After the home visits to perform U-value testing and airtightness tests with ENU, the methodology was applied as described in Chapter 4.

There were some differences between the indoor environment of the three dwelling. However, as suggested by the analysis of this chapter, occupant behaviour remained as the most important factor that impact on the indoor environment. A more comprehensive study is required to understand fully this factor. The sample presented here, even though it was gathered over a prolonged time, represents only three dwellings.

Relative indoor $PM_{2.5}$ and tVOC pollution levels were usually lower in the PassivHaus dwelling, but similar to the other case studies, some unintended consequences were observed. For instance, apparent problems with overheating in the PassivHaus were observed especially during summer. It was also observed that whereas the background levels of indoor pollution were the lowest in the PassivHaus home, pollution peaks also took longer to dissipate– especially tVOC pollution. This was also observed to a lesser extent in the Gold Standard house. A possible explanation is that both dwellings rely on MVHR systems for ventilation. However, as the PassivHaus adheres to a stricter airtightness level, the effect may be more significant.

The occupants perceived IAQ as acceptable most of the time, though a major complaint was in the Golden Standard house, as the occupants complained of the dry indoor environment. They “fixed” it by placing bowls with water over the radiator in the living room, which may have had increased the relative humidity within the house. These complains could also be related to warm temperatures and stuffy air as reported by the occupants. They related this dry environment to frequent dry, itchy or watery eyes, stating that they felt these symptoms when at home.

The findings demonstrate the importance of occupant behaviours to IAQ, especially in homes with high levels of airtightness and controlled ventilation. The findings highlight the importance of adhering to strict design strategies and best practices, in order to achieve higher levels of IAQ.

Chapter 8 Cross-project analysis and comparison

8.1 Summary

The results of the different case studies were presented individually in Chapters 5 to 7. This chapter explores the significance of the findings across the three case studies. The cross-analysis identifies patterns emerging from the IAQ data and explores possible impact of building types and ventilation on IAQ and occupants' perceptions.

The first section of this chapter compares $PM_{2.5}$ and tVOC concentrations across the three case studies, as well as hydrothermal conditions. In doing so, findings from occupants behaviours and contextual information such as potential for indoor pollution protection, overheating and humidity are compared. The second section of the chapter contrasts the measured indoor environment in the case studies to the occupants' perceptions seeking to find associations and identify variances to understand perception.

8.2 Cross-case analysis of the findings of the measured IAQ

The analysis presents a summary of the results comparing the complete datasets of each case study looking at the differences and similitudes between each of the homes. They are presented in different clusters: potential for protection against $PM_{2.5}$ and tVOC, exposure to pollutants, pollution removal rates, frequency of pollution peaks, risk of overheating and humidity.

8.2.1 Level of protection from $PM_{2.5}$ and tVOC

All dwellings exceeded the thresholds for annual mean $PM_{2.5}$ of 10µg/m^3 and daily mean $PM_{2.5}$ of 25µg/m^3 (WHO, 2000), as well as those for tVOC: 300µg/m^3 (ECA, 1992; HM Government, 2013) and 500µg/m^3 (Delia, 2012). However, $PM_{2.5}$ (Figure 8.1) and tVOC (Figure 8.2) relative levels of pollution were lower in the PassivHaus homes compared to the control homes. Although differences between indoor $PM_{2.5}$ concentrations above 25µg/m^3 in San Francisco and Dunfermline were low, background $PM_{2.5}$ levels were usually lower in PassivHaus homes as discussed in Chapters 6 and 7.

Relative levels of protection from outdoor $PM_{2.5}$ were calculated based on the percentage of time above the thresholds (10µg/m^3 and 25µg/m^3, Figure 8.3) and the I/O ratios. Whereas indoor-outdoor differences were statistically significant in most of the cases, further evaluation of the data revealed that such differences were related to occupant behaviours rather than the performance of the building itself. However, Mexico City's, San Francisco's and Dunfermline's pollution networks do not collect tVOC, so this comparison, which may have triangulated with PM data, could not be made. It is difficult to establish an absolute figure of the level of protection as indoor concentrations also depend on different indoor and outdoor factors which will differ from one home to another, as well as occupant behaviours. For instance, wind velocity, outdoor temperature and relative humidity (Wu *et al.*, 2008) have a high impact on $PM_{2.5}$ distribution; thus variations on window opening have a significant effect on indoor $PM_{2.5}$ and tVOC levels.

In periods when the windows were open, it was observed that indoor $PM_{2.5}$ levels tracked the outdoor levels and that they were intensified by indoor sources. At high outdoor $PM_{2.5}$ pollution, like in Mexico City, the observed level of protection was greater whereas at low outdoor $PM_{2.5}$, such those in Dunfermline, indoor sources were more significant. This was also observed during the fires that hit San Francisco's Bay Area (31/08/2017-05/09/2017 and 08/10/2017-18/10/2017) during this research (Figure 8.4). However, the mechanisms for this are less certain – this could be related to different occupant activities, quality and estate of the filters, window opening patterns, wall cracks, indoor sources and air flows. However, the main purpose of the MVHR filters is to protect the unit from particles and insects. Nevertheless, occupant behaviours could still be the most significant cause. In the PassivHaus in Mexico City the filters were removed before this study started, and yet there were significant differences compared to the control home.

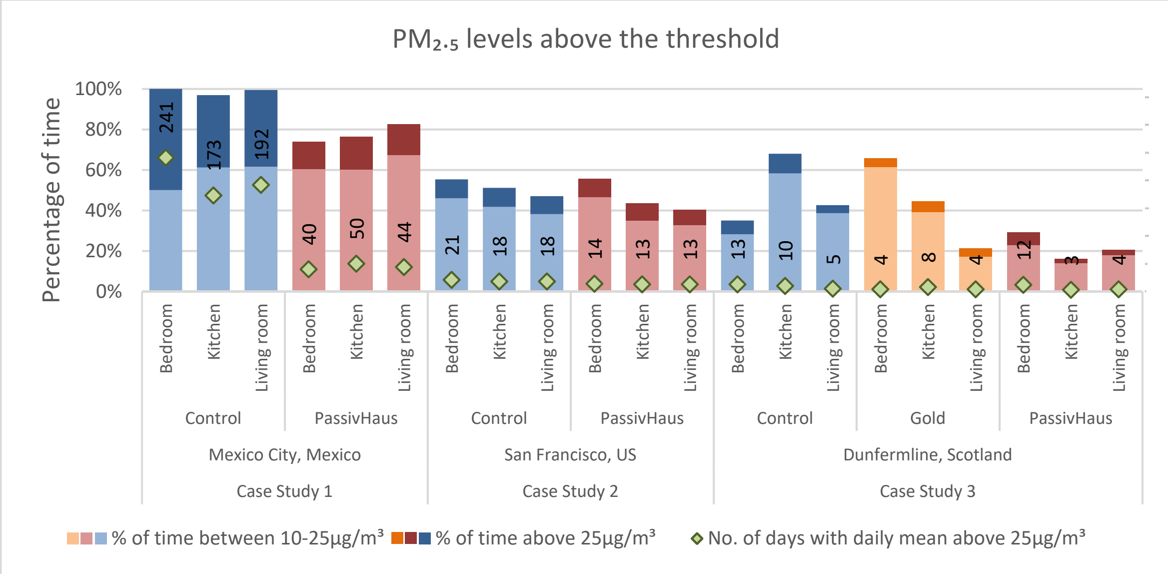


Figure 8.1 $PM_{2.5}$ levels above the thresholds during the complete period of each case study.

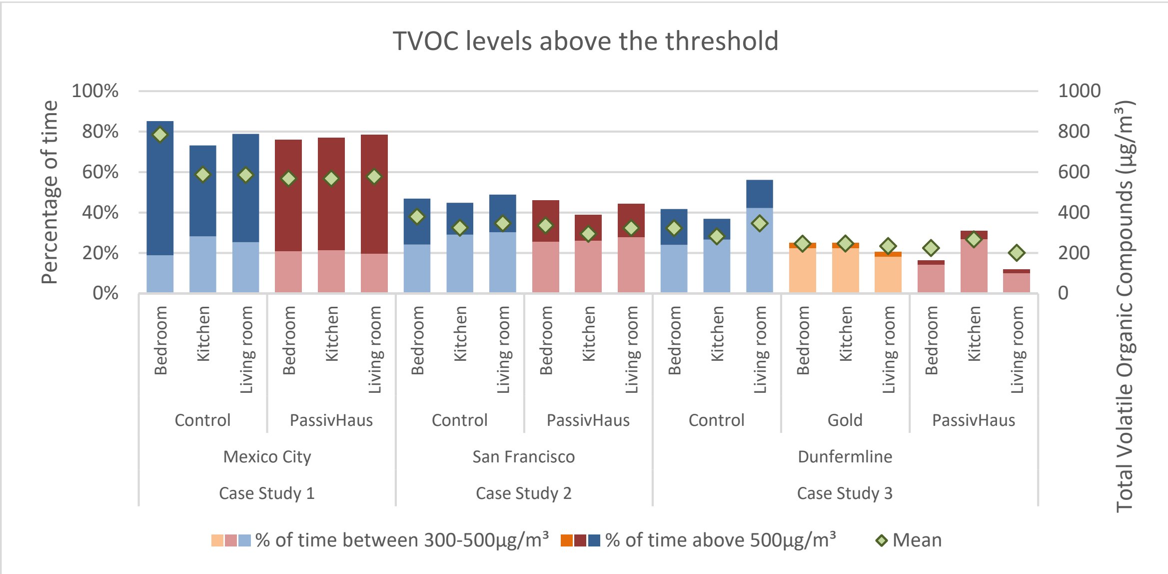


Figure 8.2 TVOC levels above 300μg/m³ and 500μg/m³ during the complete period of each case study.

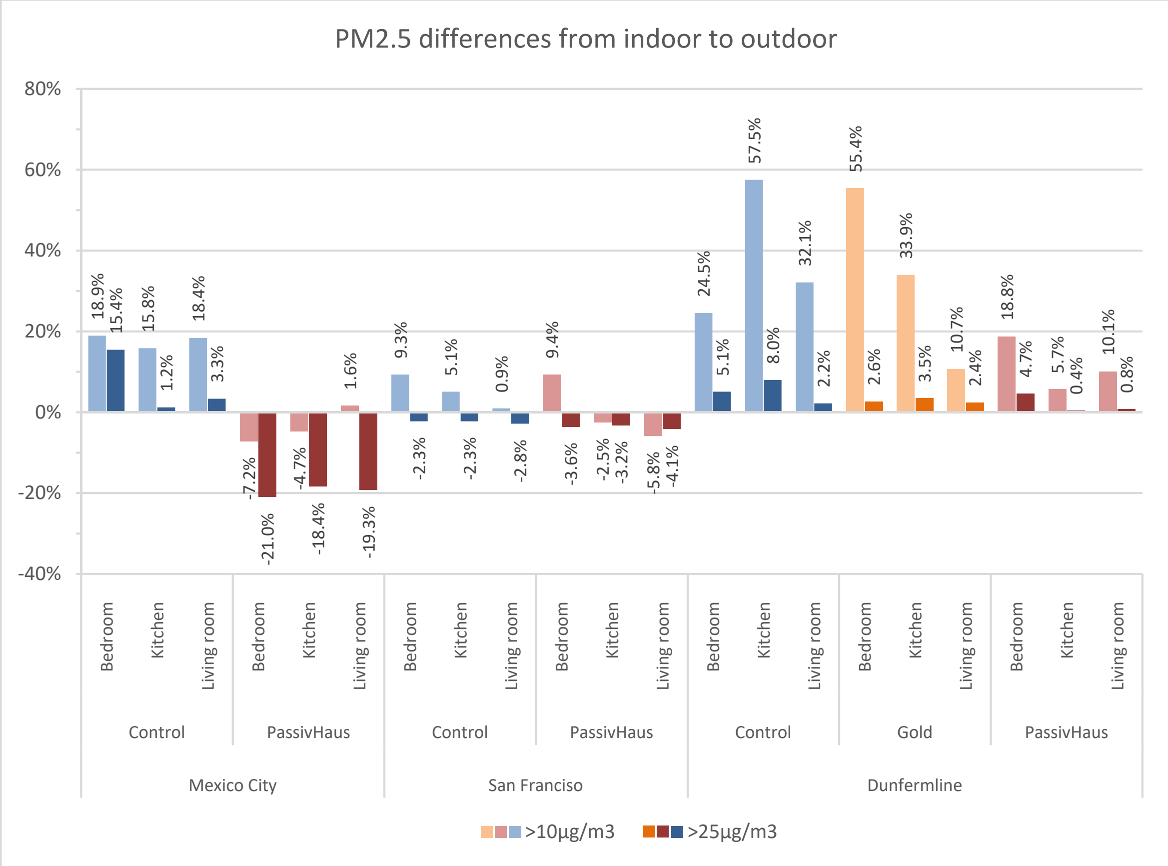


Figure 8.3 Indoor to outdoor differences of the $PM_{2.5}$ levels above the thresholds during the complete period of each case study.

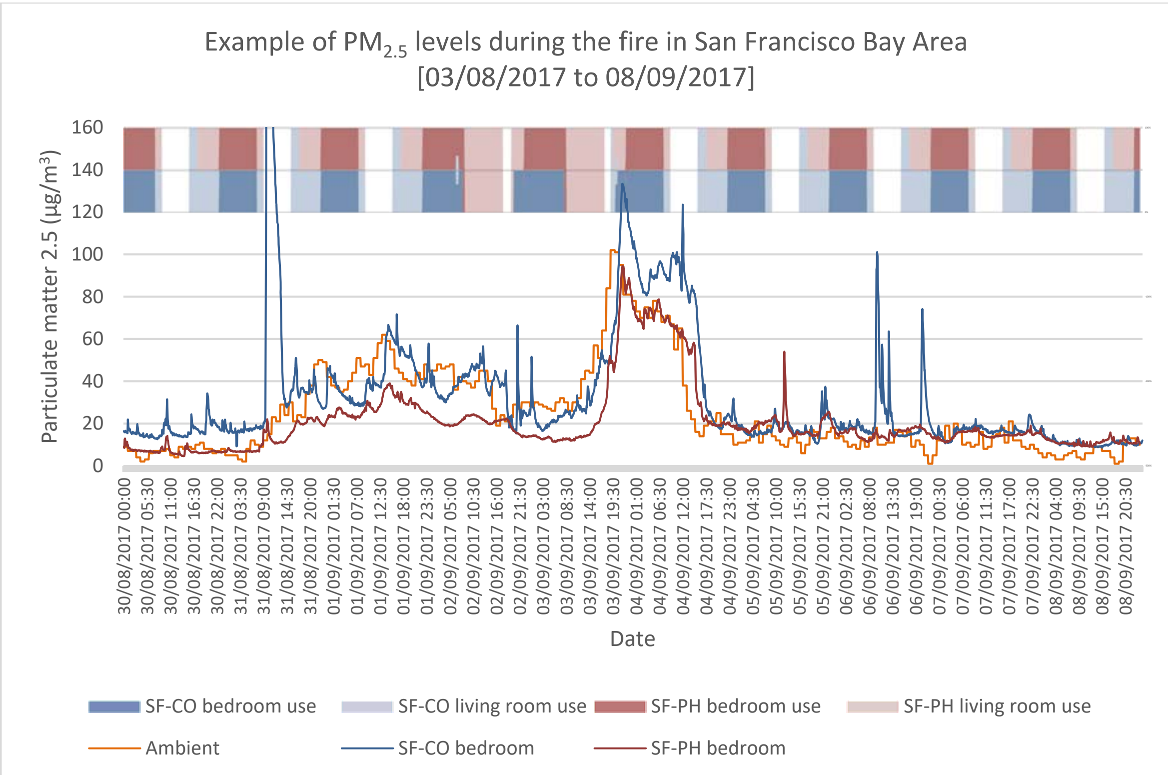


Figure 8.4 Example of $PM_{2.5}$ levels during a fire in the San Francisco Bay Area (03/08/2017-08/09/2017).

Similar to $PM_{2.5}$ concentrations, PassivHaus dwellings tVOC levels were lower than in the other dwellings. Although these differences were statistically significant, San Francisco and Dunfermline, they were minimal. This suggests that tVOC were strongly related to human behaviour and outdoor concentrations. $PM_{2.5}$ and tVOC high concentrations appear to be related to some human activities; for instance, K. H. Kim et al. (2014) found that PM and tVOC were constantly generated at high concentrations during cooking. The highest extreme in this study in terms of tVOC pollution was Mexico City, where the high outdoor concentrations (Rodolfo Sosa *et al.*, 2009), human behaviours, ventilation (Schlink *et al.*, 2004) and other conditions of the building systems, such as the flaws of the ventilation techniques described in Chapter 5, could explain this.

The high occurrence of tVOC levels above 300μg/m^3, as well as high means, suggests that background levels were relatively high with frequent pollution peaks in Mexico City and San Francisco, especially in control homes (Figure 8.5). A possible explanation for this is the lack of ventilation during nights in control homes, as windows tend to remain closed for security, when the relative trend is for high tVOC levels, especially in the bedrooms. In dwellings with mechanical ventilation, the constant air flows helped to engender a constant removal rate of tVOC. The CO_2 and tVOC graphs and analysis in Mexico City showed how the both were related emphasising the role of ventilation and occupancy on IAQ.

While this study did not measure outdoor tVOC levels, the differences between PassivHaus and control homes indicate that tVOC concentrations were higher in the control homes; though these differences were marginal in some cases, especially in San Francisco. This could be related to the different activities and *active* time spent in the dwellings.

There were some seasonal variations observed across all homes. Summer tVOC levels were higher with fewer variations (Figure 8.6) than those during winter, whereas summer $PM_{2.5}$ concentrations were lower and varied less (Figure 8.7) than those during winter. Indoor $PM_{2.5}$ concentrations in the Scottish case study were significantly higher during winter. Similarly, differences of lesser magnitudes were observed in the tVOC levels at Dunfermline. As explained before, tVOC concentrations may be influenced by human behaviours and ventilation (Schlink *et al.*, 2004), these incidences were observed in this study (see Heading 7.5.4).

TVOC concentrations are expected to rise in indoor conditions with lower ventilation and air exchanges (Rehwagen, Schlink and Herbarth, 2003); occupants were prone to keep windows closed during winter. Therefore, it could be assumed that the ventilation rates of fresh air were lower during winter. Thus $PM_{2.5}$ and tVOC concentrations were higher compared to summer when windows were frequently opened triggering higher removal rates of pollution from indoor sources, especially tVOCs.

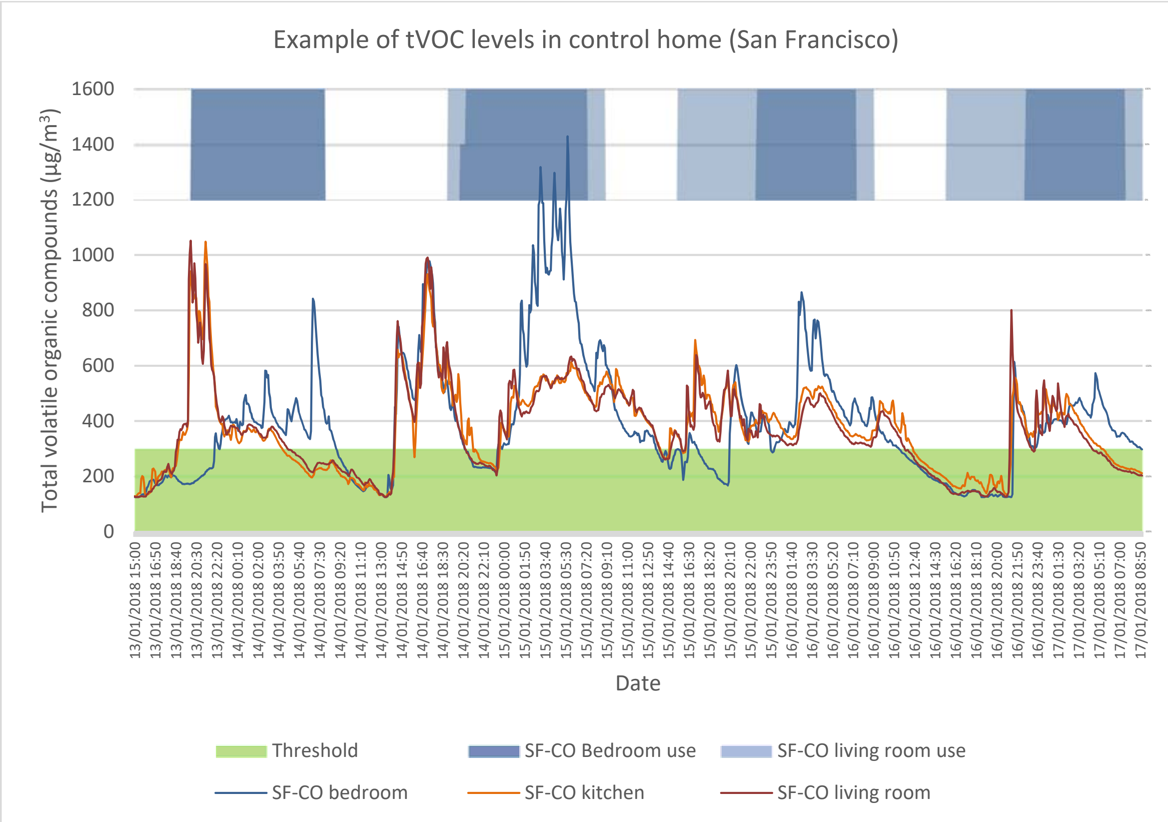


Figure 8.5 Example of tVOC background levels and frequency of pollution peaks in naturally ventilated homes (13/01/2018-17/02/2018).

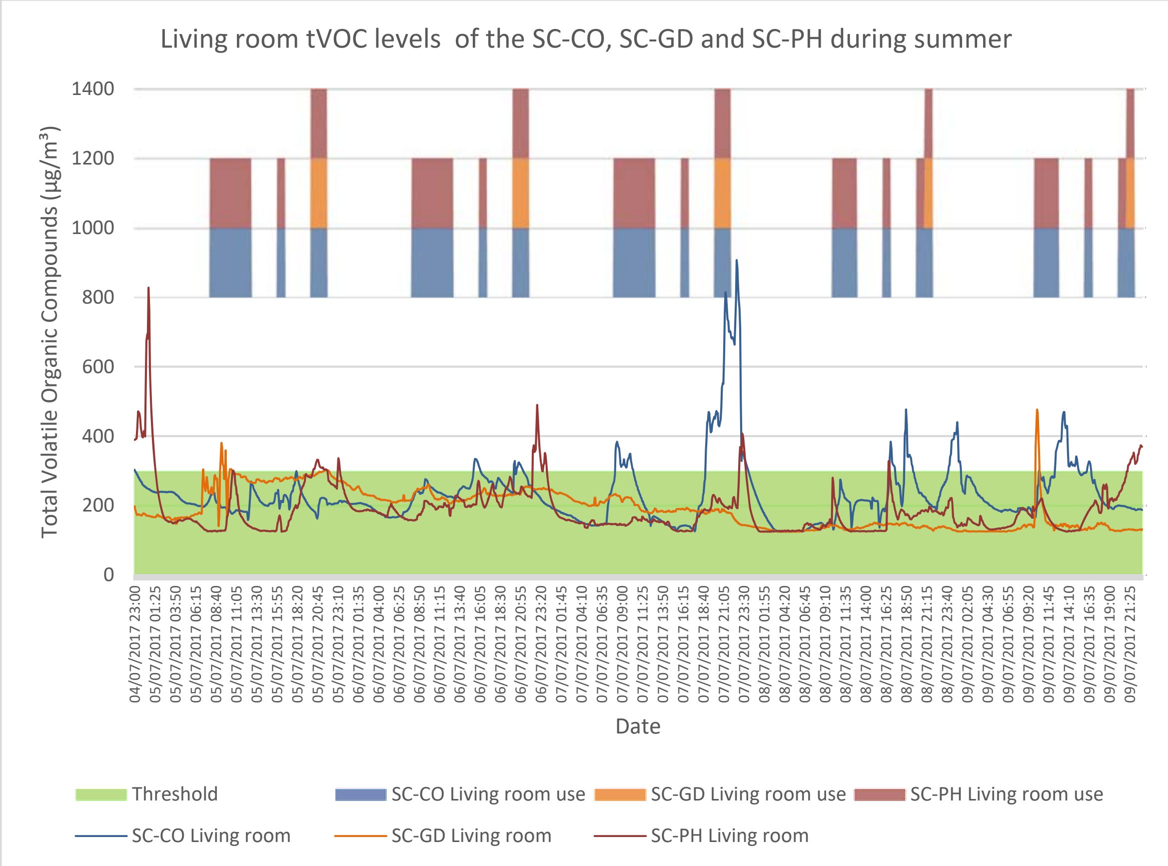


Figure 8.6 Example of a summer week of tVOC levels in the living rooms in Dunfermline (04/07/2017-09/04/2017).

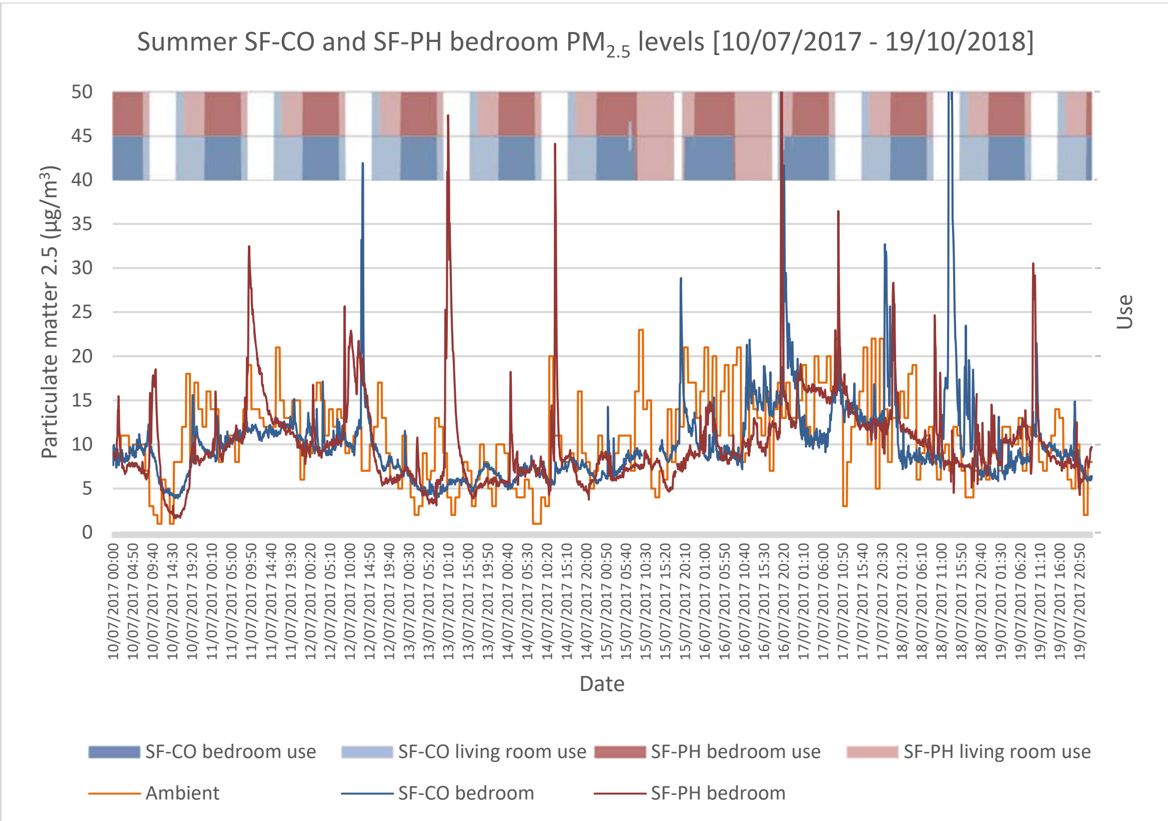


Figure 8.7 Example of a summer week of $PM_{2.5}$ levels in the bedrooms in San Francisco (10/07/2017-19/07/2017).

8.2.2 Exposure to pollutants

Reported occupancy patterns were different in all homes, and it was complex to identify exposure to pollutants in occupied periods. Periods of time with CO_2 levels above 1,000ppm in Mexico City were associated with higher $PM_{2.5}$ and tVOC levels. However, CO_2 levels were not collected in all case studies and in this study the reported occupied periods were used to identify such differences. $PM_{2.5}$ levels above 25μg/m^3 were higher during occupied periods compared to the complete- or unoccupied-period (Figure 8.8) regardless of the dwelling type. Nevertheless, homes with mechanical ventilation demonstrated a lower occurrence of time above 25μg/m^3 compared to the rest of the homes — with marginal differences in San Francisco's dwellings. Kitchens were the only room where consistently the frequency of levels above 25μg/m^3 was consistently higher during occupied periods. This suggests that indoor $PM_{2.5}$ are highly dependent on indoor sources.

Whereas tVOC in dwellings with mechanical ventilation were lower compared to control homes during the complete monitored periods, they exhibited a higher frequency of levels above 300μg/m^3 during occupied periods (Figure 8.9). Bedroom tVOC were consistently higher than the threshold limits at occupied times in all homes. Across all dwellings, the relative trends of indoor tVOC showed that levels above 300μg/m^3 in bedrooms occurred between 21:00 to 05:00 and peaked again during the morning routines (Figure 8.10 and Figure 8.11). This was observed more clearly in the control homes where the lack of ventilation during nights exacerbated the tVOC levels.

The evidence supports the notion that indoor pollution, especially tVOC, are dependant from occupant behaviours than any other factor. Indoor pollution levels of homes with mechanical ventlation was lower compared to control homes. In fact, the calculation of the area in the graphs below the pollution line indicated that they had lower exposure to pollutants, even when looking at occupied periods only.

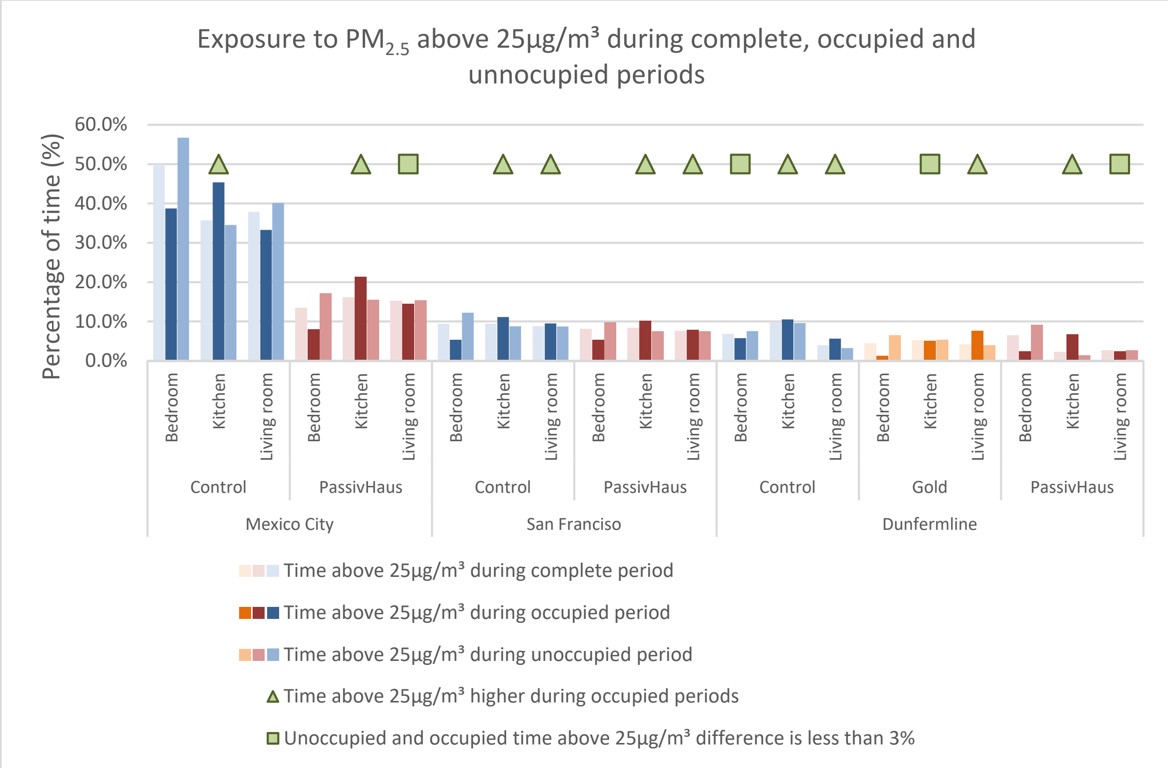


Figure 8.8 Exposure to $PM_{2.5}$ above 25µg/m³ during the complete, occupied and unoccupied periods in all case studies.

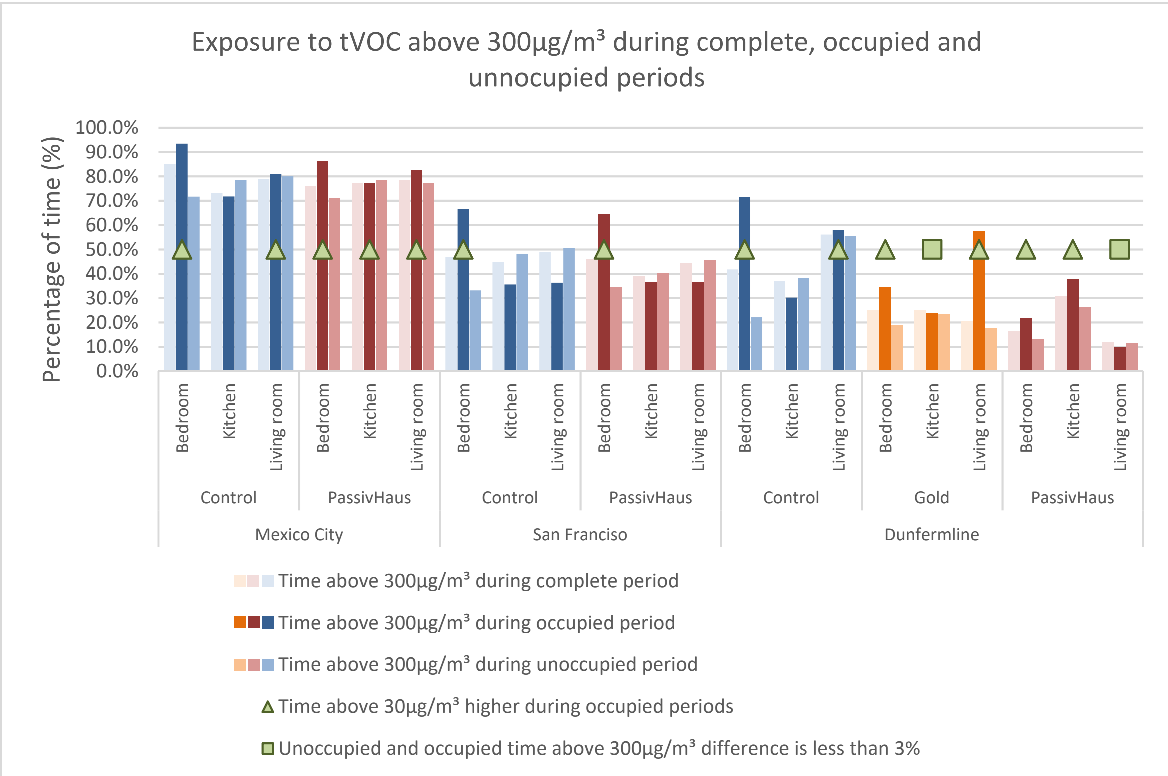


Figure 8.9 Exposure to tVOC above 300µg/m³ during the complete, occupied and unoccupied periods in all case studies.

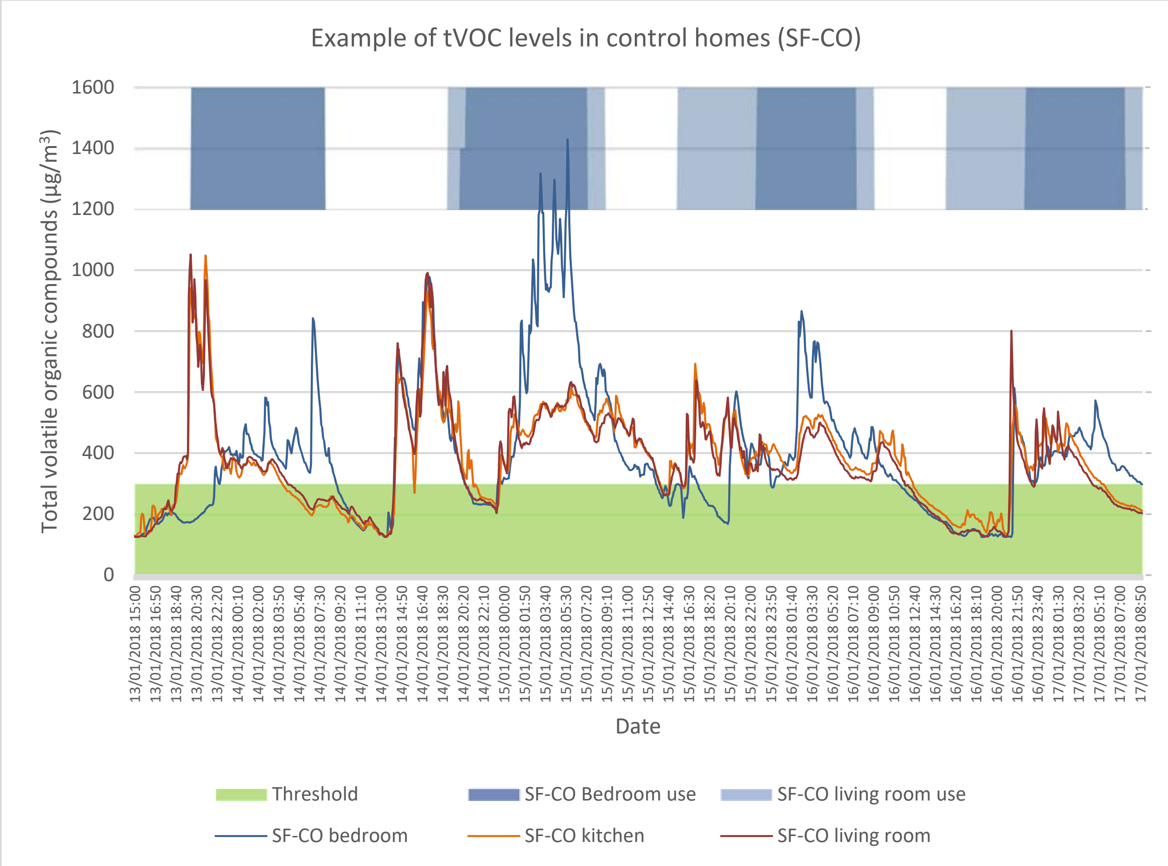


Figure 8.10 Example of tVOC trends in the control home in San Francisco (13/01/2018-17/02/2018).

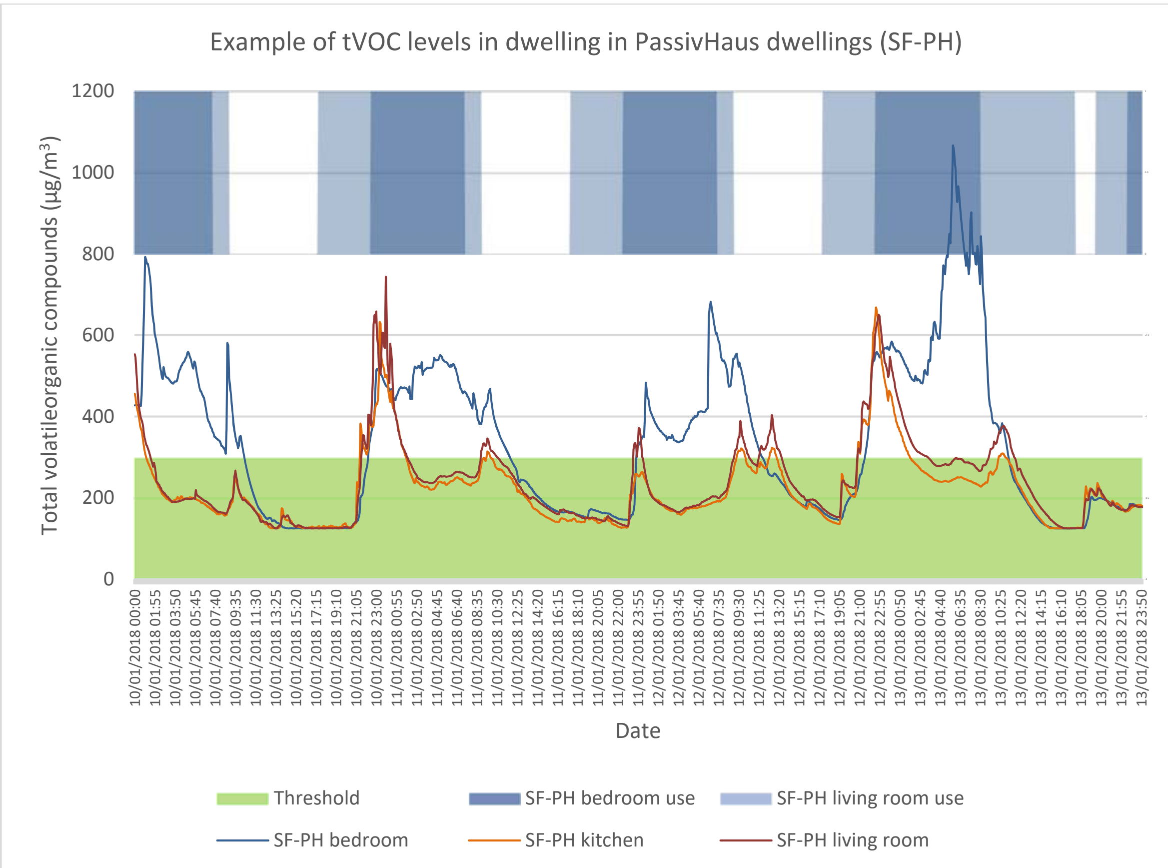


Figure 8.11 Example of tVOC trends in the PassivHaus dwelling in San Francisco (10/01/2018-13/01/2018).

8.2.3 Removal rates of indoor $PM_{2.5}$ and tVOC

Human activities, especially cleaning and cooking were likely to influence $PM_{2.5}$ production, sedimentation distribution and dissipation. As described in Chapters 5 to 7, when $PM_{2.5}$ pollution peaks where high (~>50µg/m^3), they often took longer to dissipate in the homes with mechanical ventilation compared to the control homes in cases where the windows were closed (Figure 8.12). However, when pollution peaks were lower (~>50µg/m^3), pollution in control homes took longer time to dissipate as those dwellings with mechanical ventilation (Figure 8.13). This could be explained through the characteristics of the ventilation MVHR system/fan; the settings and operation of the system and the length of the ducts can affect the distribution of particles (Bluyssen *et al.*, 2003).

If the pollution peak in the graphs is divided into two equal parts, the upper part is closest to the activity that produced it, i.e. cooking, and the bottom portion corresponds to the dissipation effect likely to be related to 'dilution' in the total volume of air in the room. The dissipation of pollution varies depending on a variety of factors, the most important being ventilation, pollution distribution and sedimentation, which themselves are affected by several parameters such as operative room temperature and relative humidity, composition of the fumes, airflows and even gravity (Lai and Chen, 2007), among other factors. The former part behaviour is very similar in all homes, but the latter part is significantly different.

The effects of particle transportation, sedimentation and distribution will continue until the particles are either removed or deposited on surfaces. However, in airtight dwellings, such as PassivHaus, air flows allow a constant but slow removal rate of pollution. Thus the dissipation may take longer. In the control homes, the removal of the pollution was faster possibly due to higher air flows when purge ventilation is used. The effect of the purge ventilation can be observed in Figure 8.12, where the bottom part of the graph compares the effect of the MVHR ventilation against the purge ventilation. Therefore, the pollution removal rates may be better in control homes, as long as windows are open. Purge ventilation could be used in PassivHaus homes, and in fact should be encouraged, for short periods to avoid energy penalties. Dissipation in dwellings with mechanical ventilation dwellings usually took longer compared to control homes, perhaps due to low ventilation rates and high levels of airtightness.

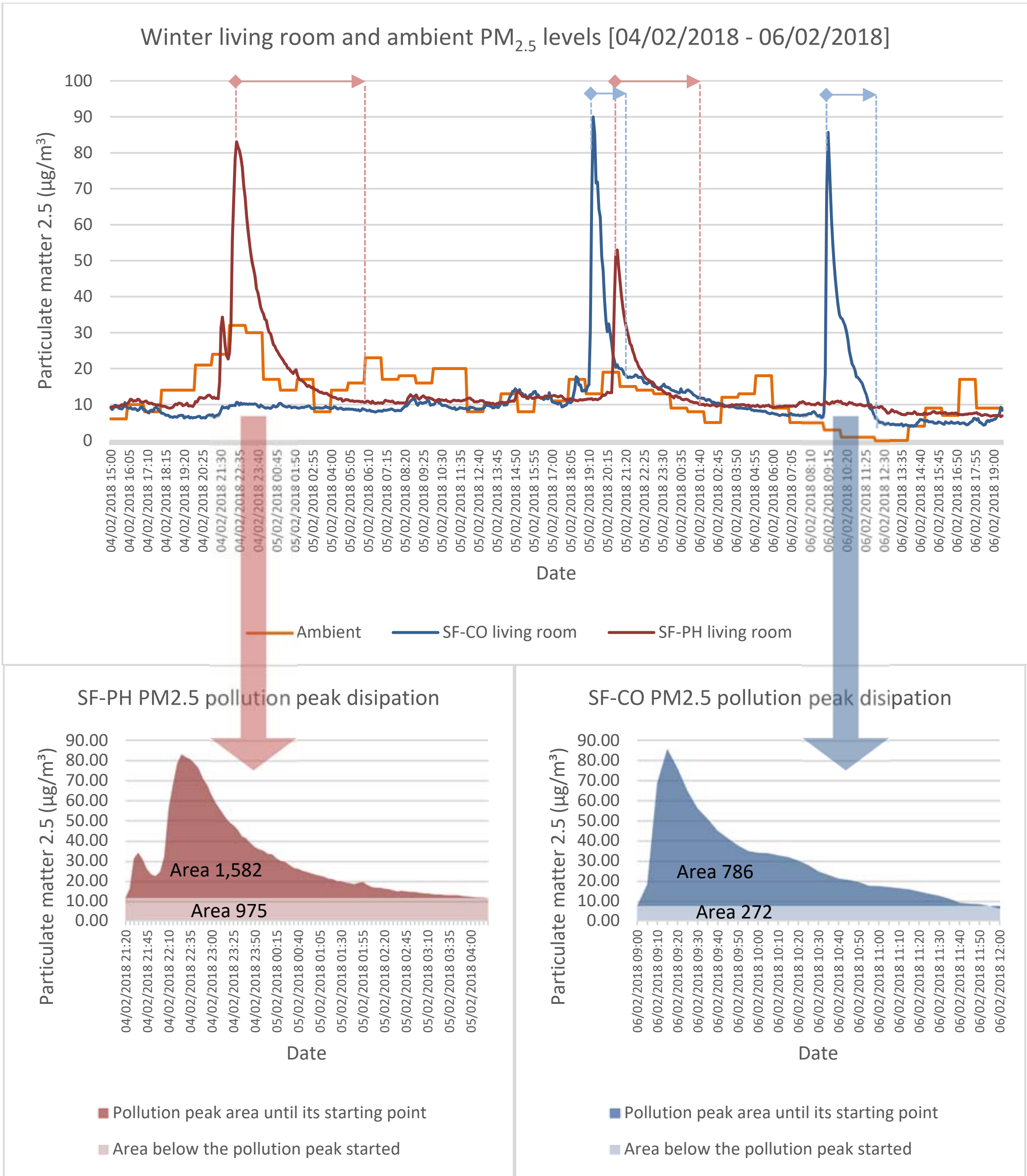


Figure 8.12 Example of pollution dissipation in the San Francisco case study (13/01/2018 06:00-19:00).

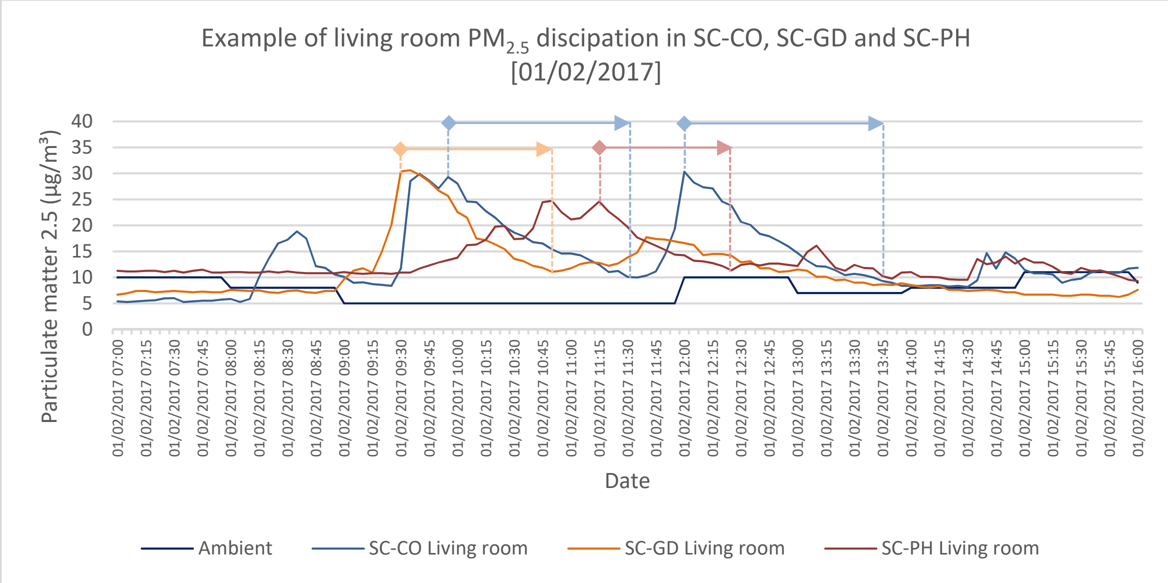


Figure 8.13 Example of pollution dissipation in the Dunfermline case study (01/02/2017 07:00-16:00).

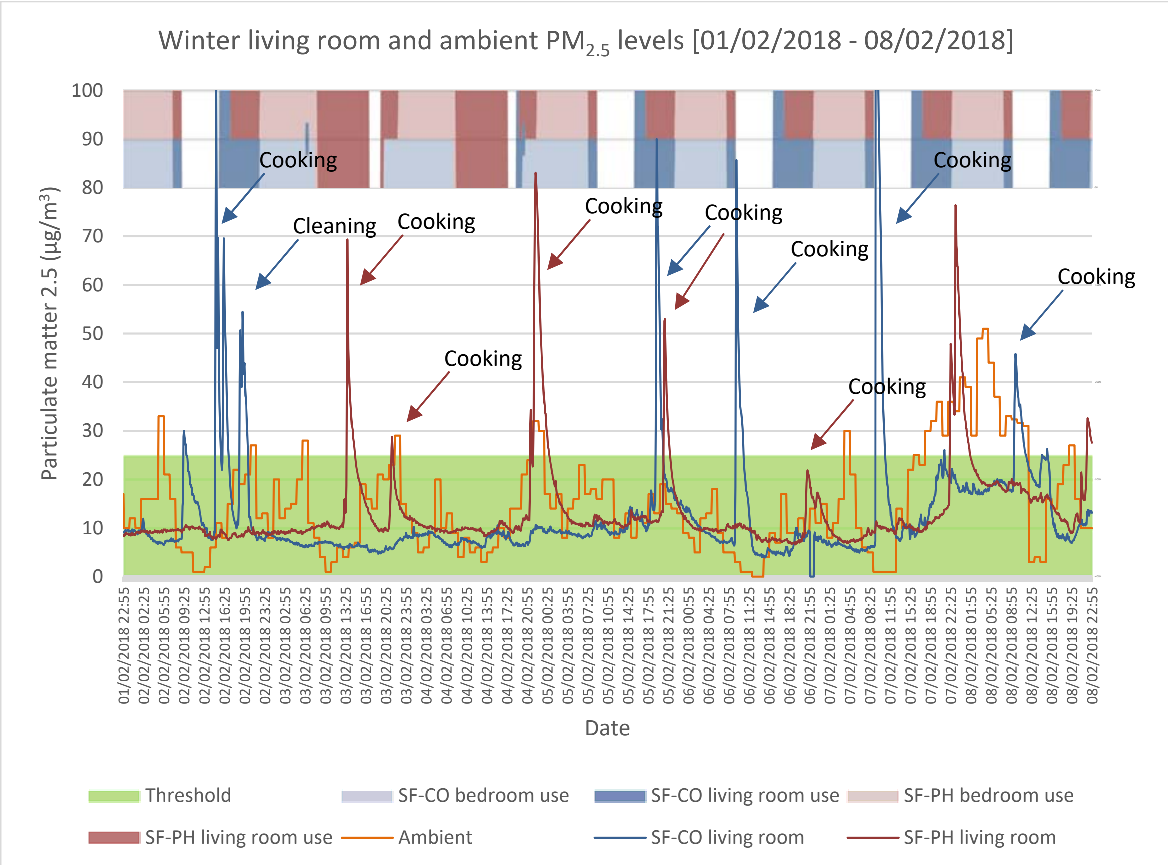


Figure 8.14 Example of $PM_{2.5}$ removal rates from the bedroom in San Francisco from the 01/02/2018 to 08/02/2018.

TVOC pollution removal rate seems to have no significant impact on the way tVOC pollution dissipates comparing the mechanically ventilated dwellign to the control homes (Figure 8.15). In both homes in Mexico, CO_2 and tVOC removal rates were very similar, which sugests that ventilation is the most important factor to control them after occupant behaviours. Most of the tVOC levels above 300µg/m^3

and pollution peaks occur during the night and early morning when windows may remain closed. The benefit of ventilation systems is the continuous air flow, thus allowing for gradual – slow and constant - removal rates compared to control homes. So, one can argue that dwellings with ventilation systems may have appropriate air exchange rates during the night compared the control homes, therefore achieving lower background tVOC levels.

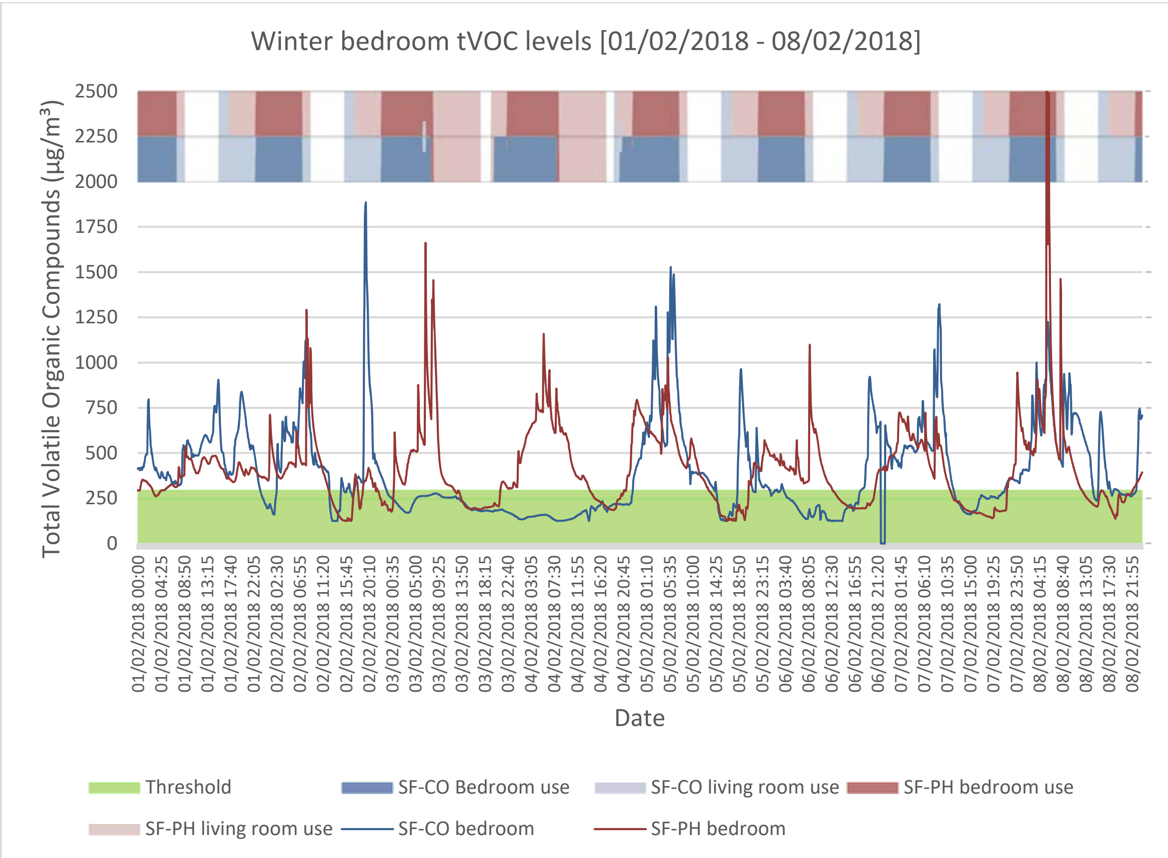


Figure 8.15 Example of tVOC removal rates from the bedroom in San Francisco (01/02/2018-08/02/2018)

8.2.4 Frequency of indoor $PM_{2.5}$ and tVOC pollution peaks

The frequency of the pollution peaks may be as important as the severity of the concentrations and removal rates, as pollution peaks are likely associated with periods of human activity (Cheng *et al.*, 2016). Activities such as cooking, cleaning and window opening have a clear impact on the frequency of pollution peaks (Figure 8.16-8.17). Nevertheless, occupant interactions with the building (use of cooker hoods, window opening, operation of the ventilation system, etc.) also impact on the frequency pf pollution peaks.

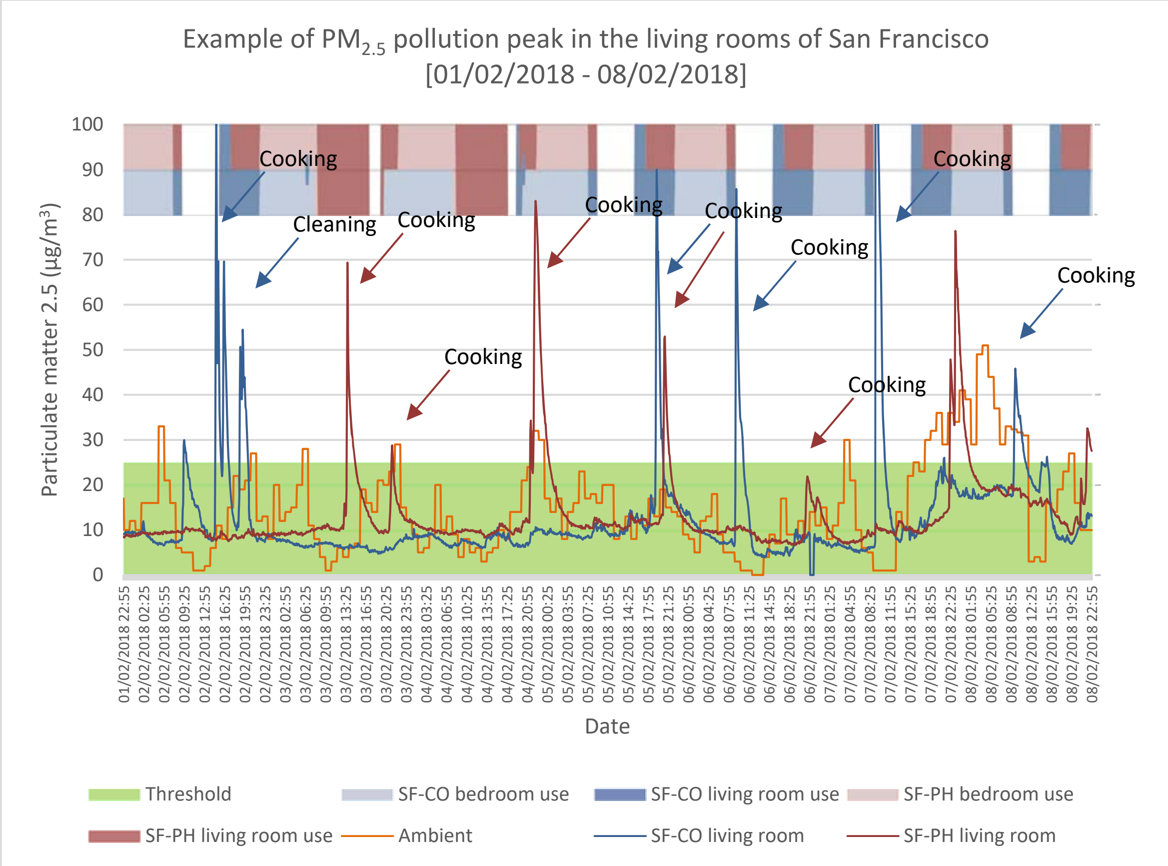


Figure 8.16 Example of PM2.5 pollution peak in the living rooms of San Francisco from the 01/02/2018 to 08/02/2018.

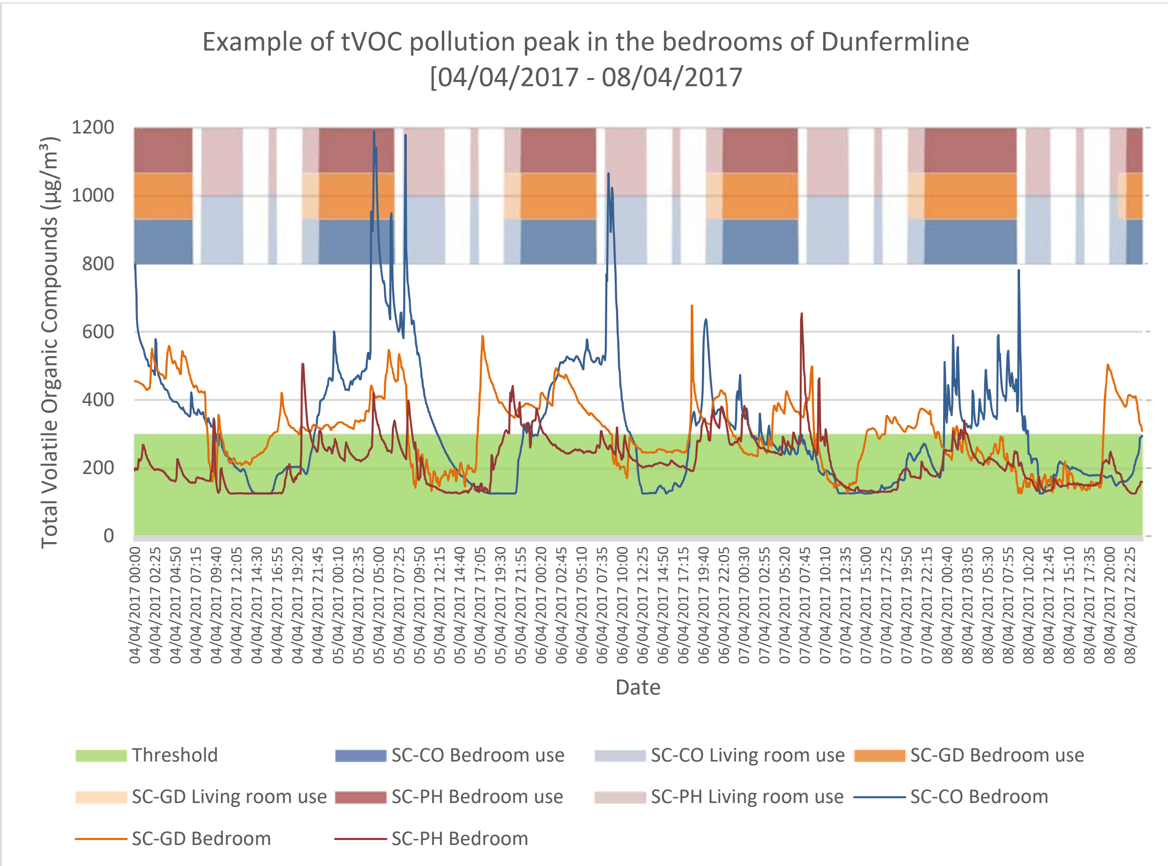


Figure 8.17 Example of tVOC pollution peak in the bedrooms of Dunfermline from 04/04/2017 to 08/04/2017.

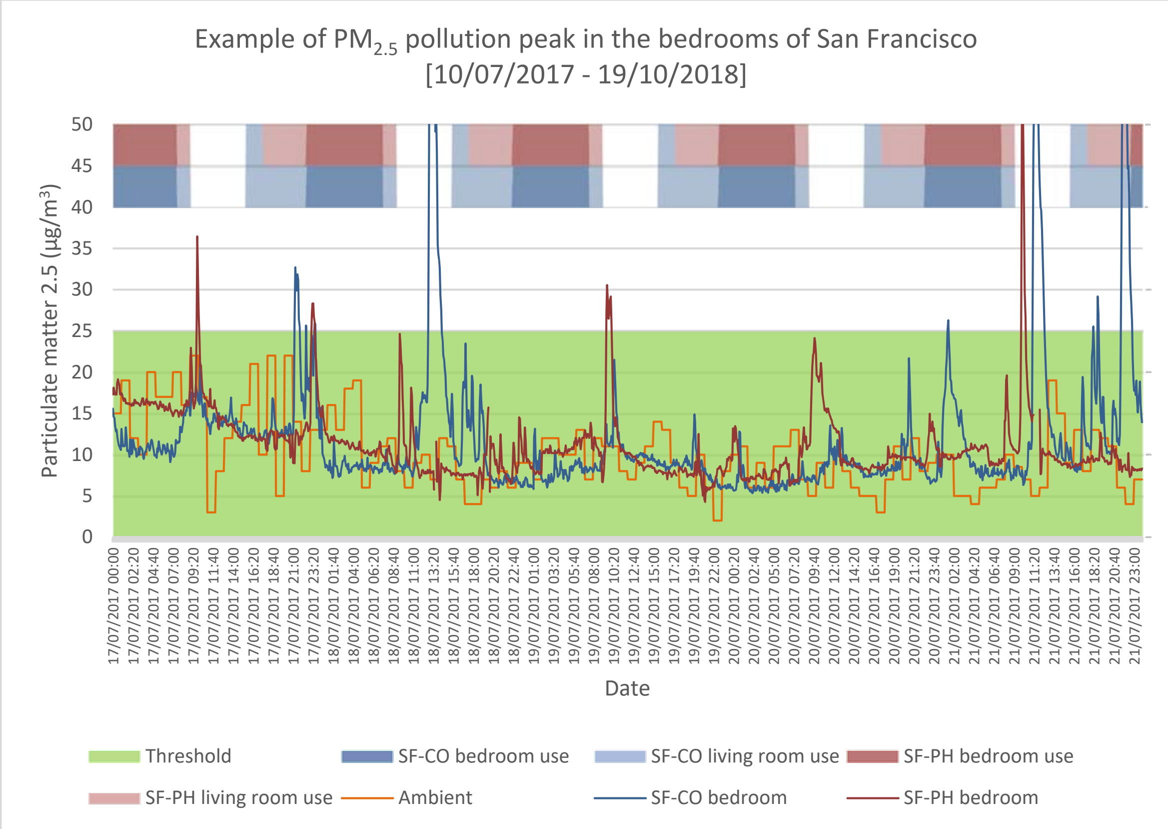


Figure 8.18 Example of $PM_{2.5}$ pollution peak in the bedrooms of San Francisco from the 01/02/2018 to 08/02/2018.

Continuous ventilation may help to dissipate and extract the cooking fumes as ventilation extraction is located in the kitchen areas. However, when windows were open, the pollution peaks were less frequent compared to periods with closed windows, especially in bedrooms (Figure 8.18). The frequency of pollution peaks were higher in mechanically ventilated dwellings but they were more severe in control homes.

Low-energy home, including PassivHaus, occupants are more dependent on the building systems (Blight and Coley, 2013) and automation (Schieweck *et al.*, 2018) as an energy-saving strategy, though they rarely engage with the systems. It has been reported that PassivHaus occupants rely more on the MVHR system to provide ventilation rather than manually opening the windows (Brunsgaard, Knudstrup and Heiselberg, 2012) resulting in lack of *purge ventilation*. In this study, the control houses were more prone to open the windows allowing purge effect, whereas PassivHaus occupants relied on the ventilation system and rarely used the boost function during activities that produced indoor pollution. This suggests that dwellings with mechanical ventilation are less efficient in dealing with peak loads, as occupants rely entirely on the ventilation system without engaging with it.

8.2.5 Overheating and humidity

PassivHaus was developed to provide low energy thermal comfort (Hopfe and McLeod, 2015) in homes, so it might have been expected that it would reduce the risk of overheating, thus providing better comfort. However, studies that have measured temperatures in PassivHaus dwellings have reported incidences of overheating and drier indoor environments (Ridley *et al.*, 2013, 2014; Figueiredo *et al.*, 2016; Fokaides *et al.*, 2016; Rojas *et al.*, 2016). For this study, the frequency of overheating was assessed accordingly to the static (PHPP and CIBSE Guide A) and dynamic (CIBSE TM52) criteria. Although, operative temperatures are used to describe the PHPP, and CIBSE criteria, for practical reasons (Dengel *et al.*, 2016) and the limitations of the Foobot (Chapter 2) air temperature was used to assess the frequency of overheating. The humidity is presented as the percentage of time below 40%RH (CIBSE) and above 60%RH (EPA), as well as with the PassivHaus criterion and the threshold for house dust mites for vapour content.

8.2.5.1 Static criteria (PassivHaus and CIBSE)

Figure 8.19 shows the percentage of hours air temperatures exceeded the PassivHaus overheating threshold of 25°C. This suggests that only the living room of the control house in Dunfermline and the kitchen in the Dunfermline PassivHaus may suffer from overheating. However there was a significant difference (>55%) between the rooms in Dunfermline’s control house: as described in Chapter 7, the analysis of the temperatures suggested that the occupants may have placed a Foobot near to a source of heat and this may have influenced the results. It is observed that PassivHaus dwellings exhibited a higher frequency of temperatures above 25°C, but they did not fail the static criteria.

Using the CIBSE threshold (CIBSE *et al.*, 2006) of 5% of the occupied hours exceeding 23°C for the bedrooms and 25°C for the living rooms (Figure 8.20) and the CIBSE threshold of 1% of the occupied hours exceeding 26°C for the bedrooms and 28°C for the living rooms (Figure 8.21), all the bedrooms failed the criteria, with exception of the Gold in Dunfermline. None of the rooms in the Gold dwelling exceded this criterion. There is no significant difference in the prevalence of overheating accordingly to the CIBSE criteria occurred in the three rooms of the control and PassivHaus dwellings; however, the analysis showed that PassivHaus homes had longer periods over the recommended operative temperatures during occupied hours than recommended by CIBSE.

A tendency of overheating was not observed in PassivHaus dwellings, based on the PassivHaus criteria, though it was under the CIBSE criteria. It was also observed that PassivHaus dwellings often recorded a higher number of hours exceeding the criteria. These differences could also be related to differences in geometry, building occupancy and occuant behaviours.

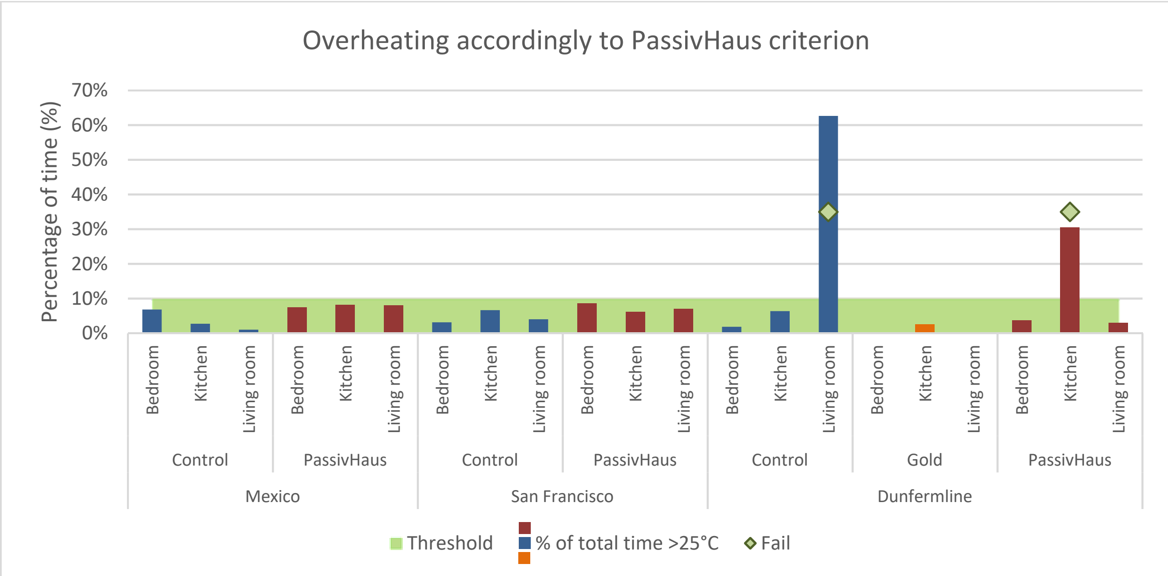


Figure 8.19 Percentage of time air temperature exceeded 25°C assessed accordingly to the PassivHaus criterion.

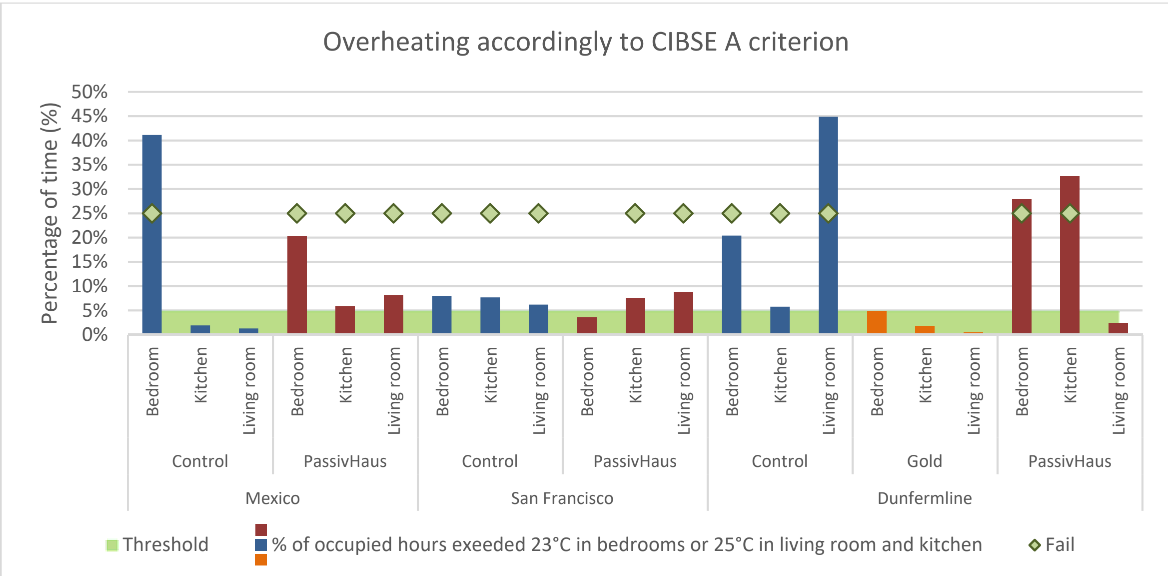


Figure 8.20 Percentage of time air temperature exceeded 23°C in bedrooms and 25°C in living rooms assessed accordingly to the CIBSE criterion A.

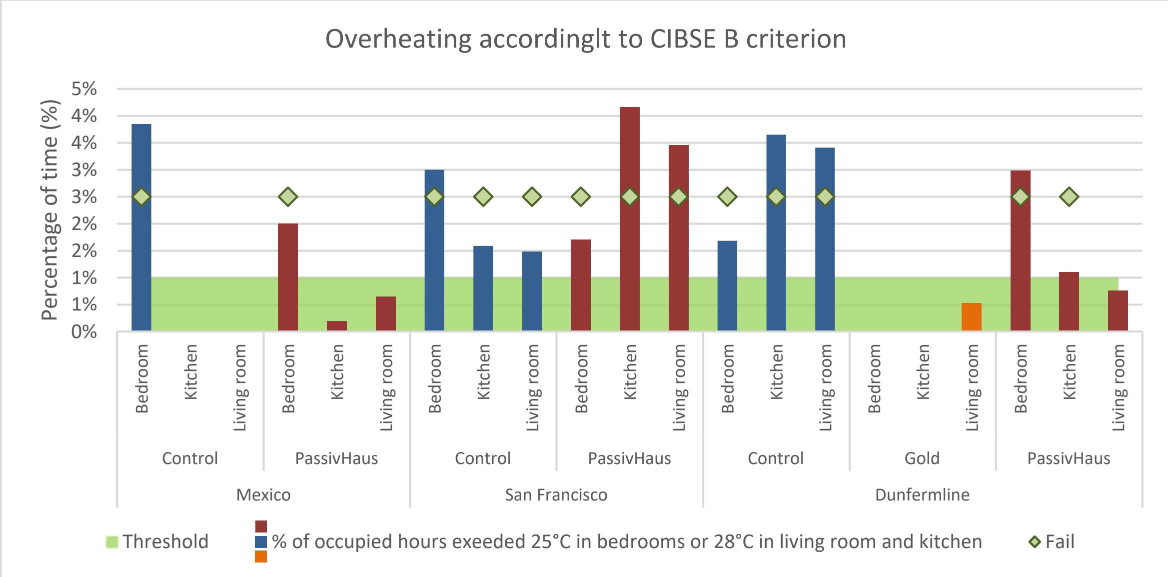


Figure 8.21 Percentage of time air temperature exceeded 25°C in bedrooms and 28°C in living rooms assessed accordingly to the CIBSE criterion B

8.2.5.2 Adaptive method

The temperature difference between the maximum acceptable and air temperature differences (ΔT) during the occupied hours were calculated for 1st May to 30th September in each of the homes. When data for the whole period was not available, it was estimated over the available hours as described in the TM52b (CIBSE, 2013). Mexico City dwellings did not fail the criteria; however, this could be related to higher outdoor temperatures which could have increased the maximum acceptable temperature, which possess the question of the acceptability of this threshold at high outdoor air temperatures. There were no significant differences between the failed criteria between the homes (Table 8.1).

8.2.5.3 Daily range of temperature variation

The range of air temperatures observed in the lightweight homes indicated that those dwellings with MVHR systems tended to have higher temperature stability. This was evident during all seasons; however, air temperatures were significantly more stable during summer compared to winter. The bedrooms had higher temperature stability regardless of the type of construction and season. However, it is apparent that the only dwelling with higher thermal mass than the others had more stable temperatures (Figure 8.22). These findings are supported by McGill et al. 2016.

Table 8.1 Overheating status based on the adaptive criteria.

			Criterion 1	Criterion 2	Criterion 3
Mexico	Control	Bedroom			
		Kitchen			
		Living room			
	PassivHaus	Bedroom			
		Kitchen			
		Living room			
San Francisco	Control	Bedroom	•	◊	○
		Kitchen	•		○
		Living room	•	◊	○
	PassivHaus	Bedroom	•		○
		Kitchen	•		○
		Living room	•		○
Dunfermline	Control	Bedroom			○
		Kitchen	•		○
		Living room	•	◊	○
	Gold	Bedroom			○
		Kitchen			○
		Living room			○
	PassivHaus	Bedroom	•	◊	○
		Kitchen	•	◊	○
		Living room	•		○

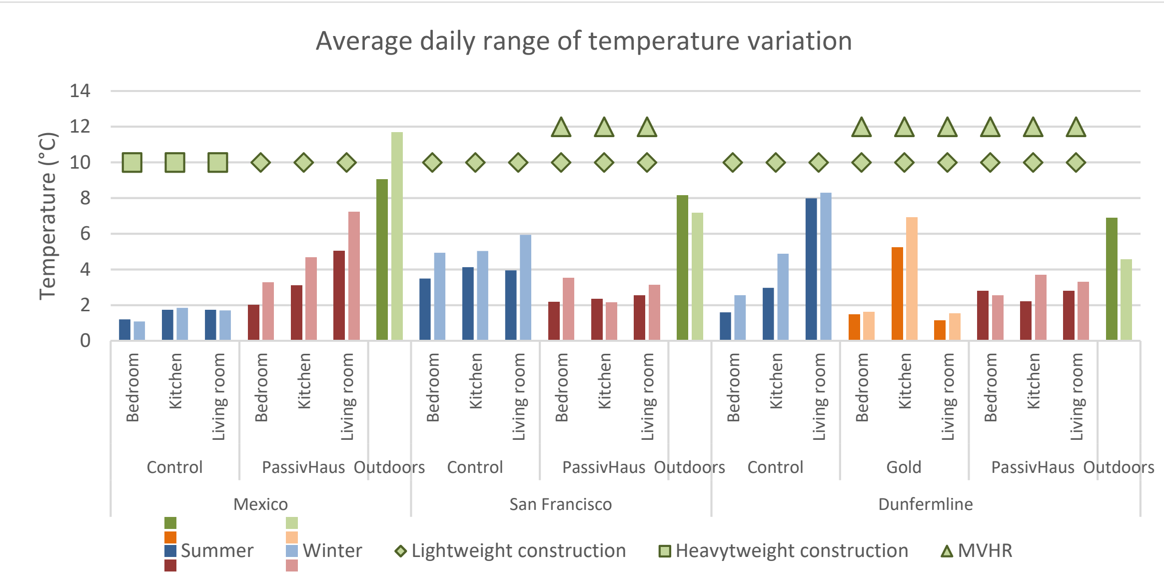


Figure 8.22 Average of daily range of temperature variation during summer and winter. Colours in the bars represent the different construction methods: blue for the control homes, red for the PassivHaus dwellings and orange for the Gold dwelling.

8.2.5.4 Relative humidity

Figure 8.23 shows the percentage of hours that the relative humidity was lower than 40%RH and exceeded 60%RH. Indoor relative humidity in all dwellings was lower than outdoors. However, PassivHaus dwellings were associated with much lower relative humidity levels and a higher frequency of levels below 30%RH compared to the control homes. The Dunfermline control home's living room was an outline, however, in this case, the unusually high temperatures in this room could be masking the real humidity levels. It is interesting to note the significant differences between the humidity levels of the PassivHaus in Mexico City and Dunfermline compared to those in San Francisco. San Francisco's MVHR system - Air Pohoda iERV-240 - was specially designed for temperate climates that allow for humidity control. Thus, the differences could be related to the settings of the relative humidity settings in the system and the use of bypass mode during summer.

Relative humidity is temperature dependent, so it is important to examine them accordingly to the comfort ranges. In this study, the ideal comfort range relates air temperatures between 20-25°C with relative humidity between 40-60%RH, whereas the extended limit uses 18-28°C and 30-70%RH. Figure **8.24** shows a summary of the psychrometric analysis and the relation between relative humidity and temperature. As the moisture content in the air is relative to the air pressure in each location, it was examined separately.

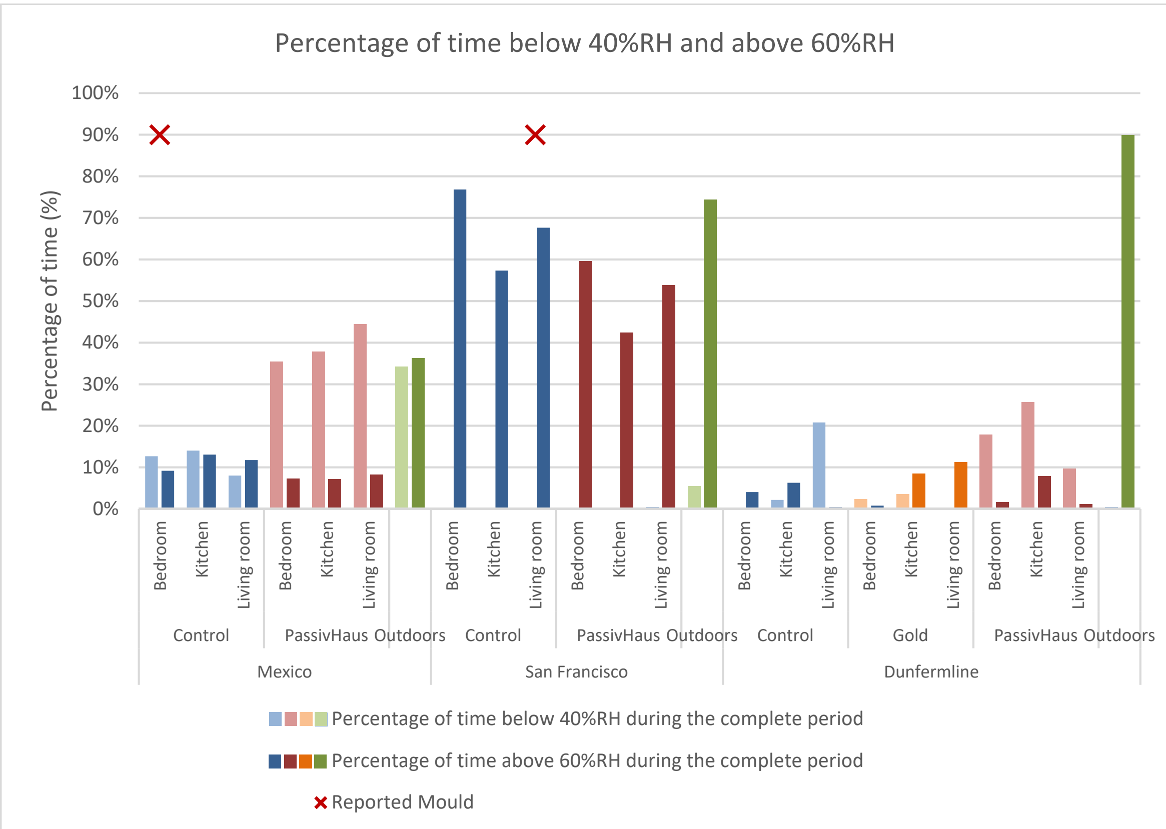
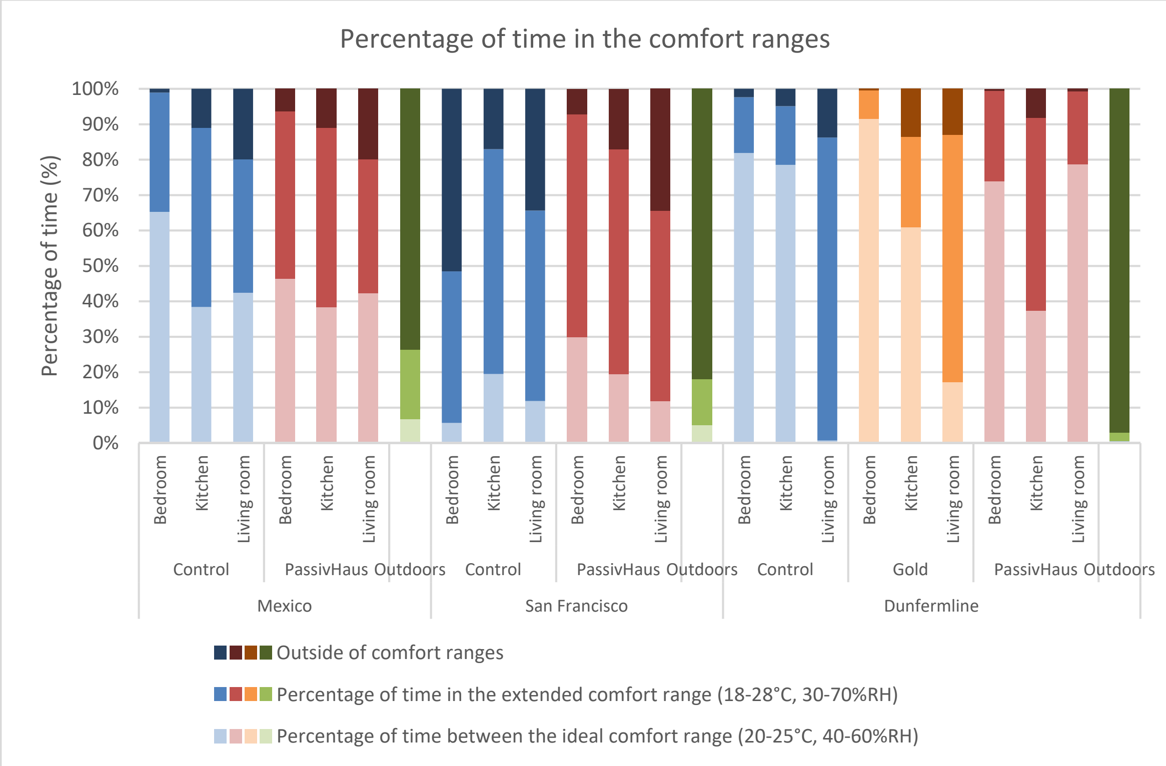


Figure 8.23 Percentage of time below 40%RH and above 60%RH.



8.2.5.5 Figure 8.24 **Percentage of time between the comfort ranges. Vapour content**

As RH is a function of temperature is more useful to examine actual vapour content. Figure 8.25 shows the percentage of hours that exceeded vapour levels of 12g/kg as described by the PHPP and the CEH *Dp* and *Df*. The frequency of levels above 12g/kg was higher in all dwellings compared to those found outdoors. This suggests that indoor sources of humidity are important regardless of the ventilation technique used. The CEH *Dp* and *Df* thresholds were significantly exceeded in both homes San Francisco, whereas the CEH *Df* was exceeded in Mexico in both flats. Only both dwellings in San Francisco and the bedroom in the control home in Mexico failed the PassivHaus humidity criteria (>12g/kg during 20% of the occupied time). Similarly to the relative humidity levels, the vapour pressure levels in San Francisco were significantly higher in the PassivHaus compared to the other PassivHaus dwellings.

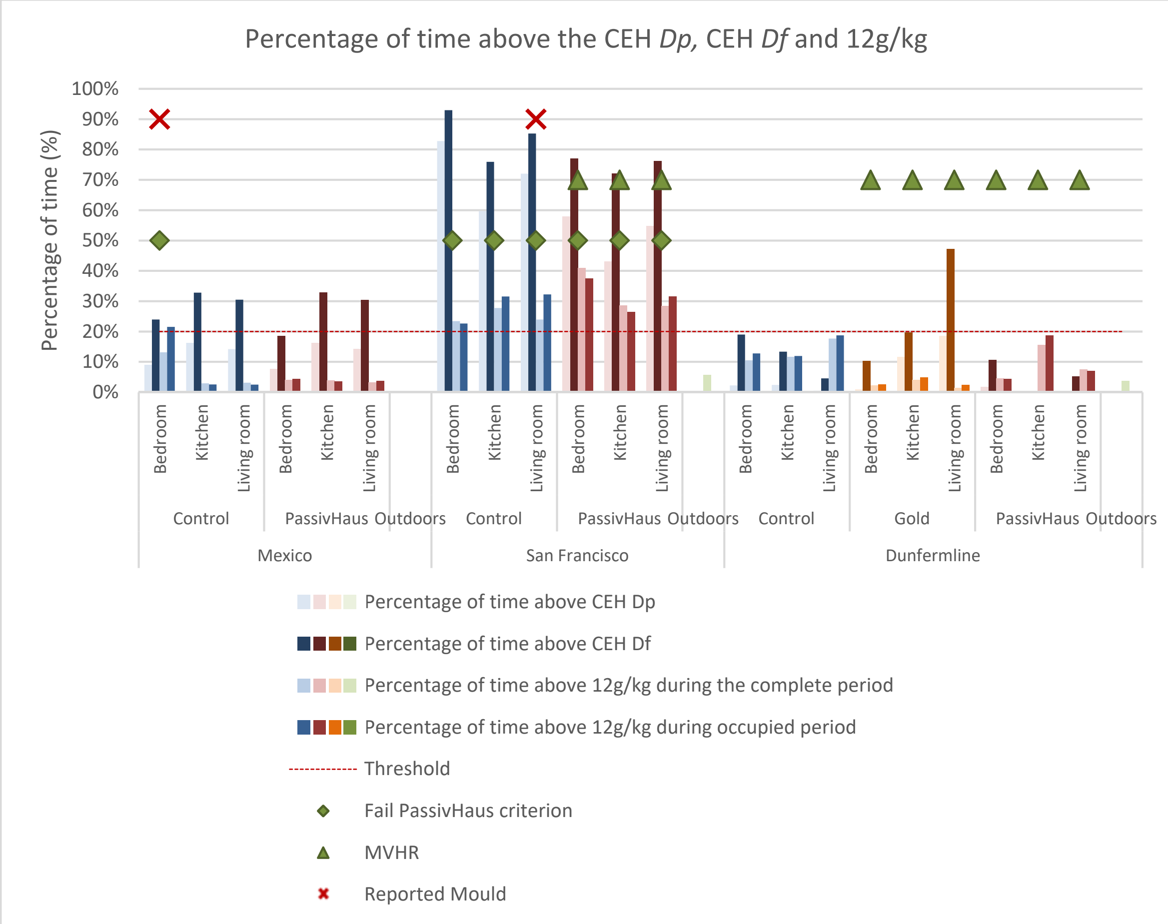


Figure 8.25 Percentage of time above 12g/kg CEH *Dp* and CEH *Df*.

8.1 Occupant perceptions

As described in Chapter 4, occupants were asked for their perceptions of IAQ and thermal comfort in their homes. On the unipolar scales (grey background), a score of higher than 3 requires further investigation (medium tone) and a score higher than 5 is a cause of concern (dark tone), whereas on the bipolar scales (green background) a score outside of the range between 3 and 5 requires further investigation (medium tone), and a score outside of the range 2 to 6 is a cause of concern (dark tone).

8.1.1 Indoor air quality perceptions

The rating of the air movement scale (still (1) to draughty (7)) suggests that there was significant variance between the households. The control homes scores were associated with the draughty side of the scale, whereas the PassivHaus and Gold dwellings tended towards the still side. However, all of the scores for the PassivHaus dwellings for summer and winter remained in the ideal range, except the winter score in Mexico City (rated as still, Figure 8.26).

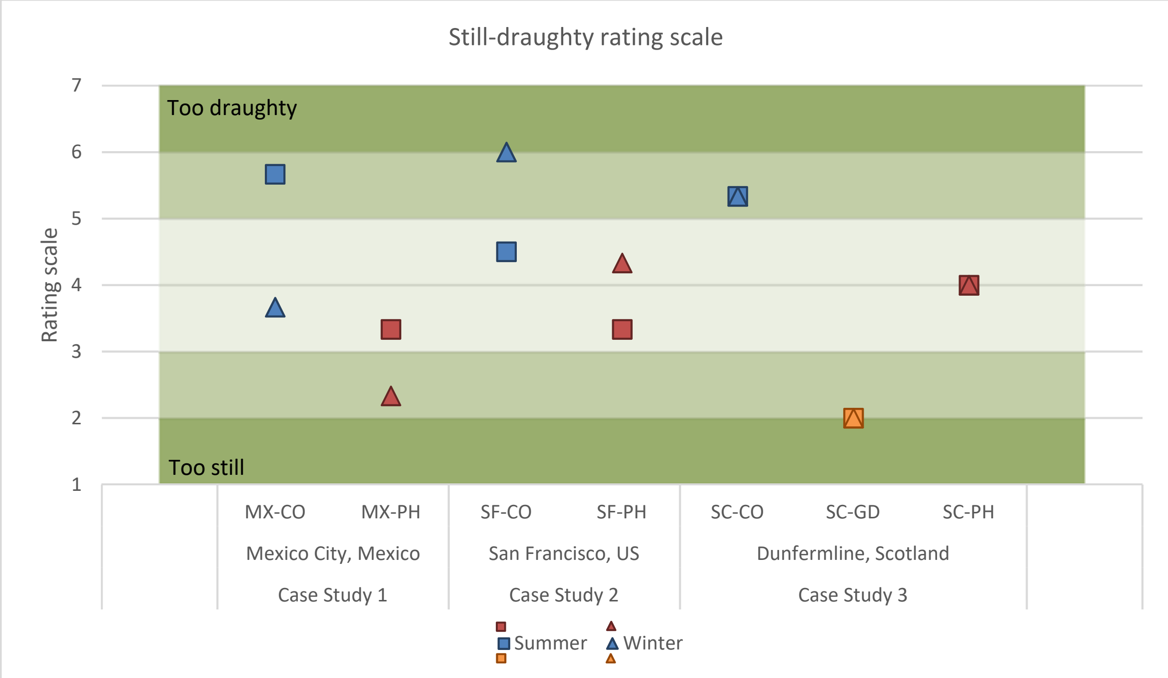


Figure 8.26 Scores for air movement on the bipolar scale: still (1) to draughty (7).

The rating for the "dry (1) to humid (7)" scale indicates that the occupants associated air to be neither humid nor dry in most cases. However, the ratings of two dwellings suggested that further investigation is needed, as the air was perceived to be humid during the summer and winter by the occupants of the PassivHaus in Dunfermline and during summer in the control home in San Francisco. Occupants of the Gold dwelling stated the air to be too dry and rated it as a cause of concern in summer and winter (Figure 8.27). Results from the humidity perception and the measured RH converge in the naturally ventilated home in Mexico City and both dwellings in San Francisco; however, in the other cases, significant differences were observed. Measured RH revealed that PassivHaus dwellings had a drier environment compared to the control homes, but this was not clear from the occupant's perception. The significant difference in the Gold dwelling results could be related to the fact that occupants perceived the air to be dry but acted to increase the humidity, as reported previously. Reported mould converges with high humidity (perception and measured) in San Francisco (mould in the living room) but is not evident in Mexico City, where the mould was reported only in bathrooms.

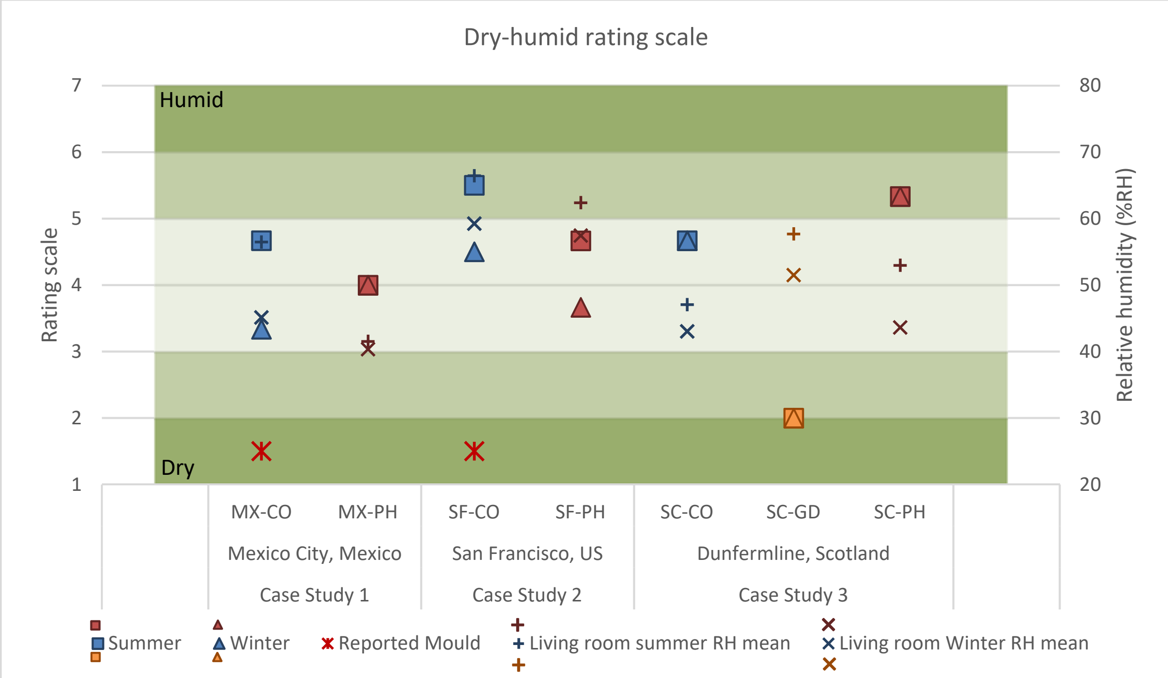


Figure 8.27 Scores for the bipolar scale: dry (1) to humid (7).

The rating of the "fresh (1) to stuffy (7)" scale indicates that winter perceptions were associated with fresher air, especially in the PassivHaus dwellings. However, a total of four homes rated the freshness of the air in such a way that they require further investigation for winter, and five for summer. The results demonstrate that the occupants were not content with the freshness of the air in Mexico City and San Francisco, or the control home in Dunfermline (Figure 8.28). CO_2 measurements were conducted only in Mexico City and compared to the perception of air freshness, only the results from winter converge to each other. Whereas the PassivHaus had lower levels of CO_2 which could be associated with higher ventilation rates and fresh air this was not perceived by the occupants and could be related to outdoor conditions.

Scores for the "odourless (1) to smelly (7)" indicate a variation between the households in both seasons. One of the households rated it as a cause of concern for summer, while two more suggested further investigation. All three were control homes. The three winter scores for the control homes suggest that further investigation may be needed, but two of them were scored 5, thus suggesting that occupants might have problems if the issue is not addressed (Figure 8.29). Odours from the outdoor, toilets and kitchen were frequently reported in the case studies, especially in the control homes.

The scores for "overall satisfaction (1) to overall dissatisfaction (7)" indicate that five of the dwellings, including the three PassivHaus buildings, were satisfied with IAQ. The control homes were associated with poor satisfaction. One of these dwellings rated overall satisfaction as a cause of concern and another as requiring further investigation for winter. The rate of two residences suggests further investigation for summer (Figure 8.30).

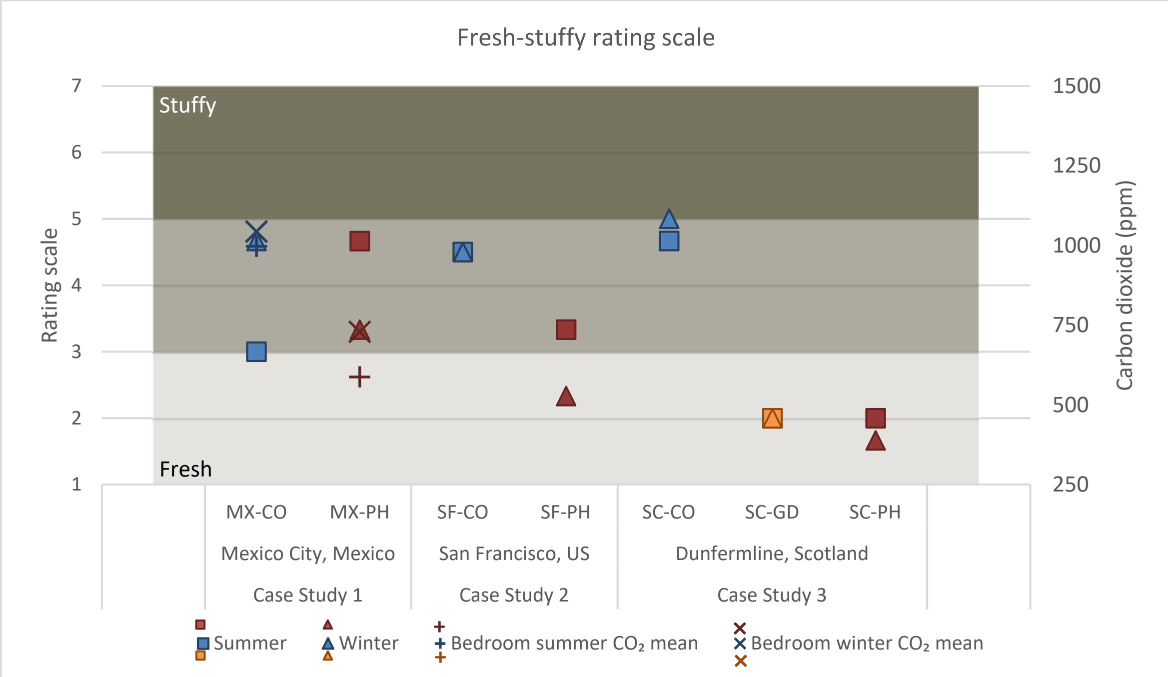


Figure 8.28 Scores for the unipolar scale: fresh (1) to stuffy (7).

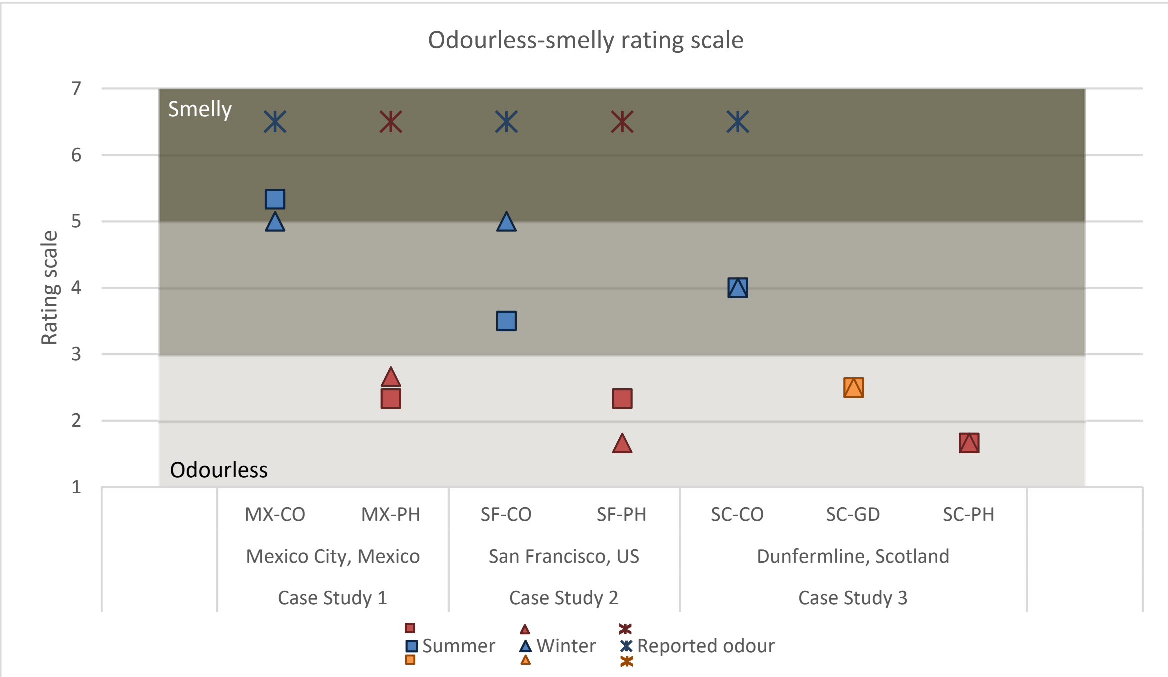


Figure 8.29 Scores for the unipolar scale: odourless (1) to smelly (7).

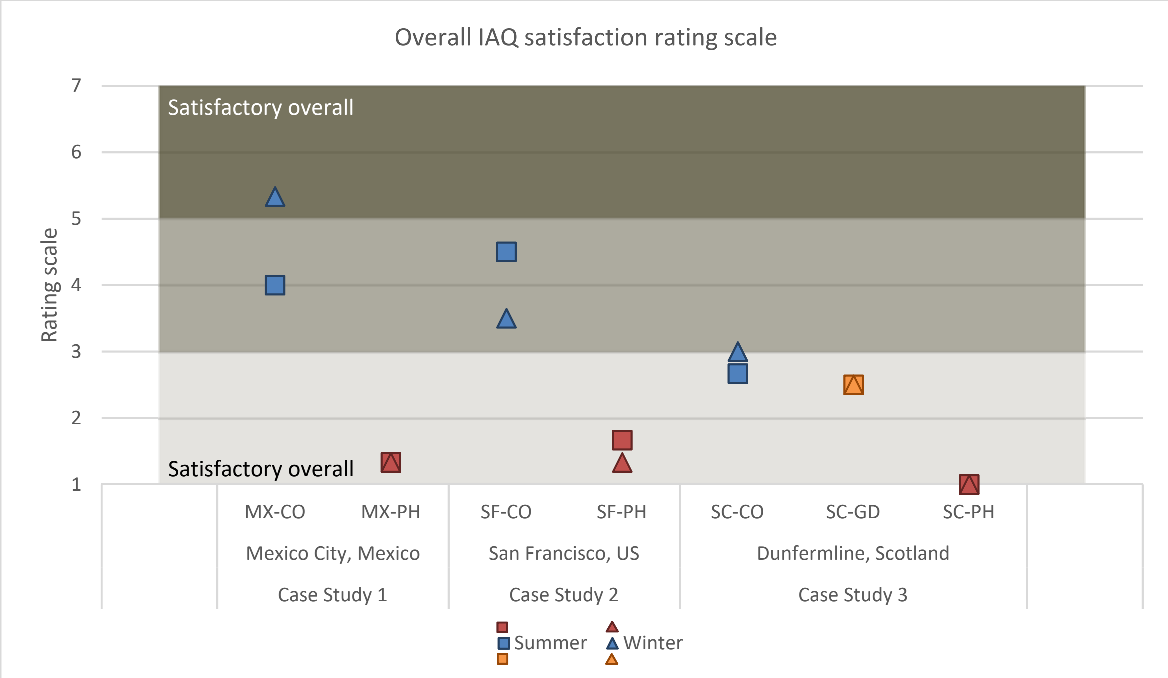


Figure 8.30 Scores for the unipolar scale: satisfactory overall IAQ (1) to unsatisfactory overall IAQ (7).

8.1.2 Thermal comfort perceptions

The results from the "comfort (1) to uncomfortable (7)" scale suggest that summer temperatures were perceived as comfortable in all dwellings, except the PassivHaus in the Dunfermline, where they were rated as a cause of concern due to warm temperatures. The results for winter comfort showed a variation in scores between the different households, with two of them rating it as a cause of concern and one requiring further investigation. The results of the control house in San Francisco for winter and summer scored 3, which indicates that comfort perceptions could change (Figure 8.31).

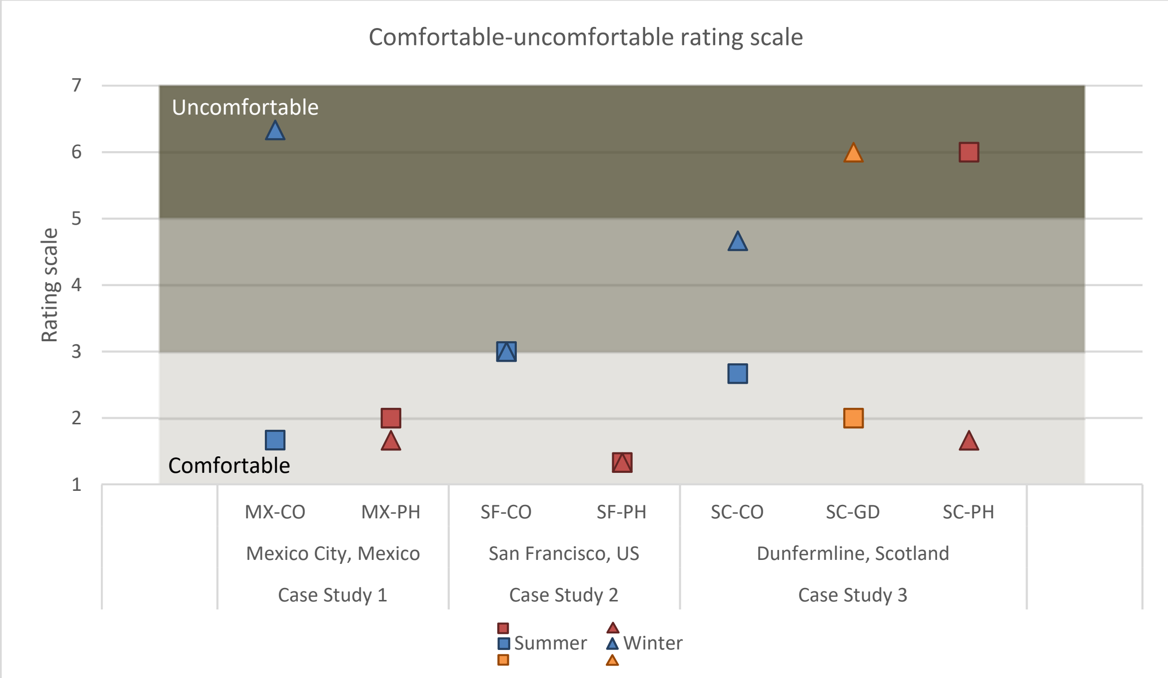


Figure 8.31 Scores for the unipolar scale: comfortable (1) to uncomfortable (7).

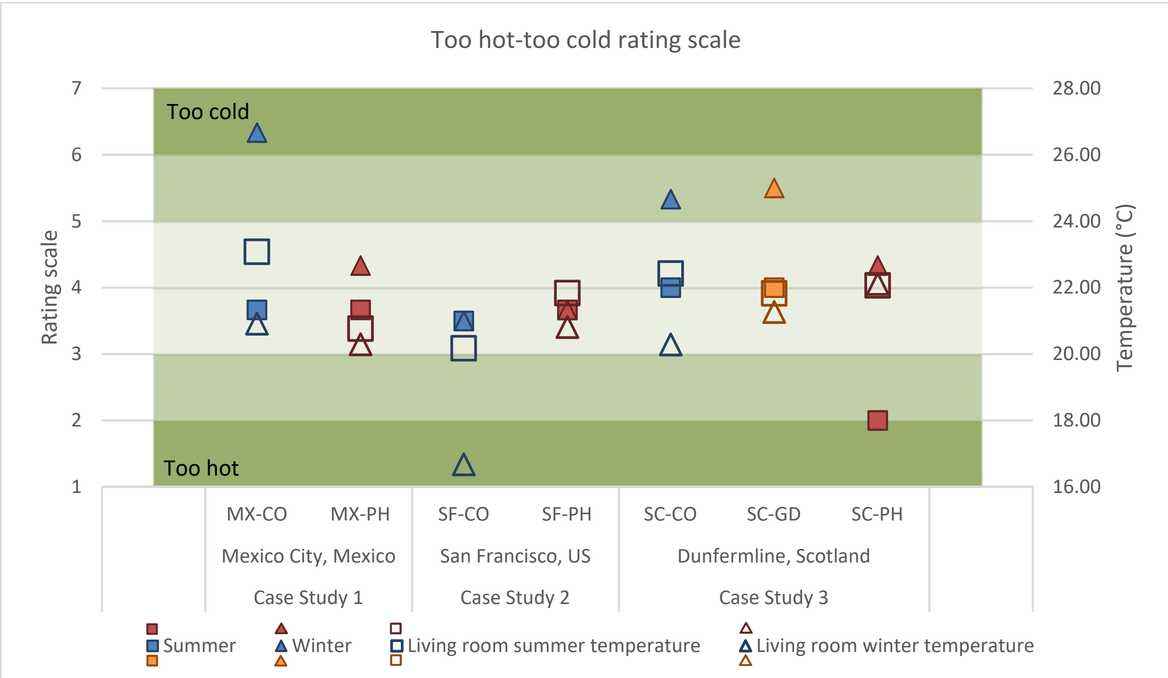


Figure 8.32 Scores for the bipolar scale: too hot (1) to too cold (7).

Scores for the rating scale "too hot (1) to too cold (7)" indicate that the occupants felt comfortable with indoor temperatures, especially during summer. However, the rating of the PassivHaus in the third case study may suggest problems with overheating with a score of just 2, which is a cause of concern which relates to the comfortable perception scale. Winter perceptions were rated as a cause of concern in Mexico City's control dwelling and require further investigation in two non-PassivHaus homes in Dunfermline (Figure 8.32). The measured temperatures converge in most of the results from the occupants' perception. In Mexico City, cold winter temperatures during the night and the lack of heating could be the reason for the perception of cooler temperature.

The temperature scale “stable (1) to varies (7) for the day” scores indicates that the occupants perceived that the temperature variation during the day was more significant than those at the PassivHaus dwellings. All Scottish dwellings and the control home in San Francisco were rated as a cause of concern in winter. Summer scores had a significant variation - two dwellings rated the temperature variation as a cause of concern, 2 required further investigation, 1 of which – a PassivHaus – was rated with 5 (the limit between to be a cause of concern, Figure 8.33). The daily temperature variation in Dunfermline is relatively low compared with the other two case studies; however, occupants perceived these variations as high. This could be related to the adaptation of temperatures from outdoor to indoor or a high expectation for stable warm temperatures all day. In the case of Mexico City, small discrepancies were also observed: whereas temperatures had a similar variation between summer and winter in the control home, as an effect from the thermal mass, occupants rated to feel higher variations during winter. This could be related to outdoor temperatures or possibly drafts from natural ventilation.

Scores for the “thermal satisfactory overall (1) to unsatisfactory overall (7)” scale were rated as ideal in all dwellings during summer, except for the control homes, which require further investigation. Winter thermal satisfaction was rated as a cause of concern in the control dwelling in Mexico City due to cold temperatures, whereas the other two naturally ventilated dwellings require further investigation. Summer and winter score ratings for the PassivHaus dwellings were rated within the ideal score ranges (Figure 8.34).

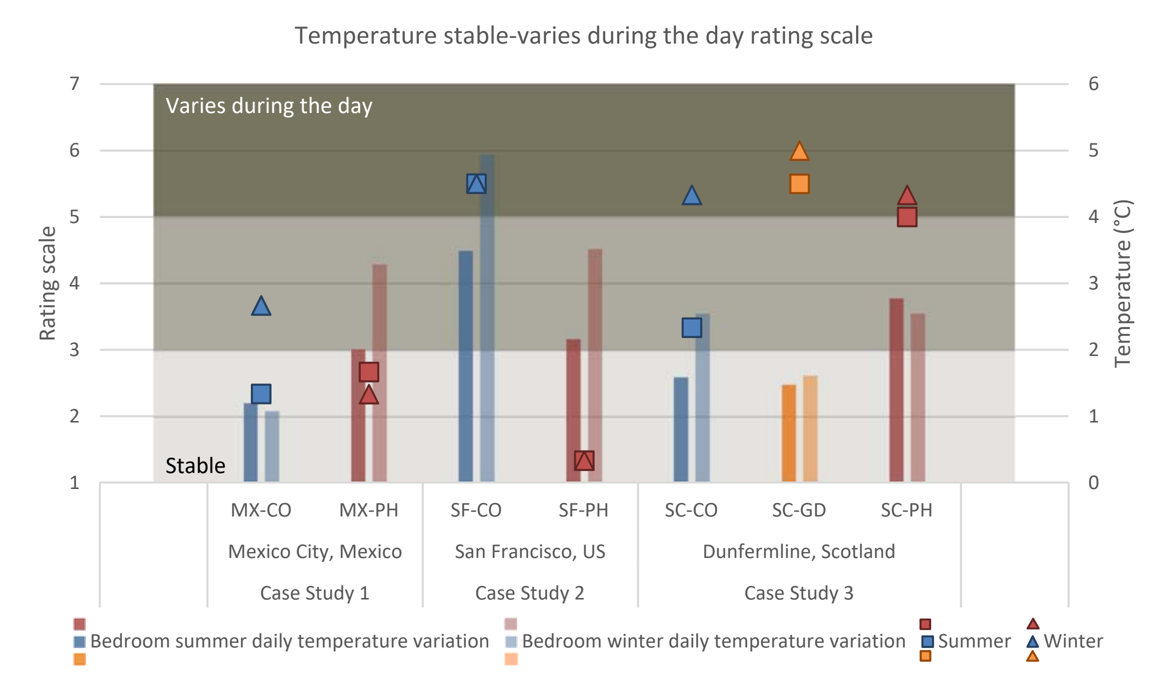


Figure 8.33 Scores for the unipolar scale: stable (1) to varies (7) for the day.

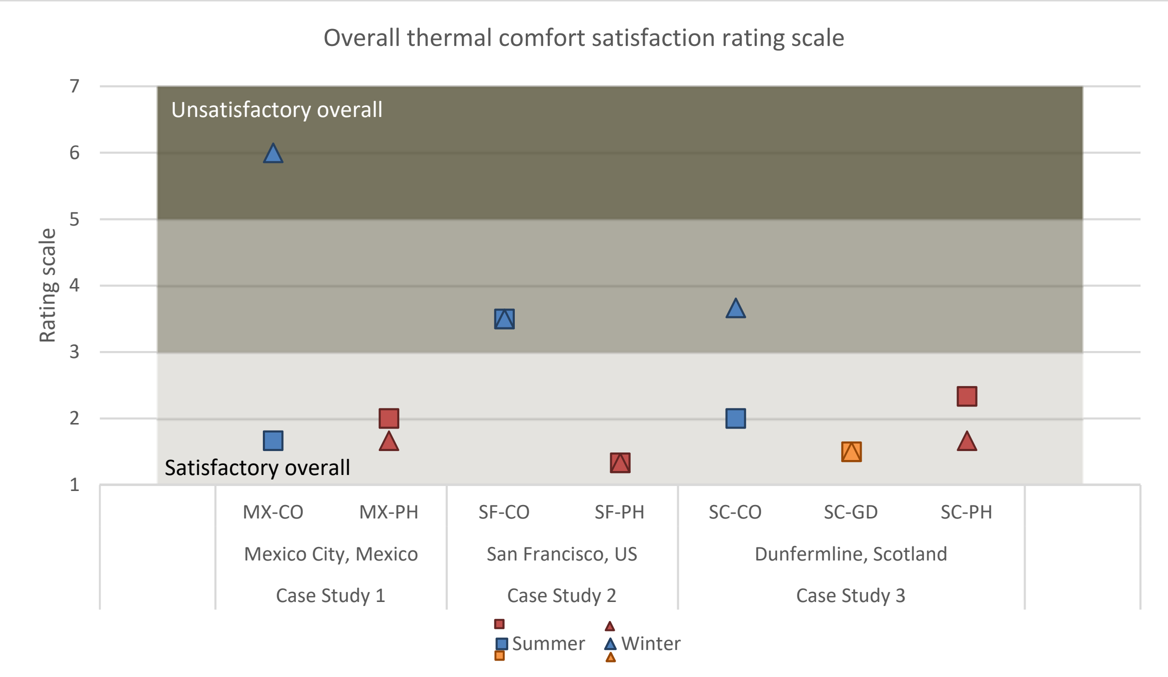


Figure 8.34 Scores for the unipolar scale: thermal comfort satisfactory overall (1) to unsatisfactory overall (7).

8.2 Chapter conclusions

This chapter presented and discussed together the results of the case studies in warm-summer mediterranean, oceanic subtropical highland and temperate oceanic climates The findings suggest that mechanical ventilation could be beneficial to reduce $PM_{2.5}$ and control tVOC. Nevertheless, indoor sources and occupant behaviours are critical factors for indoor pollutants. Those homes with mechanical ventilation offered a higher $PM_{2.5}$ protection, especially when high outdoor concentrations were observed. The $PM_{2.5}$ and tVOC differences in between the homes was statistically significant in most of the cases. This suggests that the indoor pollution was, indeed, related to occupant behaviours.

Pollution peaks were also more frequent and took a longer time to dissipate in homes with mechanical ventilation. These could be related to findings from other studies, which suggests building mechanical systems and automation make occupants dependant of them.PassivHaus occupants claimed to open the windows less frequently compared to the other homes. There is the need to establish better communication with homeowners/occupants to explain that opening the windows in PassivHaus homes is fine and explain the benefits of the MVHR system in terms of IAQ and energy saving. For instance, controlled ventilation rates could explain the frequency and severity of the pollution peaks, in that in naturally ventilated dwellings air flow may be higher when windows or doors are open, but when closed it may be drastically reduced. In dwellings with mechanical ventilation, air flow may be lower than achieved by window opening, but it will remain constant at all times. The overall $PM_{2.5}$ and tVOC exposure were lower in PassivHaus homes, as indicated by the analysis of the time spent below the measured limits.

These findings correspond to occupants' overall perception of IAQ, in that PassivHaus occupants were highly satisfied with IAQ, whereas occupants in the naturally ventilated dwellings rated IAQ as a cause of concern and to require further investigation. Nevertheless, occupants were generally unaware of pollutants, as their IAQ perceptions were dependant of thermal and olfactory responses. Indoor air was perceived as draughty in naturally ventilated homes and still in mechanically ventilated homes. Problems with odours were reported much more frequently in the naturally ventilated dwellings than in dwellings with ventilation systems.

Overheating was assessed using the PassivHaus, CIBSE Guide A and CIBSE TM52 criteria. Some problems with overheating were identified in all dwellings; however, no significant difference was observed between the homes. Nevertheless, PassivHaus dwellings, especially in the bedrooms, were associated with a higher frequency of warmer air temperatures. Unusual temperatures were observed in the living room of the control home in Dunfermline; this could have masked the humidity levels. These findings correspond to thermal comfort perceptions, whereby PassivHaus occupants felt more comfortable than those in naturally ventilated dwellings.

Whereas the findings from these dwellings cannot be generalised, they provide evidence needed for further studies which would require a large number of homes. The following chapter examines the experience of using the monitoring methodology and discusses the findings of this study, which are contextualised with existing knowledge within the field to evaluate its relevance.

Chapter 9 Discussion

9.1 Summary

This chapter is divided into four parts. First, the experience of the data collection and the remote monitoring protocol –its implications, strengths and limitations – are discussed together with an explanation of the steps taken for data cleaning. The second part focusses on the results of physical IAQ and environmental monitoring, their implications and proposes further work. Occupants' perceptions of IAQ and thermal comfort as well as the impact of their behaviour and activities on the indoor environment are discussed in the third part. Finally, some final thoughts and IAQ considerations in relation to dwellings are presented.

9.2 Data collection

9.2.1 Low-cost sensors and IAQ parameters

The actual technological context for indoor environmental monitoring has changed drastically over the last decades, especially since low-cost sensors and open software became available. As sensors became more accurate and single-board microcontrollers, such as Arduino or Raspberry Pi, became available, they have been adopted for IEQ monitoring systems. Many of these systems are proof-concepts, as the SAMBA (Parkinson, Parkinson and Dear, 2019), or project-specific tools, like the OSBSS project (Ali et al. 2016), and therefore limited in scale.

These technologies also supported the development of commercial low-cost IAQ monitors, such as Foobot, Speck and Netatmo. These monitors, although, intended for the general public have drawn attention from researchers. However, as they are not project-specific or intended for research, their measured parameters are limited. Table 9.1 compares the CIBSE KS17, EPA and WELL indoor air pollutants requirements for IAQ monitoring with those that are monitored by the Foobot.

Nevertheless, one must be cautious when approaching research with low-cost sensors. These sensors and monitors are often used as informative tools for the general public and their accuracy need to be verified by cross-referenced studies. The measurements of several days should be compared to reliable instruments, such as in this study, so that they can be relied. For instance, while the Foobot was found to be reliable for temperature, humidity, tVOC and $PM_{2.5}$, the CO_2 was deemed inaccurate. The $CO_{2\text{-equivalent}}$ and real CO_2 measurements showed significant differences. An explanation for this is the lack of a CO_2 sensor and, while perhaps not mal intentioned, the use of an algorithm to tramsform the tVOC measurements into a $CO_{2\text{-equivalent}}$.

Table 9.1 Summary of measured factors for routine IAQ assessment compared to those measured by Foobot. Based on (EPA, 2003; CIBSE, 2011; International Well Building Institute, 2019).

Factor	CIBSE KS17 Always	CIBSE KS17 Additional	CIBSE KS17 If applicable	WELL standard	EPA	Foobot
Air temperature (θ_{air})	●			●	●	●
Operative temperature (θ_{op})		●		●		
Radiant temperature (θ_r)		●				
Daily temperature rise		●				
Relative Humidity (ϕ)	●			●	●	●
Mean air speed (v)			●			
Air turbulence intensity			●			
tVOC	●			●	●	●
Main individual VOC	●				●	
Formaldehyde	●			●	●	
Aldehydes			●			
Methane			●			
Nitrogen dioxide			●	●		
Carbon dioxide	●			●	●	Not used
Carbon monoxide	●		●	●	●	
Ozone			●	●		
Radon			●	●	●	
Particulate matter 2.5μm		●		●	●	●
Particulate matter 10μm		●		●	●	
Fungi and bacteria		●			●	
Asbestos			●			

CIBSE KS17, WELL and EPA standards establish monitoring guidelines and selected factors for routine IAQ assessments for offices. In residential studies, such as this, they are adapted based on the study aims or the most common indoor contaminants. Crump et al., (2009) suggests that those are CO, CO_2, VOCs, particulates and moisture, which are similar to those suggested in the CIBSE KS17 guide.

Whereas monitors such as the SAMBA provide specific measurements for IAQ and IEQ (air temperature, relative humidity, globe temperature, airspeed, CO, CO_2, $PM_{2.5}$, formaldehyde, sound and light) at an affordable price ($220.00 US-dollars (£180.00)), they still require programming and R&D increasing their indirect costs. Commercial low-cost IAQ monitors have a market price of around $200.00 US-dollars (~£160.00) and are ready to use solutions which make them attractive for research projects with limited budgets and time.

As these low-cost systems are project-specif or proof-concepts, the data drifting over time has not been adequately explored. Similarly, low-cost IAQ monitors do not often advertise it, but instead, they claim to be self-calibrated. Data drifting in both cases could suppose a limitation for long-term monitoring projects.

9.2.2 Participant recruitment and engagement

In order to successfully develop building performance evaluation (BPE) studies, it is necessary to have support from building designers and participants. Building designers provide building layouts, construction details, design expectations and, in some instances, introduce the BPE professional to homeowners. For practitioners, this involves additional time and resources and could be perceived as a burden, but also casts building designers as 'gatekeepers'. Architects and building designers are often reluctant to participate and dedicate resources to BPE studies, thereby missing the real benefits of these studies.

The participation and engagement of homeowners or building occupants are also critical. In many BPE studies gaining access to participants and homes is the foremost obstacle, though the initial cost of the instruments, time, lack of skilled researchers (Hadjri and Crozier, 2009), liability, safety, privacy and ethical issues should also be considered. Approach home occupants directly could, in principle, intensify safety, privacy and ethical concerns. In this instance, the support from landlords, designers, housing associations or other institutions could help to reduce these concerns, but it could also compromise the objectiveness of the results. These issues have been major barriers to understanding the cause of the 'unintended consequences' in large scale BPE studies, where BPE professionals face concerns about uncovering delivery expectation gaps, thus unveiling possible lapses in the professional integrity of the 'research partner' and exposing them to liability problems.

A further concern relates to participants engagement and how to encourage participants to conclude the study. Though motivating participants can be difficult, the BPE professional should not cross ethical lines. Payment of expenses to cover the additional electricity used by the equipment for example or other remuneration for participation depending on the tasks involved in the study are standard practices. However, participants may also consider other factors before deciding to take part in a study: such as availability, time framework, the purpose of the study, funding sources, researcher status and privacy. Perhaps the most critical elements are privacy and safety, as residential projects have a significantly lower number of occupants than other kind of buildings. The participant-researcher contact establishes a relationship. In small studies, such as this, it is easier to develop a good rapport, which itself can grant to a degree of freedom and better data collection.

In BPE studies, it is important to develop the appropriate research methodology and monitoring protocols, especially in residential projects where access may be restricted and remote data retrieval may be challenging. Data collection, particularly through low-cost monitors with remote access is rapidly evolving and becoming more accurate. However, there are still some barriers for using low-cost monitors that need to be addressed: variable accuracy, data drifting, loss of data, sensor failure and shorter lifespan may all be more frequently encountered than with traditional monitors.

The monitoring approach developed for this study seeks to use the strengths of low-cost monitors and help to mitigate some of the ethical concerns and difficulties of recruiting participants through ‘gatekeepers’. For instance, as the Foobots were sent by post, there was no need to visit the participants’ homes, allowing for a higher degree of privacy and perhaps being perceived as less intrusive. Another strength is that the participants and the researcher do not need to have face-to-face contact, which should help to reduce the change in certain participant behaviours that may affect the research. However, these characteristics can also be limitations, and so their use needs to be appropriate, in order to minimise their impact.

This work faced several difficulties in terms of participant engagement, whereby some were very enthusiastic about participating while for others it was somewhat taxing to maintain the same level of engagement. PassivHaus homeowners were usually more eager to participate, as they were keen to test the performance of their homes. Participants from the control homes did not engage to the same level as the PassivHaus owners, and in some cases, it was not possible to collect complete information for the houses. Participant engagement was, therefore, challenging to maintain until the completion of the study. Simple actions helped improve relations with the participants and reduce the risk of withdrawal; for instance, 'thank you' cards were posted at the beginning and the end of the study. On completion of the study, participants also received small tokens of gratitude that included chocolates or other sweets as well as the option to keep one of the Foobots.

Some limitations were difficult to avoid in this methodology, as it was not possible to check the correct location of the instruments or collect the complete technical data. This approach may not be ideal for small projects, but it would benefit larger studies, where large datasets can compensate for individual outliers. However, if this approach is to be reproduced the author suggests to have a more robust approach to collect building data, improve data collection regarding occupancy levels and automatically back up the data on a daily basis. The following sections discuss the experience of using this approach, suggest some improvements and describe processes in detail.

9.2.3 Data retrieval

The approach to data retrieval for this study faced several difficulties. At the beginning of the study, when the number of homes was small, it was possible to download the data from the Foobot dashboard, despite having considerable limitations. Downloading data was limited to a total of 290 data entries (rows) for each request, which was just enough to retrieve a full day at five-minute intervals (288 entries). Moreover, the system does not allow the user to request information for the desired interval, so it automatically calculated the best option (five, ten, fifteen, thirty or sixty minutes) to retrieve the most possible data entries between dates input by the user. Therefore, the information was downloaded manually daily and then merged into a single file. This process proved to be time-consuming, inefficient and inconvenient as the number of houses increased. Additionally, the Foobot dashboard does not recognise missing data entries (i.e. due to a lack of internet connection). Therefore, it did not leave empty rows for the missing data but assigned the data of the following day instead (Figure 9.1). Data intervals and missing entries needed to be manually checked and insert empty rows inserted as needed, so that information for all Foobots in each case study would be concurrent. This led to the development and commissioning of elementary software for downloading the data. The software recognised missing entries and left the row with the date and empty values for each parameter (Figure 9.2).

5	1465412400	08/06/2016 14:00	53.38002	24.085	49.1075	2240	618.5	96.81311
6	1465412700	08/06/2016 14:05	50.62	24.085	47.247	1537	424	78.63333
7	1465413000	08/06/2016 14:10	51.77	24.0975	47.182	1645.5	454	81.95477
8	1465420800	08/06/2016 16:20	17.04001	24.116	45.822	1727	477	56.79001
9	1465421100	08/06/2016 16:25	17.04001	24.1645	46.192	2039	563	63.95668
10	1465421400	08/06/2016 16:30	14.74002	24.29	46.891	2606	719	74.65669
11	1465421700	08/06/2016 16:35	14.97002	24.3235	47.0085	2478	683.5	71.92835
12	1465423800	08/06/2016 17:10	11.06	24.107	48.635	2431	671	66.97666
13	1465424100	08/06/2016 17:15	11.29001	24.181	48.635	2581	712	70.62334
14	1465424400	08/06/2016 17:20	11.98001	24.361	48.626	2732	753	74.73001
15	1465424700	08/06/2016 17:25	11.98001	24.4	48.671	2752.5	759	75.23001
16	1465425000	08/06/2016 17:30	11.98001	24.499	48.783	2788	769	76.06334
17	1465426500	08/06/2016 17:55	12.90001	24.6695	49.239	2916	804	79.90001
18	1465426800	08/06/2016 18:00	13.36002	24.688	49.472	2945	812	81.02669
19	1465427100	08/06/2016 18:05	13.36002	24.6955	49.599	2947.5	812.5	81.06835

Figure 9.1 Example of data retrieved from the Foobot dashboard. The red text was highlighted to evidence of the missing information; however, all text was black when downloaded.

2066	1.47E+09	########	18.14002	24.482	54.115	3425	944.5	96.84835
2067	1.47E+09	########	18.14002	24.47	54.101	3356	925	95.22334
2068	1.47E+09	########	17.91002	24.468	54.0845	3369.5	929	95.32668
2069	1.47E+09	########						
2070	1.47E+09	########						
2071	1.47E+09	########						
2072	1.47E+09	########	19.06	24.486	53.867	3249	896	93.72667
2073	1.47E+09	########	18.83	24.479	53.873	3234	892	93.16334
2074	1.47E+09	########	18.60001	24.465	53.902	3242	894	93.10001

Figure 9.2 Example of data retrieved by the data retrieval software. The software automatically detected missing entries and left empty rows for each of them.

The use of Foobot, as mentioned in Chapter 4, placed a limitation on data storage as Foobots lack internal memory, relying on an internet connection to store the data on the AirBoxLab servers. Therefore, data points were lost when the internet connection was interrupted. This was a significant limitation in Mexico, where the internet service was frequently interrupted by thunderstorms and network problems, but it was less frequent in San Francisco and Dunfermline. This approach could be improved using a monitor that has not only an internet connection but also memory to store the data.

Data retrieval from the surveys was straightforward. The use of Survey Monkey allowed the data to be retrieved on demand when needed. The free function provided by Survey Monkey allowed for analysing the information in the form of a summary (all the surveys for the same dwelling at once) or individually. This feature was used not only to retrieve information about occupants' perceptions of a particular case study but also to identify specific building characteristics and behaviours in each of the homes. This method could be improved using another survey site, i.e. google forms, which would allow collection of more responses per survey and to have a single survey divided into different sections, rather than four sections in four different surveys. Too many surveys proved to be confusing for participants in this study.

9.2.4 Data quality

Standard protocols, learned on several projects working in MEARU, were applied to this investigation. This section, however, describes specific 'data-cleaning' methods and other processes applied to the data to ensure data quality. It is essential to understand the data handling and interpretation processes for IAQ assessments as, although well intentioned, they could change their meaning. After downloading the data from each Foobot, this information was merged into a single file containing the data for each room in the case study. Data cleaning was then performed, followed the calibration equations described in Chapter 2. Finally, an algorithm was developed using Excel commands to calculate the mean of each data entry (row) for each Foobot parameter in the same room, thereby creating a fourth – and final – dataset used for the analysis.

Perhaps one of the most significant issues with low-cost IAQ monitors, such as Foobot, is the accuracy of their sensors and the need for 'data-cleaning'. Using the mean from three monitors per room helped to mitigate these potential differences between monitors. Data repetition and corroboration not only were used as a means to provide robust data but also to identify outliers and spikes. Data corroboration was performed manually through a visual comparison of graphs in Excel. A graph for each parameter using the data from the three Foobots in each room, an example of which is shown in Figure 9.3, was created to corroborate all the information. Differences in the data from one Foobot to another were expected, as they may have been placed in different locations in the room. However, similar background/relative levels were also expected. This was true for most of the time, but on some occasions, some data drifting was observed (Figure 9.4). Whereas manual corroboration was possible in this study, large-scale projects may benefit from automated software using advanced algorithms to detect significant changes in the data.

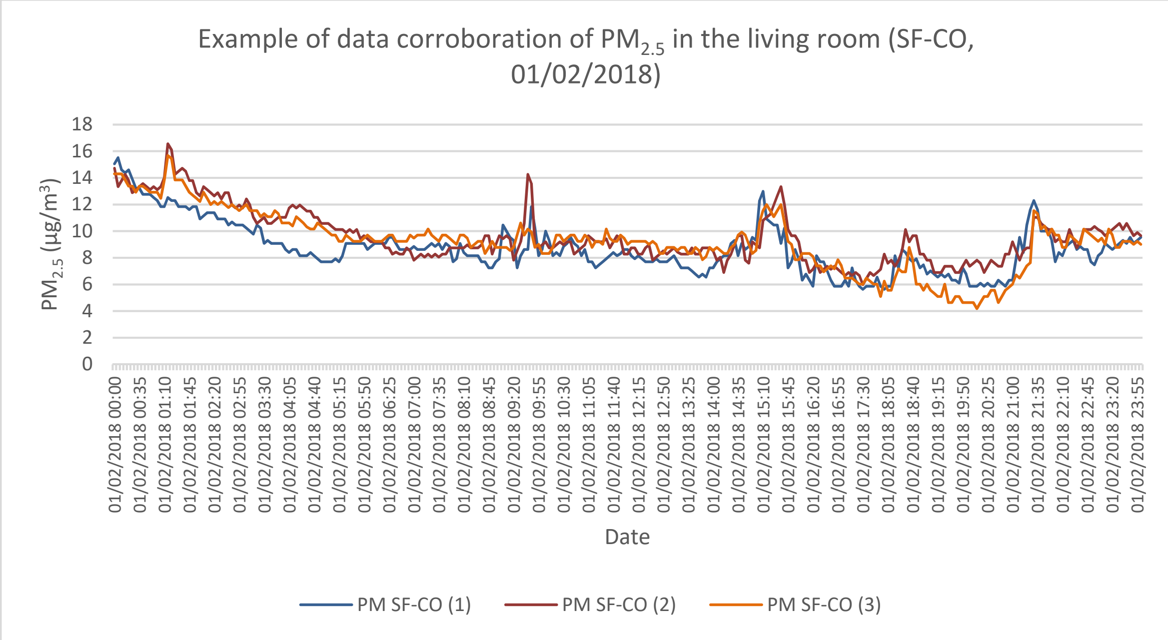


Figure 9.3 Example of data corroboration of $PM_{2.5}$ data in the living room of the control house in San Francisco on 01/02/2018.

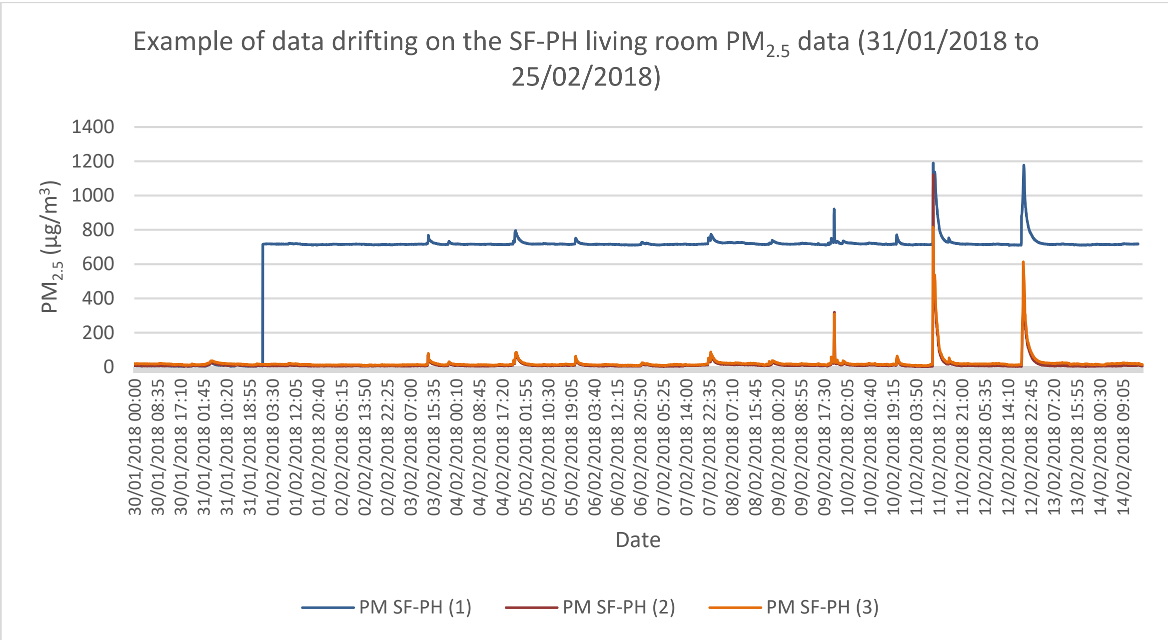


Figure 9.4 Example of data drifting as a result of the "learning process" performed by the Foobot algorithms.

The Foobot maker explained in personal communication that they had developed an algorithm that was continually evolving and could, on some occasions, cause such data drifting, but that it should also automatically detect it and correct the error. This algorithm considers environmental factors, age and usage of the sensors, data history, data input by the user in the Foobot app and a factor of correction to avoid data with negative values[9]. They also explained that because

[9] AirBoxlab explained the algorithm in greater detail. However, a non-disclosure agreement was signed, as they consider the algorithm a company secret.

of the evolution of the algorithm, the data output could vary. AirBoxLab only stores 'raw' output from the sensors at a given time. Therefore, if the algorithm had evolved over a month or a week and the data not downloaded before this change, the "current" algorithm would be applied to all historical data, causing, in some cases, misleading measurements. In order to avoid this issue, the data were downloaded within a timespan of fifteen days or less. Even though this precautionary measure was used, on some occasions the data drifting phenomenon was observed and understanding of the analytical process of this "environmental learning algorithm" became vital during the data cleaning process (Figure 9.5). Figure 9.6 and Figure 9.7 show a close up of the data before and after correcting for data drifting. More extensive studies may benefit from developing a similar software package which automatically downloads and securely stores the data daily.

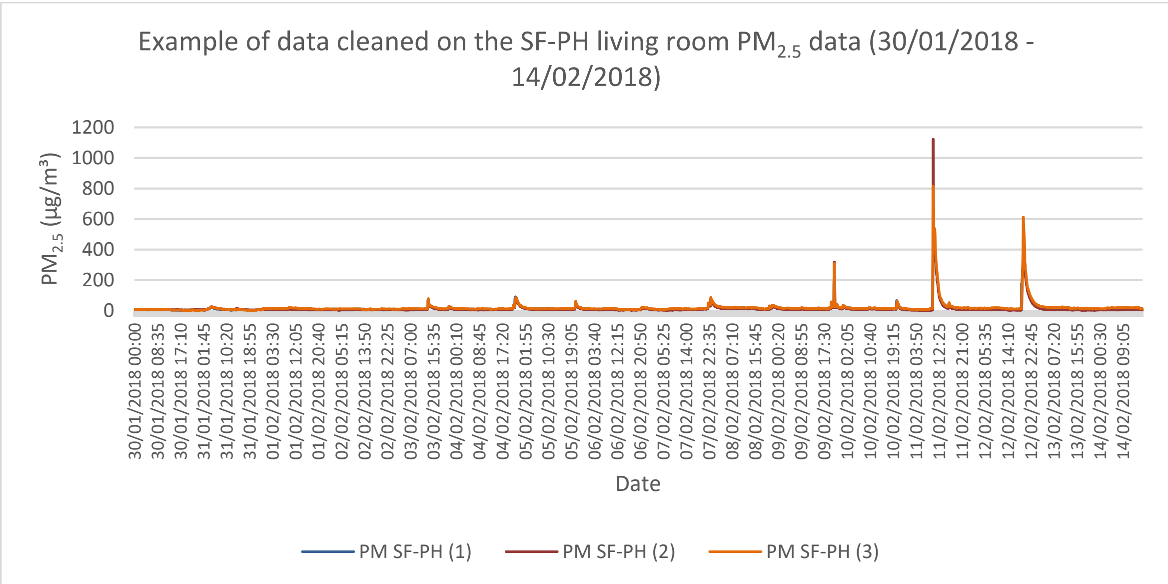


Figure 9.5 Example of the data drifting and correction data cleaning.

Data cleaning and data drifting correction were performed, individually for each parameter before applying the calibration equations described in Chapter 2. Following this, the algorithm to calculate the mean of the monitors in each room was applied. This algorithm was developed using Excel formulas for three primary functions: to identify missing data, to calculate the mean of a given time, and to mix the output of both parts, identifying missing data and miscalculations (i.e. when all data were missing), thus preventing error outputs (Figure 9.8). This algorithm was developed further to create a dataset for SPSS analysis, whereby the value of "-99" substituted the missing cases. SPSS functionalities identified this value and enabled it to be changed for the dataset mean value for statistical analysis purposes.

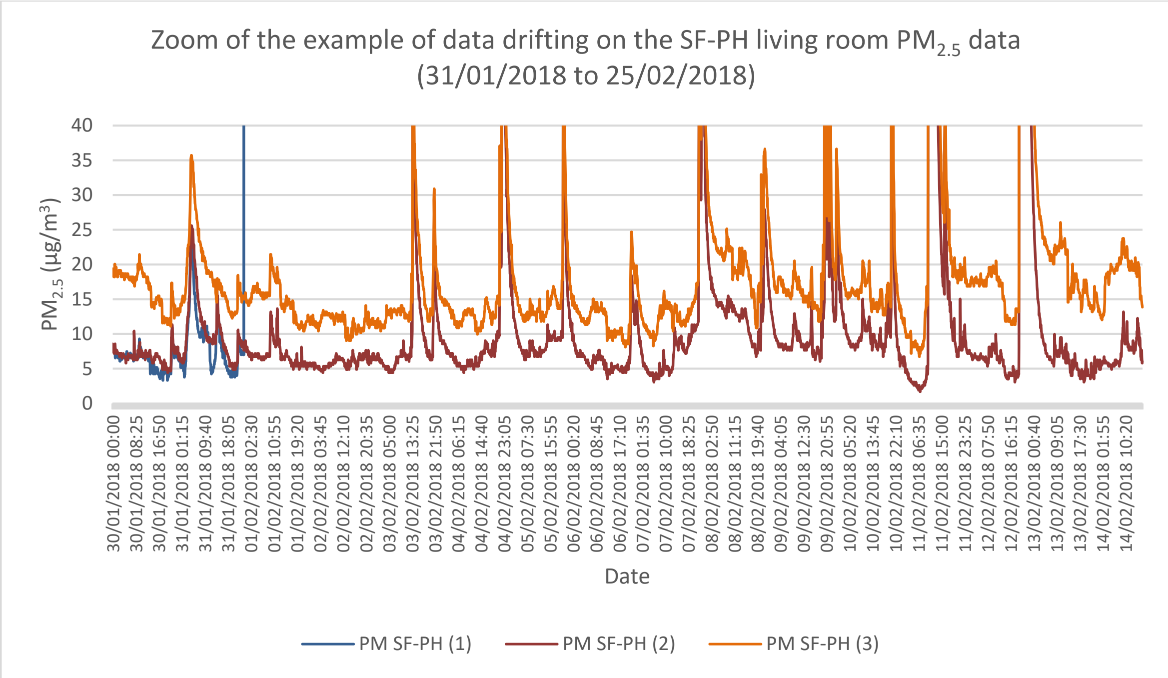


Figure 9.6 Zoom to the example of data drifting in Figure 4.7. The maximum $PM_{2.5}$ axis scale was set up to 40µg/m³.

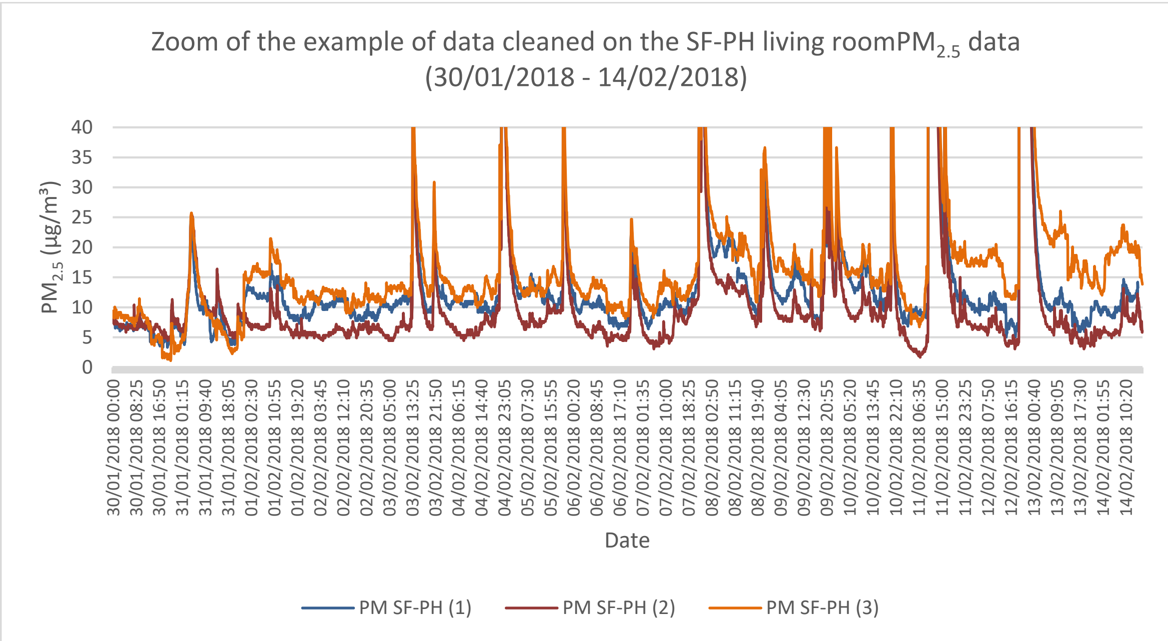


Figure 9.7 Zoom to the example of the data drifting correction and data cleaning of Figure 9.5. The maximum $PM_{2.5}$ axis scale was set up to 40µg/m³.

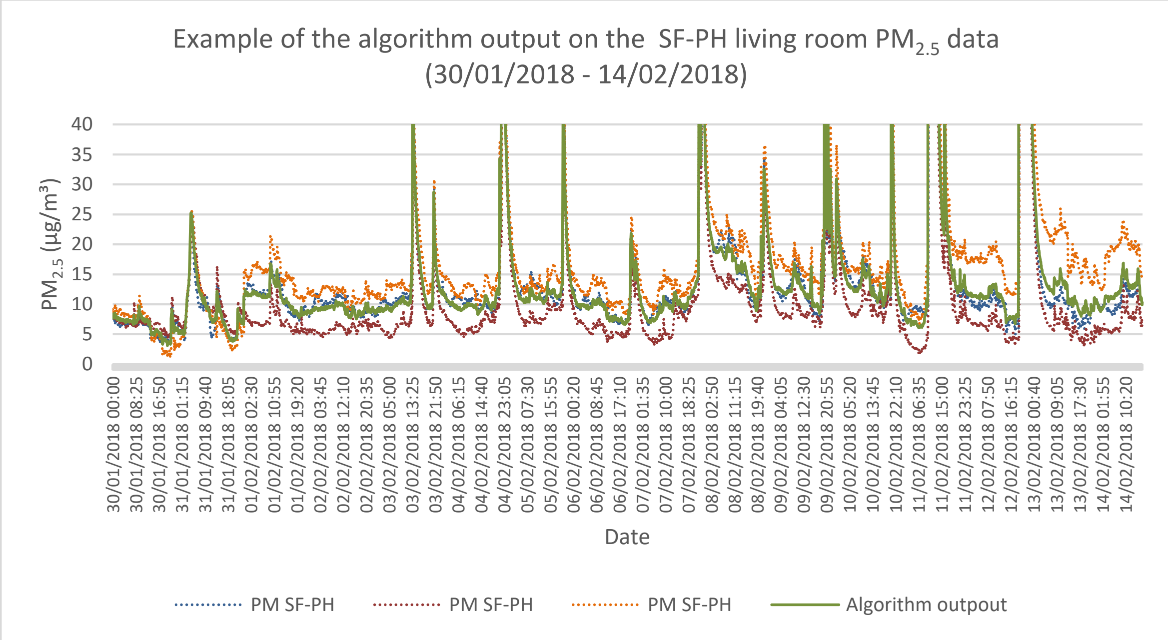


Figure 9.8 Example of the algorithm output.

9.3 Indoor air quality and environmental measurements

9.3.1 Relative levels of protection

This study investigated the relative level of protection from air pollutants using low-cost IAQ monitors. Whilst it is clear that indoor air quality is a pressing matter (WHO Regional Office for Europe, 2000; Zhang and Smith, 2003), it remains unclear the real effects of modern high-performance dwellings. Some studies, presented in Chapter 3, tested IAQ in PassivHaus homes, however, they often lack long-term $PM_{2.5}$ and tVOC measurements and formulate findings based on spot or daily measurements. The data in this study provides evidence from long-term (>6 months) indoor $PM_{2.5}$ and tVOC monitoring in PassivHaus dwellings.

Analysis of the frequency of $PM_{2.5}$ - annual $PM_{2.5}$ mean of 10µg/m^3 and daily $PM_{2.5}$ mean of 25µg/m^3 (WHO, 2000), and tVOC - concentrations of 300µg/m^3 over 8 hours mean (ECA, 1992; HM Government, 2013) and 500µg/m^3 (Delia, 2012)concentrations above the thresholds found that all homes exceeded these limits. However, PassivHaus achieved better ‘relative levels of protection’ as indoor $PM_{2.5}$ and tVOC levels were lower compared to the control homes in each of the case studies. This was attributed to activity and behavioural differences; specifically, cooking for $PM_{2.5}$ and chemical ingredients for day-to-day products for tVOCs, rather than buildign differences.

There were some particular differences in the $PM_{2.5}$ and tVOC pollution behaviours between the homes, thus highlighting the need for further examination of the implications of design methods and occupant behaviour on pollution decay rates and the severity of pollution peaks originating from human activity.

A key issue in relation to the assessment of IAQ is the way indoor $PM_{2.5}$ and tVOC are assessed. Although this study used recognized thresholds for $PM_{2.5}$ (WHO, 2000) and tVOC (ECA, 1992; HM Government, 2013), there are two fundamental problems: they are principally based and adapted from outdoor studies; and there are many other guidelines (IEA, 2015) to follow which makes it difficult to compare the results from this study to others. The criteria usually refer to a mean over a specified time frame, i.e. above 25μg/m^3 in a 24-hour mean. In some studies, these levels are used as absolute thresholds when spot measurements or period below 24-hour were examined without taking into account the exposure period. Thus IAQ is associated with inadequate pollution levels. The criteria do not take into account a difference between occupied, unoccupied or complete monitored periods (such as the CIBSE Guide A for overheating (CIBSE *et al.*, 2015)) – in other words, the degree to which occupants may be exposed. Finally, there are no well-defined criteria on how to assess the severity of occupant exposure to pollutants. For instance, in this study, all dwellings exceeded the 25μg/m^3 threshold. Nevertheless, significant differences were observed between the percentage of time above the threshold among PassivHaus and control homes, the quantification of the duration of the exposure-concentration ratios (graph areas below the measured limits), as well as significant differences between occupied and unoccupied periods above the thresholds for $PM_{2.5}$ and tVOC.

The use of real-time monitoring and occupant diaries are a crucial factor in understanding indoor sources of indoor pollution and they enable observation of specific causes of polluting events. However, in long-term studies, such as this one, it can be difficult to engage occupants to keep a detailed record of their activities. Instead, participants were asked for typical weekly behaviour, and it was assumed that the activities and reported occupancy for that week were representatives of normal conditions and this resulted in difficulties in making associations between specific behaviours and pollution peaks. Some of them occurred within the time frame stated by the occupants, such as cooking or personal cleaning, but it was difficult to link other activities and window/door opening patterns. Further investigations may benefit from real-time monitoring activities, which could use moving sensors and sound to identify number of people and activity types.

Control home occupants in Mexico and San Francisco reported opening windows more frequently than the PassivHaus occupants. Occupants of homes with MVHR systems (Brunsgaard, Knudstrup and Heiselberg, 2012) and building systems (Blight and Coley, 2013) increase their dependency on them to provide desired levels of IAQ. This result in limited building interaction and benefits from the building operation.

The results from this study are different from those in other studies, that suggest that buildings with higher levels of airtightness have been associated with problems concerning IAQ (Mendell, 1993; Godish *et al.*, 1996; Seppänen and Fisk, 2002; Carrer *et al.*, 2009). However, indoor pollution in highly airtight buildings, such as PassivHaus dwellings, may be associated with ventilation, human interaction and activities, rather than airtightness. Human interaction in PassivHaus dwellings has previously been associated with a temporal increase in volatile organic compounds, such as alkanes, benzene and aldehydes (Derbez *et al.*, 2014).

9.3.2 Particulate matter 2.5μm and tVOC behaviours

While indoor $PM_{2.5}$ and tVOC levels were lower in the PassivHaus dwellings, these differences were small. PassivHaus dwellings were associated with extended decay rates, especially fine particles after cooking. This is supported by Militello-hourigan & Miller (2018) who found that the $PM_{2.5}$ pollution decay in PassivHaus ($1.1h^{-1}$) was longer compared to conventional homes ($0.24h^{-1}$). They also found that even if the MVHR boost mode was used during and after cooking the effects were significantly lower in PassivHaus dwellings than those measured in homes using exhaust hoods. Similar to this study, a spike of $PM_{2.5}$ was measured immediately after the cooking events, but levels dropped quickly and then the peak concentrations began to decay gradually. In this study, higher stability of $PM_{2.5}$ levels across the different rooms was noted in PassivHaus homes. This indicates the likely transport of particles from the source room to others, assisted by longer decay rates and doors opening/closing between spaces facilitating further distribution of $PM_{2.5}$.

Current policies are pushing for higher levels of airtightness to achieve CO_2 reductions, nonetheless airtightness on its own may exacerbate IAQ issues. Better ventilation practices should also be implemented. Very airtight buildings using MVHR systems may filter up to 80% of outdoor $PM_{2.5}$ (Shrubsole, 2017) and help to control indoor tVOC. At the start of this study, the author expected that the MHVR system would significantly reduce $PM_{2.5}$ and offer a better way to control tVOC, nonetheless, the MVHR system had a little impact in terms of pollution removal. Therefore, indoor sources become more important. The MVHR filters main purpose is to protect the unit, thus in many instances, filters with low filtration are installed only to protect from solid contaminants and insects. Filters F7 or higher levels of filtration are designed to filter $PM_{2.5}$ and are recommended for PassivHaus. However their use could lead to higher fan demands, noise, filter costs, maintenance and even energy penalties. Ventilation rates and particle sedimentation primarily influence PM2.5 decay rate; whereas tVOC may depend on operative room temperature and relative humidity. However, proper ventilation remains the best way to control indoor pollution. In this study, it was observed that window opening behaviour was the most effective technique to control indoor pollution.

This study compared different geographical locations to test the impact differences of ventilation techniques to indoor $PM_{2.5}$ and tVOC. The results show that there are substantial differences between the locations due to differences in outdoor levels of pollution. The main indoor pollution contribution was from occupant behaviours. Ventilation was the main factor for pollution control regardless of the different locations, occupant groups and behaviours.

After outdoor pollution, human activities have the major impact on indoor pollution. Thus they could represent a more immediate risk. In order to reduce this risk, it is important to have a good handover explaining to residents how to operate the ventilation system, but also the importance of using the right filters. This handover could use examples of what to do during the most frequent pollution events.

Although this study compared different locations, a limited number of homes were explored. Future BPE in PassivHaus homes should focus on comparing a higher number of dwellings not only to find the potential for decarbonization but also to improve IAQ and occupants' health by exploring the possible causes of indoor sources of $PM_{2.5}$ and assess the impact of specific human behaviour. This study only focussed on recently built homes, but its impact may be better in terms of investigating the potential of retrofitted dwellings focusing on pre- and post-retrofit investigations for properties measuring the impact on $PM_{2.5}$ and other pollutants. In addition to the physical measurements, pre- and post-intervention surveys and improved handovers should be considered to gain a better understanding of occupant behaviour. Detailed monitoring may be needed for specific tVOC to evaluate the impact from building materials and consumer products, and their potential associations with temperature and humidity.

9.3.3 Overheating

The aim of looking at overheating temperatures was to associate the frequency of overheating to different IAQ issues and observe differences between the homes. Whilst it is clear that overheating is a recognized issue in PassivHaus dwellings (McLeod, Hopfe and Kwan, 2013; Ridley *et al.*, 2013, 2014; Tabatabaei Sameni *et al.*, 2015; Figueiredo *et al.*, 2016; Fokaides *et al.*, 2016; Rojas *et al.*, 2016), very little data exists on how the frequency of overheating in PassivHaus dwellings relate to other types of dwellings during the same time frames. This study, although limited in dwelling's number, provides base evidence for this.

It is difficult to determine the frequency of overheating, as each of the guidelines suggest different frequency of overheating. Accordingly to the CIBSE Guide A criteria found that most of the rooms in this study were overheated. The analysis with the PassivHaus threshold suggests that two rooms in Dunfermline (living room and kitchen) were defined as overheated. Finally, the adaptive approach suggests that dwellings in San Francisco and Dunfermline suffer from overheating. This could be attributed to the differences in lengths of the examination periods – annual hours for the PassivHaus threshold, annual occupied hours for the CIBSE Guide A guidelines or non-heating season (May to September) occupied periods for the CIBSE TM52.

A vital issue for the assessment of overheating is the way that it is defined by the CIBSE Guide A and TM52 criteria. The analysis of the occupancy criteria was based on the general weekly use provided by the occupants, but this could have variations, especially in those in the Mexican case study due to the nature of this home as an Airbnb rental property. This could introduce variability between the actual and 'reported' occupancy patterns. Whereas occupancy in the bedrooms could be related to a weekly routine or schedule - around a job schedule, for example - living room occupancy depends on wider activities and factors that are difficult to forecast, especially when providing the occupant diary at the start of the study.

Another factor is that comfortable temperatures in the bedrooms and living rooms are different. As explained in CIBSE et al. (2006), bedroom temperatures above 24°C may cause sleep deprivation, and so it is recommended that temperatures never exceed 26°C, whereas these thresholds in living rooms are 25°C and 28°C. The CIBSE Guide A takes into account these differences, whereas the PassivHaus and the Adaptive criteria do not. The use of the adaptive criteria may allow for a temperature range to be significantly higher than these temperatures, especially in bedrooms. For instance, the upper limit for the temperature range for the adaptive method allows for temperatures up to 29.54°C in Mexico City, 29.78°C in San Francisco and 27.55°C in Dunfermline.

During the heating season, this study found overheating in Dunfermline PassivHaus and control homes, which indicates internal heat gains by either active or passive heating gains. However, this issue is becoming more common in the US (Dentz, Varshney and Henderson, 2014) and may be due to improved building envelope performance with no changes in heating behaviours (Howden-Chapman *et al.*, 2007), low ventilation provision (T. Sharpe *et al.*, 2014) or with higher expectations of the indoor condition in high-performance dwellings (Herring and Roy, 2007). For instance, PassivHaus occupants expect temperature stability throughout the house (Zhao and Carter, 2015), which was observed in this study. However, there is an emergent body of research which suggests that temperature fluctuations could be beneficial for health (Parkinson and Dear, 2015; Schrauwen and Lichtenbelt, 2016) and are desirable in buildings (Lichtenbelt *et al.*, 2017).

This study did not find a significant difference between the risk of overheating in the control homes and PassivHaus homes in Mexico, San Francisco and Dunfermline. However, the data suggests that temperatures were warmer in PassivHaus compared to the control homes. Although this study did not intend to examine thermal comfort directly or to assess the frequency of overheating in the case studies, it raises questions about the impact of current building practices to thermal comfort considering predicted future climate change. A more comprehensive study may, therefore, be needed to understand the effect of super-insulated and the high-airtight buildings in warm climates, as well as the implications of MVHR systems on internal hygrothermal conditions.

The findings regarding thermal comfort issues suggesting the need to incorporate additional passive strategies for ventilation and shading into new-build sustainable homes (Alders, 2017). Such strategies should, therefore, be encouraged for new dwellings by re-shaping current building standards, PassivHaus among them. However, a more controlled implementation would require the development of local policies to promote free-running passive cooling techniques or other passive design strategies so that energy savings and thermal comfort are achieved together. Such studies should also incorporate adequate ventilation to ensure that IAQ is not compromised.

9.3.4 Indoor humidity

The aim of looking at the humidity levels was to examine associations between the homes with IAQ problems and humidity. The analysis of the prevalence of relative humidity outside of the 40-60%RH levels based on the CIBSE Guide A (CIBSE *et al.*, 2015) and EPA in the US (EPA, 2012) found that levels below 40%RH and above 60%RH were measured in all homes.

The findings raise questions about the appropriateness and benefits that using MVHR systems may bring to PassivHaus. MVHR systems were designed to accomplish energy savings and satisfy the need to maintain comfortable indoor temperatures. Whereas, they can be used successfully to reduce relative humidity (Fernández-Seara *et al.*, 2011; Mardiana-Idayu and Riffat, 2012; Cuce and Riffat, 2015) and control moisture buildup to prevent damage to the building structure, they may not be appropriate to reduce dust mite proliferation in homes (Niven *et* *al.*, 1999), especially in homes where the high frequency of warm temperatures may hide the real humidity levels. One example is the Air Pohoda iERV-240 used in the San Francisco, which may allow for specific humidity control important in temperate or humid-warm climates but its effectiveness was not clear in this study. While the relative humidity was lower in the PassivHaus, moisture content in the air was higher compared to the control home.

The presence of mould was reported in the living room and bedroom of the control homes in San Francisco and Mexico City, respectively. This suggests that natural ventilation rates may not be enough to remove excess indoor moisture effectively. The analysis of the vapour pressure excess indicates that PassivHaus dwellings had lower vapour pressure excess than the naturally ventilated dwellings. Although this study looked at the relative humidity, it did not look in detail at appropriateness of the MVHR to regulate indoor RH. Further studies may focus on studying the impact of the PassivHaus design approach in warm climates, as well as personal exposure to low relative humidity levels and the suitability of MVHR systems to appropriately regulate the vapour content in humid climates. It will also be necessary to determine house dust mite proliferation in the current conditions and to assess the suitability of PassivHaus compared to standard buildings.

9.4 Occupants' perceptions and behaviours

The Questionnaire for Studies of Sick Building Syndrome by the Royal Society of Health (Raw, 1995) was the model base for the questionnaires to investigate the occupants' perception, for both, IAQ and thermal comfort. The survey was adapted for the specific purposes of this research, as stated by Raw (1995, p.1): *"It may be necessary to adapt the questionnaire if it is going to be used for a specific research project or to gather data on particular potential causes of SBS."* As the aim of this investigation was not to determine SBS, the survey was adapted to collect information related to IAQ and thermal comfort.

9.4.1 Indoor air quality perceptions

One of the principal objectives of this study was to link the occupant perceptions to the measurements of the IAQ and to compare how occupants from PassivHaus rate their homes against ratings from conventional homes. While previous studies show that the levels of acceptance from PassivHaus occupants are better compared to other dwellings (Schnieders, 2003; Schnieders and Hermelink, 2006; Mlecnik *et al.*, 2012), there is very little research about how this relates to indoor pollutants. So far, most of the studies in PassivHaus have only measured CO_2 as an IAQ metric and very few focused on locations with non-European climates. This study, however, reflected on the associations between occupants' perceptions of the quality of the air and the measurement of $PM_{2.5}$, tVOC, RH and CO_2 (only in Mexico City) in different climates.

The overarching picture indicates that PassivHaus occupants were significantly more satisfied with the indoor conditions than control homes participants. The state of the air could only be related to CO_2 levels in Mexico City, where the measurements agree with the perception of the freshness of the air during winter in both dwellings but differ in the summer measurements. Although the data is limited, some associations between CO_2 and tVOC were demonstrated. Data analysis suggested that similarly CO_2 and absolute moisture relations could be found. Although the mean room differences in the homes reflect nuanced contrasts, the CO_2 differences are clear. Further investigation is required to compare occupants' perceptions of air freshness with CO_2 measurements, as in this study the monitoring of CO_2 was not possible in all cases. Odours were reported in two PassivHaus and three control homes, though PassivHaus occupants stated that the odours might be from outdoor sources. Thus this could have influenced their perceptions when rating the indoor air.

The scale rating does not take into consideration individual comfort expectations, preferences or adaptability to change adaptation. Moreover, human senses may not be adequately sensitive to pick up certain chemicals or fine particles, as these may be odourless or tiny and sensitivity to environmental parameters may change, depending on individual circumstances. Therefore, the results should not be taken as definitive and should always be contrasted with physical measurements. For instance, the dry-humid scale supports this statement. Occupants in the San Francisco dwellings rated indoor air as ideal during summer, but absolute humidity levels were higher compared to the control home. PassivHaus occupants from Dunfermline perceived the air as humid, whereas the environmental monitoring campaign showed that the absolute humidity in the PassivHaus and Gold dwellings were lower than those in the control home. These discrepancies indicate that further lines of enquiry should address individual preferences in terms of the indoor environment, to address these inconsistencies between occupants' IAQ perceptions and physical IAQ measurements, especially in single dwellings.

Other studies in which perceptions of IAQ were compared to IAQ measurements, albeit mostly only in regards to CO_2 in PassivHaus and conventional dwellings (Mahdavi and Doppelbauer, 2010; Tuohy, Murphy and Deveci, 2012; Derbez *et al.*, 2014; Langer *et al.*, 2015; McGill, Oyedele and Keeffe, 2015; Wallner *et al.*, 2015, 2017; Guillén-Lambea, Rodríguez-Soria and Marín, 2016; Rojas *et al.*, 2016), support the findings of this study. Furthermore, drier environments have been found in PassivHaus dwellings compared to standard homes (Berge & Mathisen 2015; Wallner et al. 2015; Rojas et al. 2016; Wallner et al. 2017). Further research should focus on linking occupants' perceptions to physical measurements in different locations.

9.4.2 Thermal perceptions

Whilst thermal comfort was not the principal aim of this study, it was investigated as the immediate IAQ perceptions when entering a building or room depend strongly on temperature and humidity. Whereas studies show that PassivHaus occupants often are satisfied with the thermal comfort compared to standard homes occupants (Schnieders, 2003; Schnieders and Hermelink, 2006; Mlecnik *et al.*, 2012), there are exceptions (Brunsgaard *et al.*, 2012; Brunsgaard, Knudstrup and Heiselberg, 2012). However, most of these studies have been carried out in European climates and very few address thermal comfort in warm and humid locations. This study presents evidence on the first thermal comfort study in PassivHaus homes in Latin America and compares the results with findings from similar studies in other climates.

There is minimal variation between the reported comfort of the PassivHaus in the three locations, all PassivHaus' occupants stated to be highly satisfied with the thermal comfort in their homes, whereas control homes' occupants were not completely satisfied, especially during winter. Thermal perceptions, though, depend on six factors, four of which can be classified as environmental parameters - air temperature, mean radiant temperature, air relative humidity and air velocity - and the other two as personal factors - metabolic rates and clothing insulation (Al horr et al. 2016; Katafygiotou & Serghides 2015). Individual adaptations to each factor depend on the characteristics of each person, but some building envelope characteristics – insulation, airtightness and thermal mass among others – influence the indoor environment.

The high thermal mass in the control home in Mexico City may have served to store heat during the day and release it at nights, improving thermal comfort and achieving minimal temperature variation. Although, this technique is dependent on day-night temperature swings. This suggests that PassivHaus home in warm climates may benefit from the use of thermal mass to regulate temperatures. Thermal mass could be combined with insulation efficiently: whereas the insulation protects the building from excessive heat, internal thermal mass could absorb the heat excess from internal gains. This approach would be recommendable in cases where no MVHR systems are installed, such as the PassivHaus in Mexico City. However, thermal mass may not be recommendable in buildings that use active cooling or are used intermittently, as this could result in energy penalties.

The use of thermal mass would also help to regulate daily temperature changes: whereas changes in the PassivHaus in Mexico were not perceived out of the ideal range, they were considerably higher than those at the control home. However, these perceptions are also influenced by personal expectations, as the measured variation in Scotland were the shortest, but occupants rated them as a cause of concern. The scores on the too hot-too cold scale indicated that PassivHaus occupants felt the temperatures to be warmer compared to the control homes, but in Scotland, they were stated to be too warm. A possible explanation is that in warmer locations, participants may expect to feel warmer temperatures. As explained by Nicol (2004) at warmer outdoor temperatures, building occupants may tolerate warmer indoor temperatures. These changes do not suggest significant differences in terms of off-gassing, as in most cases mean temperatures remained between 20°C-22°C. However, in warm climates this could suppose a health concern as tVOC may increase off-gassing to 1.26 times higher at 30°C those observed at 23°C and 1.57 times higher at 35°C and such levels are removed efficiently with air changes above 1.2ach during at least 4 hours (Lv *et al.*, 2016). In PassivHaus buildings, the ventilation rates respond to a need for air humidity and the Passive House Institute suggests that levels between 0.3ach to 0.4ach should be taken as a reference, the ventilation rates should not be higher than 0.8ach during short times. If these ventilation rates are to be kept up, occupants should be aware of the effect of temperatures on off-gassing and use purge ventilation when needed. The comparison of the temperature stability scale indicates that participants in the PassivHaus dwellings in cold climates may have higher expectations of the thermal comfort and this could be related to social or cultural expectations.

9.4.3 Self-reported health

The prevalence of sick building syndrome (SBS) symptoms were assessed through validated questionnaires (Raw, 1995; Raw *et al.*, 1995; Burge, 2004). These questionnaires were designed for office buildings or other workplaces where the effects of the building environment on occupants' health could be easily perceived. Thus the intensity of the SBS symptoms decreases or disappears when away from the building, subsequently improving the occupants' health (Redlich, Sparer and Cullen, 1997). It was designed specifically for crowded spaces, and as a result application in residential buildings may not be entirely appropriate. However, due to the lack of specific residential questionnaires to assess occupants' self-reported health conditions, this marker was used to identify possible symptoms.

The higher prevalence of symptoms in naturally ventilated dwellings was represented by blocked, stuffy and/or runny noses, whereas in the PassivHaus dwellings dry throats and eyes were more common. These findings may not be related exclusively to the indoor environmental conditions of the dwellings, as occupants also disclosed that they suffered from hay fever or allergies, in addition to the ambient weather. Hay fever condition tend to be atopic to mould spores, although not measured in this study they are related to high humidity and low ventilation.

9.4.4 Activities and occupant behaviour as pollution sources

Relative humidity is perhaps one of the most important environmental parameters to control, not only in relation to improving IAQ but also as a way of controlling house dust mites. All households reported doing laundry at home, and four of the homes reported drying passively indoors. This may increase moisture content and the prevalecencse of some mould spores significantly (Porteous *et al.*, 2014), with an increased risk of house dust mite proliferation and trigger atopic conditions. Window opening patterns, especially during winter, may aggravate the situation further, especially for overnight drying when the windows are usually closed and no purge ventilation is in action. Van Strien et al. (1994) related indoor humidity, window opening and indoor drying, among other building characteristics, to the proliferation of house dust mites.

Building maintenance, especially the ventilation systems, and design - avoiding hiding cavities and voids, especially in airtight and warm environments in the building fabric, proper ventilation design, and correct installation of drains and sewerage pipes - can significantly reduce the proliferation of mould and house dust mites (Singh, Wah Francis Yu and Tai Kim, 2010). Therefore, health and safety issues related to these issues should be addressed by architects, contractors, developers and building owners. Building owners should inspect heating and air systems periodically and program routine maintenance, whereas building professionals should try to avoid designing cavity walls and adhere to best ventilation practices. House dust mites are not the only issue with indoor passive drying, though, as VOCs are frequently released through the use of softeners and other cleaning products, thus deteriorating IAQ (Porteous *et al.*, 2012).

Other sources of VOCs were identified from the online survey results. Five of the dwellings used air fresheners and/or burned scented candles or incense. However, more important is the frequency of such behaviour, as this affects the overall exposure. These are sources of benzene, formaldehyde, polycyclic aromatic compounds among other VOCs (Derudi et al. 2012; Orecchio 2011) as well as particulate matter (Guo *et al.*, 2000). Cooking is one of the primary indoor sources of ultrafine particles, after smoking, and none of the participants smoked indoors. Therefore, cooking is the primary $PM_{2.5}$ indoor source. Cooking fuel has a significant impact, with gas burners producing a higher number of particles below 10μm than electric (Wallace *et al.*, 2008). This is of special consideration here, as more than half of the measured dwellings used gas as a primary source for cooking, and fumes generated by cooking can disperse quickly within other spaces and increase background concentrations by about 4 times in the kitchen and by 1.5 in living rooms (Wan *et al.*, 2011). Cleaning activities also have an impact on the behaviour of $PM_{2.5}$: vacuuming lead to the short-term stirring up of particulate matter (Corsi, Siegel and Chiang, 2008), while brushing may provoke higher suspensions. Sweeping, dusting and vacuuming are indoor cleaning activities that act as indoor sources of $PM_{2.5}$ pollution (Corsi, Siegel and Chiang, 2008), and all of them were reported in the case studies.

All of these activities raise concerns regarding the real impact of human activities as sources of indoor pollution, especially in airtight dwellings with controlled ventilation rates. Continuous ventilation may help to dissipate indoor pollution. Architects and designers should take control of indoor sources through careful selection of building materials and finishes which may lead to VOCs off-gassing. However, it is also vital that building occupants and owners take responsibility, and it is essential that they communicate, when possible, their concerns about building materials and finishings with designers, helping to design and select the most appropriate maintenance plans for their homes. In order to achieve the best results, not only is frequent maintenance to building systems needed, but it is also essential to select the healthiest cleaning, laundry, cosmetic and personal cleaning products, as well as reduce or avoid the use of scented candles or similar products.

Finally, spaces with appropriate ventilation for drying should be considered by architects and house designers about providing adequate purge ventilation and means to control relative humidity levels, such as halls and living rooms. Further studies should focus on the impact of human activities and indoor pollution in homes by comparing background levels to those increased by human activities. Such studies should monitor the entire dwelling simultaneously, to investigate the real impact of pollution travelling throughout the house as a result of internal door opening or ‘gaps’ between rooms required for MVHR ventilation.

9.4.5 Other factors

Responses to the questionnaire helped to identify diverse factors related to ventilation or IAQ in the dwellings: noise, keeping plants indoors and pets. Only the PassivHaus occupants of the Mexican case study complained about noise coming from the ventilation system, as the owner and Airbnb guests usually complained about issues with noise and difficulty in activating/deactivating the fan. One of the guests stated: “*The fan was noisy, especially during the night; it* *caused problems sleeping.*" There were also problems with the automated ventilation system, as Airbnb guests were not instructed on how to use the system or issued with a guide during handover.

A vast majority of the studies that identify problems with mechanical ventilation systems refer to noise as a reason why they are not used as intended (Kurnitski *et al.*, 2007; Hady *et al.*, 2009; Balvers *et al.*, 2012; Brown and Gorgolewski, 2015; McGill, Oyedele and Keeffe, 2015; Sharpe *et al.*, 2016), and often occupants need to choose between intolerable noise or inadequate IAQ (Harvie-clark *et al.*, 2016). Currently, there are no studies addressing ventilation nuisance in airtight dwellings or its effects on human health in the Mexican context. Noise nuisance may also depend on the local context, individual expectations, but most important to the quality of the system and its intallation wich could result in additional costs. For instance, Pluijm (2010) reported that German and Swedish homeowners do not report this sort of problem. Further studies should, therefore, be carried out in Mexico, to assess noise nuisance caused by mechanical ventilation and to determine its impacts on health in conventional and airtight homes.

Other issues related to the owner were also observed, such as maintenance, as the filters were removed due to the difficulty finding F7 filters. The market for PassivHaus building supplies is not fully developed in Mexico, and so in many cases services and building materials need to be imported from other countries, thus elevating the cost of construction and maintenance. The owner of the PassivHaus removed the filters for the following reasons: "*These filters are difficult to find in Mexico*" and "*I am not prepared to perform the necessary periodic maintenance*". The owner stated that the filters were clogged and this blocked the air to the house, causing it to be still. This indicates that demand for PassivHaus building components may be growing at a faster rate than the market supply. This is an issue even in countries such as the UK, where the market for replacement filters does not exist (Sullivan *et al.*, 2012), and where additional costs (Sharpe *et al.*, 2016) persuade homeowners to reduce maintenance. Further studies should address the technical feasibility and cost effectiveness of PassivHaus, as well as investor-purchaser acceptance and user behaviour in real-world conditions. Developing pilot units or case studies, as intended by the NAMA for sustainable housing (Kaineg *et al.*, 2012; GIZ, 2014) in Mexico, should help to develop market demand and a supply chain in Mexico, and promote high-energy performance construction.

This study did not specifically address keeping plants or pets indoors, but the implications are discussed here. Indoor plants can help improve air quality, with several studies demonstrating that indoor plants can reduce a range of VOCs and CO_2 (Wolverton & Wolverton 1993; Yoneyama et al. 2002; Tarran et al. 2007) and fine particles (Lohr and Pearson-Mims, 1996) regardless of the available light (Tarran, Torpy and Burchett, 2007). However, this effect has been documented in only a small number of species. It was challenging to identify species of plants kept indoors in each of the three case studies. Therefore, it was not possible to determine the exact relationship between indoor plants and background pollution levels.

Online surveys revealed that pets were kept indoors in five of the dwellings. Both dwellings in San Francisco reported having a cat, small dogs were kept in the control homes in Mexico City and Dunfermline, and a tarantula in the PassivHaus in Dunfermline. Pets (dogs, cats and birds) can be a source of domestic indoor allergen reservoirs for house dust mites and a source of $PM_{2.5}$ (Rutgherford, 2000). Furthermore, some studies have related pets to a higher risk factor in terms of asthma and allergies (Ahlbom *et al.*, 1998), but results on how this relates to human health are not conclusive (Sundell, 2007). The higher prevalence of health complaints was associated with those homes that had pets, but due to the lack of resources, this study did not address the matter. Further investigation would, therefore, require analysing samples of pet hair from a large-number of homes in different seasons, to determine the risk of asthma, allergens and mite population, comparing results in low-energy buildings and conventional buildings and then checking their relationship with IAQ.

9.5 IAQ considerations in PassivHaus

The PassivHaus standard considers ventilation based on German standard DIN 1946, which to a degree includes good IAQ practices. However, it only takes into consideration CO_2 levels, which should not pass the 1,500ppm threshold, emphasising that this is a metric for ventilation. After a review in Chapter 3 of the principles required to achieve the PassivHaus certification, it is evident that

PassivHaus prioritises thermal comfort and energy savings over other factors, such as IAQ and other aspects of occupant well-being. An official guideline that promotes IAQ by regulating indoor pollution and source control in PassivHaus buildings does not exist.

A few architects and designers go beyond the fundamental standards needed to achieve certification. Architects should make emphasis on material specification and strategies to protect occupants' health is much needed. These strategies should help to prevent excess moisture and control indoor pollution sources ensuring adequate IAQ provision, which could be enhanced with adequate ventilation. Further studies are recommended to evaluate in detail the impact and importance of pollutants related to building sources and to develop guidelines for PassivHaus dwellings.

Given the actual and expected levels of airtightness and ventilation levels in PassivHaus dwellings for energy conservation, passive or active design strategies should be adopted to meet high IAQ standards, especially moisture and airborne contaminant control. These techniques should include best practices for controlling building material sources (Ng *et al.*, 2018) and ventilation, especially in kitchens (Kim, Walker and Delp, 2018) and bedrooms. Changes to the current approach may be needed so that these solutions for PassivHaus dwellings can be implemented. However, these changes should be adaptable rather than rigid, so that they can be adjusted depending on the location and specific needs of each project, in tandem with the current criteria for PassivHaus certification. Optional criteria may include standardised protocols to monitor IAQ or other tools to provide real-time feedback to occupants about the quality of the indoor air, thereby minimising health risks. Therefore, a specific IAQ section should be considered in the PassivHaus design tool (PHPP), as interest in providing healthier environments grows among architects and home designers. To increase knowledge and awareness of IAQ in PassivHaus design, interdisciplinary research needs to be conducted to develop IAQ guidelines, as well as mandatory and optional IAQ credits.

Studies to evaluate the adoption of IAQ practices should be made in conjunction with the PassivHaus Institute, or at least obtain its support. In order for this to happen, more research is required to establish the real benefits to health made possible in airtight homes, as required by PassivHaus buildings in conjunction with different ventilation techniques (MVHR, hybrid, natural). Therefore, there is an urgent need to increase IAQ knowledge and undertake additional BPE studies that perform holistic objective and subjective evaluations of the building, indoor environment, IAQ, economic factors and technical viability. This could result in a detailed protocol that can be adapted to a worksheet in the PHPP calculation, making IAQ credits mandatory for certification. These IAQ credits should stipulate the intended objectives and the proposed techniques or strategies to improve the IAQ design of PassivHaus dwellings.

9.6 Chapter conclusions

This chapter discussed the implications and suitability of using low-cost IAQ monitors, in particular, the Foobot for BPE studies. Whereas the use of commercially available IAQ monitors could enhance IAQ research, there are two major limitations. Firstly, the measurements provided by low-cost sensors or monitors should be corroborated with cross-referenced studies comparing their results to more reliable instruments. After a cross-referenced study, the Foobot was found to be reliable for temperature, relative humidity, $PM_{2.5}$ and tVOC, but not for CO_2. This demonstrates the need to evaluate their accuracy before undertaking any measurements. Secondly, the monitoring capabilities limitations of this method; as established routines for IAQ assessments recommend more comprehensive monitoring parameters. The aims of the study need to be carefully set as this limitation impacts the study boundaries. Some project-based or proof-concept systems have allowed researchers to monitor indoor spaces simultaneously successfully, although they are limited in their applicability. The methodology developed for this research using commercially available IAQ monitors proved to be valid to collect IAQ data for research. The use of additional units in each room provided additional data quality measurement for identifying data drifting and data cleaning.

This chapter also contextualised the results of this study within the current research and proposed further work. The lack of IAQ guidelines or criteria to evaluate IAQ or even a universal pollution index, make challenging the comparison of IAQ studies. The analysis of the environmental factors suggests that the indoor pollution differences between PassivHaus and control dwellings were related to human behaviours. The relative level of protection may not depend on the climate, but outdoor pollution and occupant behaviour. After outdoor pollution, occupant behaviour and activities were the most important sources of pollution. Nevertheless, in order to achieve the desired level of protection, designers, contractors and occupants must adhere to the best practices of IAQ.

Whereas this study did not find any significant difference between the prevalence of overheating between PassivHaus and control homes as defined by CIBSE and the PassivHaus, two key differences were noted. First, temperatures in PassivHaus dwellings were usually warmer than those in control homes regardless of the location. Second, PassivHaus occupants from warmer location expressed feeling more comfortable at warmer indoor temperatures than those in cold locations, thus expressing a higher satisfaction with the indoor environment.

An alternative monitoring protocol using low-cost IAQ monitors could provide not only real-time information to building occupants so that they can react to the current state of the air but also benefit large-scale projects where quantity over detailed data is needed to set the basis for detailed research. The work in this research opens up a new line for BPE professionals to conduct investigations and collect highly needed IAQ data in low-energy homes with high levels of airtightness and controlled ventilation, such as the case for PassivHaus. A summary of the key findings and implications for further work is presented in the next chapter.

Chapter 10 Conclusion and further work

10.1 Summary

This study aimed to examine the suitability of low-cost IAQ monitors in residential buildings. Each of the chapters addressed one or more objectives to achieve this aim. In doing so, this study presented a novel methodology for IAQ investigations, including remote detailed IAQ data collection. Future IAQ research may benefit from low-cost monitors; nevertheless, their accuracy, life span and monitoring parameters range limit their application. The application of this methodology in real-life residential settings served to both, evaluate the application of the methodology and the IAQ in dwellings over extended periods. The findings of the monitored homes indicated that the most significant factor for IAQ, after outdoor pollution, is the occupant's behaviours. Further studies should focus on establishing IAQ guidelines or indexes, so that results from future BPE studies can be compared.

This chapter provides a summary of the study's aims and objectives, followed by a recapitulation of the work presented in each chapter. The key findings of the study are then presented alongside their relation to other studies, together with the research implications and further lines of enquiry. Finally, the critical limitations of this study are outlined.

10.1 Study purpose

The purpose of the study was to examine the suitability of low-cost IAQ monitors to collect remotely IAQ data. To accomplish this the criteria to assess IAQ were identified, a methodology for gathering IAQ through low-cost IAQ monitors was explored, to measure indoor pollutants and hygrothermal conditions, an IAQ monitoring protocol was developed to assess IAQ remotely. It was tested in three different locations collecting indoor air pollutants and hygrothermal measurements and occupants' perceptions of IAQ, thermal comfort, their behaviours and self-reported health. The monitoring methodology was tested in Mexico, San Francisco and Dunfermline. The results of this monitoring campaign were presented examining a number of characteristics for IAQ. In doing so, this study evaluated the first residential PassivHaus building in Latin America and unique certified dwelling in Mexico.

10.2 Thesis structure

The work presented in Chapter 1 outlined the context of the study and discussed the drivers for building low-energy buildings. PassivHaus was presented as an efficient way to achieve ultra-low-energy homes and it was demonstrated that IAQ had not been addressed as thoroughly as in other low-energy certifications. The development of a methodology to conduct the research, in particular, the use of low-cost monitors and their use in research were discussed in Chapter 2, together with a test of the accuracy of a low-cost monitor, namely the Foobot, used in this research. Chapter 3 defined the PassivHaus approach and explained in detail its principles and possible IAQ implications, followed by a short discussion of several IAQ studies in PassivHaus dwellings. Furthermore, it outlined the IAQ parameters examined in this study based on standard IAQ assessment routines and presented their sources and potential health impacts briefly. Chapter 4 described the use of the Foobot in this research, together with the study design, a pilot study, research scope, limitations, replicability and the quality of the research.

The following three Chapters test the use of the monitoring methodology. In doing so, quantitative and qualitative results for the Mexico City (5), San Francisco (6) and Dunfermline (7) were presented after a brief description of the building and household characteristics. Chapter 8 presented the cross-analysis of the findings of the case studies and associated them with the occupants' perception. Chapter 9 discussed the implications of the monitoring protocol, its differences to IAQ assessment routines and described how the Foobot data were used to achieve high data quality. The IAQ — quantitative and qualitative — measurements are also discussed in Chapter 9 in terms of relative levels of indoor pollution protection, overheating, humidity and occupant behaviour. These discussions also set the findings into the context of other research and propose further work. Finally, in this chapter, a summary of the main findings, further research and limitations are presented.

10.3 Main findings

This research outlined the suitability of the Foobot to measure indoor IAQ and the use of online surveys to collect participants' perceptions remotely. The application of the monitoring protocol proved to be efficient to collect IAQ data.

The Foobot, however, was limited on the range of monitoring parameters compared to the CIBSE KS17 and the EPA protocol for IAQ monitoring and proved to be unreliable for CO_2 measurements by providing $CO_{2\text{-equivalent}}$ from tVOC. Other aspects such as reliability of the sensors and algorithms, data drifting over long periods (one year) and life span should also be considered in this approach. Project-based or proof-concept IAQ monitoring systems could be developed based on specific needs for research projects.

One of the significant barriers of undertaking this type of research up until now has been the difficulty in collecting actual pollutant data – most studies have used proxy data such as CO_2. The review of IAQ monitors revealed a clear need for monitors that that can measure hygrothermal conditions, although they lack specific parameters for thermal comfort assessment such as radiant temperature and air velocity. Air temperature can be used, however, this may not be ideal in public buildings where large walls are more common. Current low-cost IAQ monitors are capable of measuring the most common pollutants without being cost-prohibitive. Low-cost monitors, such as the Foobot, may be a good option for overcoming initial costs, but their life span, requisite skills and accuracy need to be considered. It is expected that any sensors may drift over long periods and require periodic calibration. However, this may not be possible with low-cost monitors, unless sensors are replaced but may be possible in mid-range monitors. The use of calibration equations and data corroboration is the current optimum (and possibly the only) data quality practice to reduce the accuracy bias of low-cost sensors.

The approach to IAQ data collection made it possible to collect data on indoor pollution simultaneously in a dwelling for extended periods, thirteen months in Mexico City, nine months in San Francisco and eight months in Dunfermline. This is believed to be the first study to collect data simultaneously at five-minute intervals on $PM_{2.5}$ and tVOC, in three rooms of each dwelling, in the same case study and for thirteen months in a building performance evaluation (BPE) study. As shown in the literature review, most of the studies that addressed IAQ have significant spatial and temporal limitations. Therefore, this study presents an innovative methodological approach to BPE.

The analysis of the data revealed that IAQ is highly related to artificial conditions — occupant behaviours and outdoor —, building related factors such as ventilation and airtightness may impact on the dissipation, sedimentation and extraction of indoor pollutants. However, in order to achieve better results, building designers, PassivHaus consultants and homeowners need to adhere to the best IAQ practices – the effects of occupant behaviour should not be underestimated. The review of the PassivHaus standard revealed the lack of attention to IAQ details, particularly around source control and the need for better ventilation design. Material selection, design strategies and compulsory criteria in PassivHaus design are drawn towards energy efficiency, and less attention is given to other factors such as healthy environments, beyond the mandation of air change rates. However, this is particular not only to PassivHaus but also in most low-energy buildings.

While there was not a significant overheating difference prevalence between PassivHaus and control homes as defined by CIBSE or PassivHaus criteria, warmer temperatures were usually measured in PassivHaus dwellings, especially during summer, thus lending PassivHaus dwellings to a higher risk of overheating. Mechanically ventilated homes were associated with dry air perception by the occupants, although the moisture content analysis revealed that this was not always the case. The reliance on mechanical ventilation systems to provide fresh air in dwellings may exacerbate pollution spikes from indoor sources and slow their dissipation. Whilst these conclusions were made based on a limited number of homes; they provided the outline evidence required to support large-scale research programmes to record physical and qualitative evidence of indoor pollution.

This study presented the BPE of the first and unique PassivHaus in Mexico collecting qualitative and quantitative data about the indoor environment. This is the first comprehensive indoor environmental review of a certified PassivHaus dwelling in Latin America, alongside an emphasis on IAQ. The findings of this study may not be comparable to other studies in terms of location or context, but higher levels of satisfaction and IAQ were measured in other studies (Tuohy, Murphy and Deveci, 2012; Fischer, Langer and Ljungström, 2014; Wallner *et al.*, 2015, 2017; Langer *et al.*, 2016; Rojas *et al.*, 2016; Wang *et al.*, 2018), thus supporting the case study findings.

To ensure that acceptable levels of IAQ are achieved in dwellings, the best practices for design, material selection, construction and building maintenance should be implemented. A key issue is the information and guidance that is provided to homeowners and users. To maintain good IAQ through source control, this may extend beyond the physical use of the building, to include advice on pollutant sources, for example, cleaning and personal care products. Some common perceptions may also be addressed, for example, benefits of window opening for purge ventilation. Therefore, it is not only necessary that building designers, architects and homeowners work together, but a case for new enquiry lines, dealing with IAQ practices, guidelines and possible health impacts, is well understood. Research in this area tends to focus on negative aspects, but there is scope for looking at health benefits of PassivHaus approaches – the original intention was to identify the protective effects of the PassivHaus approach in a polluted environment.

Clear guidelines for IAQ are much-needed requirement to ensure that compulsory IAQ criteria can be added to the PassivHaus design approach, possibly resulting in an additional worksheet in the PHPP. This should start not only driving attention toward IAQ, but also promote healthier environments in PassivHaus buildings.

While the main interest of this work was not to measure IAQ, it developed and tested the performance and suitability of a novel IAQ monitoring methodology using low-cost monitors, in order to promote a healthier environment. Therefore, the author hopes that this study will serve as a platform to promote a better understanding of occupants' health and their exposure to pollutants in dwellings, aligned with the application of best practices for IAQ.

10.4 Research implications for IAQ low-cost monitors

The findings of this research suggest that low-cost monitors have the potential to be used for IAQ studies. Nonetheless, they should be used with caution as they require additional quality measures to ensure data quality. The use of low-cost IAQ monitors/sensors could impact on current data collection approaches, building systems automation and to inform building occupant's. To achieve acceptable IAQ levels, it is necessary architects, building designers and homeowners work together to set up best practices for ventilation, cooling and thermal and moisture control, to ensure healthier indoor environments.

The current data collection approaches for IAQ require instruments with accuracy that may be excessive for IAQ continuous monitoring. Low-cost sensors can provide these readings, although a stricter maintenance routine may be required. This should include checking the data and if possible, compare them to traditional instruments to detect data drifting and identify if calibration is required before the expected date. Low-cost IAQ monitors make affordable simultaneous monitoring of different spaces strengthening data collection for IAQ studies. Data from the whole building could serve to understand better indoor pollution, occupant exposure and to quantify the impact of human behaviours to IAQ. Current IAQ monitors are limited in the range of the parameters and may not be possible to measure all the parameters suggested by established IAQ assessment routines. Nevertheless, low-cost sensors can be adapted for project-specific systems for advanced IAQ monitoring.

Low-cost sensors also open the opportunity for building systems automation, especially for ventilation. The most common ventilation automation systems are based on individual temperature, relative humidity or CO2 sensors. Whereas this is a logical approach, they are designed based on thermal comfort, ventilation needs or energy reasons. A more comprehensive range of IAQ and thermal comfort sensors could be an alternative approach to regulate ventilation, as well as diluting and removing indoor pollutants. IAQ monitors may use a more sophisticated metric for automation that could benefit thermal comfort, ventilation needs, energy savings and indoor health.

Finally, IAQ low-cost monitors can provide real-time information to building occupants so that they can take informed decisions to manipulate the indoor environment. This could impact the way occupants engage with the building operation, especially in dwellings. It can also be of interest for commercial and industrial building managers. In overall, the use of low-cost monitors has the potential to transform current approaches for IAQ monitoring and building automation, while providing better information to building occupants.

10.5 Further research

Based on the findings herein, specific research gaps were identified and are presented in the following sub-sections.

10.5.1 IAQ guidelines and awareness

In order for IAQ criteria to be blended into residential design, research needs to focus on establishing the real benefits of the design principles to human health. Interdisciplinary research needs to be conducted to develop universal IAQ guidelines, based on the health risks associated with exposure to air pollutants. One of the key challenges when assessing indoor pollution in contemporary research is the diversity of guidelines, thresholds and policies that change from one jurisdiction to another (i.e. $PM_{2.5}$ Australia 8µg/m^3 (Environment *et al.*, 2003), in Canada 25µg/m^3 (Commission, 2015) and with no safe value in the UK (Laxen *et al.*, 2010)). This makes it difficult to compare the results from one study to another or to compare the results of an IAQ monitoring project to a database and evaluate the suitability of a building design strategy.

IAQ data could be gathered pre- and post-occupancy together with building information and human interaction so that meta-studies can take place. Future work should be carried out between indoor environmental scientists, medical researchers, building designers, engineers and other building professionals to develop appropriate IAQ guidelines, especially for homes. This could be achieved through the incorporation of architects, building scientists and professionals in existing international networks that promote training, internships, exchanges (for students, researchers and practitioners) and knowledge transfer partnerships (KTP) to study IAQ. This, in turn, would facilitate the development of the knowledge and skills to be applied across different bodies, countries and building typologies. Architects and building professionals should focus on developing skills and knowledge to ensure the best practices for IAQ, ventilation and airtightness in contemporary low-energy buildings, while scientists need to evaluate the impact of those practices on IAQ, and their potential health risks. More importantly, the incorporation of KTP programmes should help to secure the best way to transfer this knowledge to built environment professionals already in practice. However, the best approach is to ensure that early career (researchers and built environment professionals) have a good understanding and awareness of IAQ and ventilation.

Some studies have attempted to compare the exposure guidelines for indoor air pollutants; they are hampered, however, by a lack of connection to human response and the absence of standardised IAQ guidelines or even protocols for data collection, analysis and interpretation. Appreciation of these factors should lead to a universal IAQ index so that buildings can be compared no matter their location or level of sustainability. This IAQ index should include defining minimum levels of indoor pollutants based on their impact on health as well as their likelihood to be present in buildings, considering building materials and occupant behaviour. In the first instance, this approach should include basic indoor pollutants such as $PM_{2.5}$, tVOC, formaldehyde, radon and carbon monoxide. Additionally, the use of carbon dioxide as a metric for ventilation and hygrothermal measurements could be developed further as our understanding of indoor air pollutants grows. A specific selection of pollutants and an IAQ index would facilitate the incorporation of IAQ criteria for dwellings, which can then be used to measure objectively.

10.5.2 PassivHaus IAQ performance

Several studies examine the IAQ performance of PassivHaus building around the globe. However, it is difficult to compare their results, as they are based on different research objectives, thresholds and criteria. The findings of this study add evidence that PassivHaus buildings may have better IAQ performance compared to standard buildings in temperate, warm/humid and cold climates. However, the criteria from this study may differ from others. In order to compare PassivHaus buildings, it is fundamentally necessary to develop specific IAQ criteria, which would help in collecting similar data comparable to other PassivHaus buildings. More importantly, it would help studies adhere to the same criteria and monitoring practices, even between buildings with different levels of sustainability.

The definition of IAQ criteria for PassivHaus buildings would help to gather much-needed evidence to establish the real benefits of the PassivHaus design strategies, to improve IAQ and occupants' health. This would establish the reference point so that large-scale studies could take place to evaluate IAQ from pre- and post-occupancy data to evaluate causal links between IAQ and PassivHaus occupants. It may also be beneficial to create a database in which the same IAQ criteria are evaluated so that IAQ metadata studies can be compared among other PassivHaus or non-PassivHaus buildings.

10.5.3 Occupant behaviour and activities

The examination of the literature review and the data from this study made evident the need to gain a better understanding of the impact of occupant behaviour on IAQ. Therefore, future studies should focus on developing a methodology that allows for collecting data about their activities and behaviours, without being too intrusive or demanding, while also guaranteeing data collection and occupant privacy and anonymity. More importantly, further work should focus on understanding the impact of occupants' behaviour and activities on IAQ, especially $PM_{2.5}$ and VOC emissions, by identifying the risks of specific activities and how occupants perceive their impact on IAQ and health. It would also be of great interest to conduct studies to understand the importance of changing occupants' day-to-day habits, in order to improve IAQ.

10.5.4 Monitoring instruments

The analysis and comparison of the IAQ monitors currently available on the market showed an apparent gap regarding the accuracy, cost of monitoring devices and range of parameters. Nowadays, BPE professionals are forced to choose between highly precise or low-cost IAQ monitors. The accuracy of the highly precise analytical instruments may be excessive for IAQ studies, where the objective is to evaluate whether the pollutant concentration exceeds a threshold value. They are further made unsuitable through their size, characteristics, skilled handling and cost, which makes them unviable for simultaneous monitoring in different dwellings. Low-cost IAQ monitors may be an economical option that bypasses such limitations, but these need additional measurements to ensure the robustness and quality of the data.

The development of a mid-range IAQ monitor would be beneficial for IAQ and to establish the health impacts of air pollution studies while helping to develop IAQ guidelines. This monitor should provide reliable data without the need for additional measurements and be economically affordable for research projects. The interest of such monitors has been discussed with other BPE professionals, among them architecture offices, many of whom are convinced that it would be advantageous to collect data about current IAQ performance and compare them with future design changes. A solution should be explored to provide the best compromise between accuracy and cost, thereby allowing for calibration to increase the life span of IAQ monitors.

Other forms of ambient monitoring should also be considered. Current approaches collect limited outdoor data either due to the availability from local networks or the cost of instruments to take outdoor measurements. In order to evaluate the levels of protection and control of indoor sources, it is essential that outdoor measurements of tVOC or other specific pollutants not collected by traditional means be obtained.

Finally, activities and occupant behaviours are usually collected through occupant diaries. It was noted that occupants do not always report correct activities, densities and occupancy times. A monitoring system using movement detection and sound could help to identify the type of activity and real occupancy patterns so that they could be matched to IAQ pollution.

10.6 Main limitations

This study focused on development and testing of an IAQ monitoring method using low-cost IAQ monitors. It is important to recognise that this study experienced identifiable limitations. First, the accuracy of the data is dependent on the Foobot capabilities. Therefore, the collected data should not be understood as absolute values but as relative values . This innovative approach was tested in PassivHaus and control dwellings. The collected data provided insights about the IAQ behaviour over extended periods, which may not have been possible using the current monitoring approach. Second, differences between sensors and data quality assurances from the Foobot to ambient data may presume differences in the data. Finally, the findings are based on a limited number of case studies and homes, but given the data collection approach, this study provide much-needed evidence to develop alternative methods for IAQ monitoring, especially in dwellings.

10.7 Conclusions

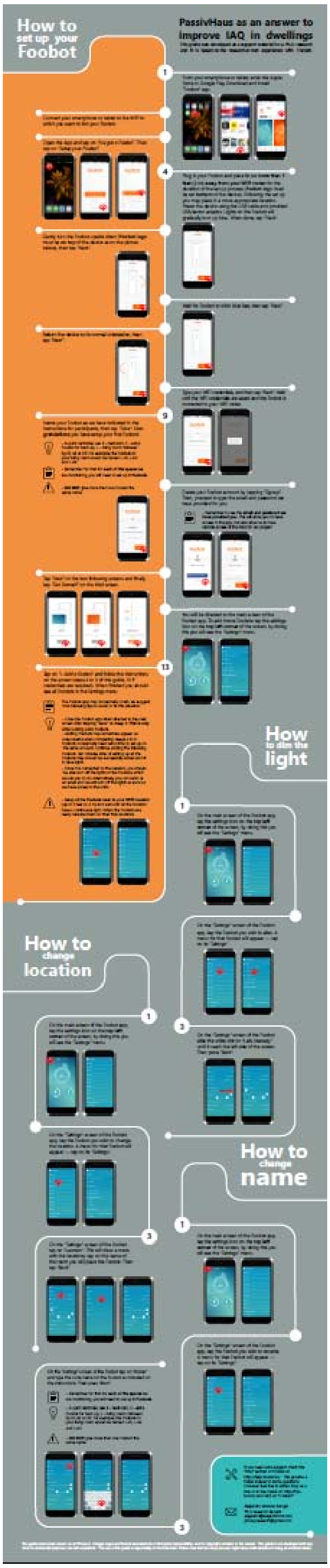
This study suggests that BPE studies focusing on IAQ may benefit from alternative methods for IAQ monitoring. In this study, a low-cost IAQ monitors, the Foobot, was used to demonstrate and test this approach. This innovative approach was perceived to be less intrusive for BPE studies evaluating IAQ in homes. Low-cost IAQ monitors also offer the possibility for retrieving the data remotely and monitoring simultaneously different spaces. This approach may benefit certain ethical issues such as privacy and anonymity in BPE studies, but current low-cost IAQ monitors need additional measures, such as calibration equations and data corroboration, to strengthen data accuracy and quality.

During the testing of the low-cost IAQ monitoring method, this study undertook what is believed to be the first comprehensive indoor environmental review, with an emphasis on IAQ, of a certified PassivHaus dwelling in Latin America. Qualitative and quantitative data of the indoor environment and IAQ were collected in seven dwellings in Mexico, San Francisco and Dunfermline. The analysis of the data suggested that IAQ is influenced by three main factors: occupant behaviours, outdoor pollution and ventilation.

It is hoped that the findings of this study may serve to stimulate building scientis to explore alternative methods for IAQ monitoring and for the development of tools with more precise and wider monitoring criteria. More importantly, the use of low-cost IAQ monitoring systems should be included in further research to inform our understanding of occupants' behaviour in relation to the IAQ, thereby promoting higher levels of well-being and a reduction in health risks.

Annex 1 – Foobot setup materials

A hard copy of the Foobot setup guides is available at the end of this thesis.



Where to place your Foobot

Bedroom

PassivHaus as an answer to improve IAQ in dwellings

This guide was developed as a support material for a Ph.D. research and it is based on the researcher own experience with Foobot.

1

Follow the instructions on our guide *"How to setup your Foobot".*

- Additional content: guide *"How to set up your Foobot".*

Select the THREE locations to place the Foobots on your bedroom. This could be all together or separately.

- It is best to place Foobot at the **head height relative level** to the purpose of the room. For example, chests of drawers or night tables are ideal locations in your bedroom as you may spend most of your time sitting or lying down.

- The most suitable to spot to place a Foobot is in an **OPEN SPACE.**

- **Avoid** placing Foobot **near to a wall or another element that may block air flow.** A bookshelf is a good example of furniture that might block air flow; if this is the option put it closer to the edge rather than the wall.

- **Avoid** placing Foobot **near sources of excessive heat or moisture.** Radiators and fireplaces are good examples of what to avoid.

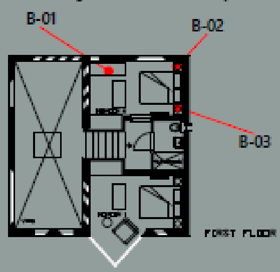
- **Avoid direct sunlight** to the Foobot.

- **Avoid** placing Foobot **near to an open window, inlets/outlets of the ventilation system.** These present the greatest interference with sensor readings in a room as they provoke localized air flows.

Place the Foobots in their final location and power them.

- Remember to power the Foobot using the USB cable and **provided USB/sector adaptor.**

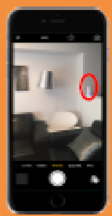
On the floor plan sketch mark the locations each of Foobot, annotating the sketch if necessary.



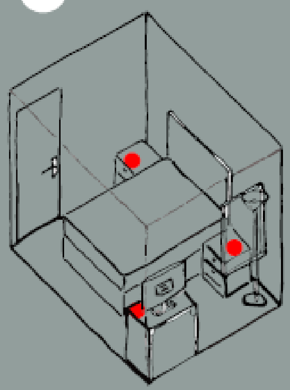
Indicates a radiator.

Take pictures of each of the Foobots you have located with the surroundings.

We can help you on finding the best spots if you provide us photographs or on a video call.



Location Example



The dots indicate the best places to set place your Foobot.

Foobot **SHOULD NOT BE USED** on outdoors, next to water, next to flames, or next to heat sources.

If you need extra support check the *"FAQ"* section of Foobot at: http://help.foobot.io/ . This provide a faster answer to some questions. However feel free to either drop us a line or to the maker at: http://foobot.io/ and click on *"Contact".*

Alejandro Moreno Rangel
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alejandro@alejandromr.com
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Where to place your Foobot

Kitchen

PassivHaus as an answer to improve IAQ in dwellings

This guide was developed as a support material for a Ph.D. research and it is based on the researcher own experience with Foobot.

1

Follow the instructions on our guide *"How to setup your Foobot"*.

- Additional content: guide *"How to set up your Foobot"*.

Select the THREE locations to place the Foobots on your bedroom. This could be all together or separately.

- It is best to place Foobot at the **head height relative level** to the purpose of the room. For example, as you are more likely to be standing in the Kitchen a shelf or the Kitchen countertop are good places to put them in the Kitchen.

- The most suitable to spot to place a Foobot is in an **OPEN SPACE.**

- **Avoid** placing Foobot **near to a wall or another element that may block air flow.** A bookshelf is a good example of furniture that might block air flow; if this is the option put it closer to the edge rather than the wall.

- **Avoid** placing Foobot **near sources of excessive heat or moisture.** Radiators and fireplaces are good examples of what to avoid.

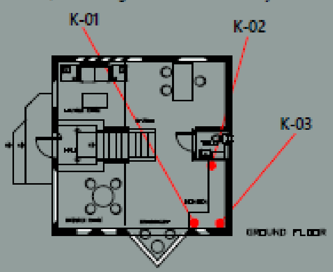
- **Avoid direct sunlight** to the Foobot.

- **Avoid** placing Foobot **near to an open window, inlets/outlets of the ventilation system.** These present the greatest interference with sensor readings in a room as they provoke localized air flows.

Place the Foobots in their final location and power them.

- Remember to power the Foobot using the USB cable and **provided USB/sector adaptor.**

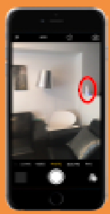
On the floor plan sketch mark the locations each of Foobot, annotating the sketch if necessary.



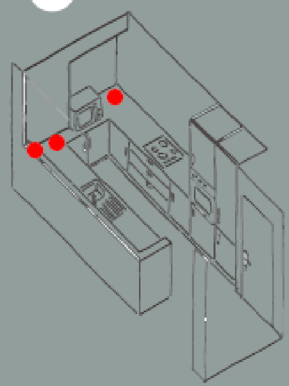
Indicates a radiator.

Take pictures of each of the Foobots you have located with the surroundings.

We can help you on finding the best spots if you provide us photographs or on a video call.



Location Example



The dots indicate the best places to set place your Foobot.

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Where to place your Foobot

Living room

PassivHaus as an answer to improve IAQ in dwellings

This guide was developed as a support material for a Ph.D. research and it is based on the researcher own experience with Foobot.

1

Follow the instructions on our guide *"How to setup your Foobot"*.

- Additional content: guide *"How to set up your Foobot"*.

Select the THREE locations to place the Foobots on your bedroom. This could be all together or separately.

- It is best to place Foobot at the **head height relative level** to the purpose of the room. For example, TV bench or side tables are ideal locations in your living room as you may spend most of your time sitting.

- The most suitable to spot to place a Foobot is in an **OPEN SPACE.**

- **Avoid** placing Foobot **near to a wall** or another element that may block air flow. A bookshelf is a good example of furniture that might block air flow; if this is the option put it closer to the edge rather than the wall.

- **Avoid** placing Foobot **near sources of excessive heat or moisture.** Radiators and fireplaces are good examples of what to avoid.

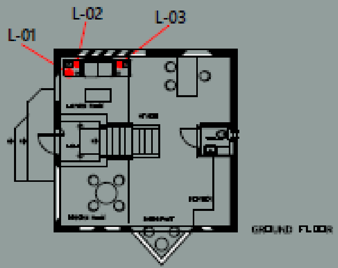
- **Avoid direct sunlight** to the Foobot.

- **Avoid** placing Foobot near to an **open window, inlets/outlets of the ventilation system.** We want to have a characterization of the air quality on the spaces.

Place the Foobots in their final location and power them.

- Remember to power the Foobot using the USB cable and **provided USB/sector adaptor.**

On the floor plan sketch mark the locations each of Foobot, annotating the sketch if necessary.



Indicates a radiator.

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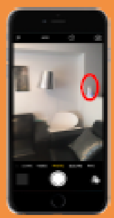
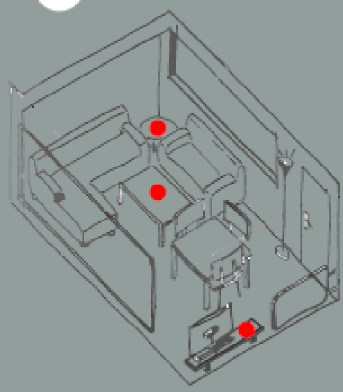
We can help you on finding the best spots if you provide us photographs or on a video call.



Location Example



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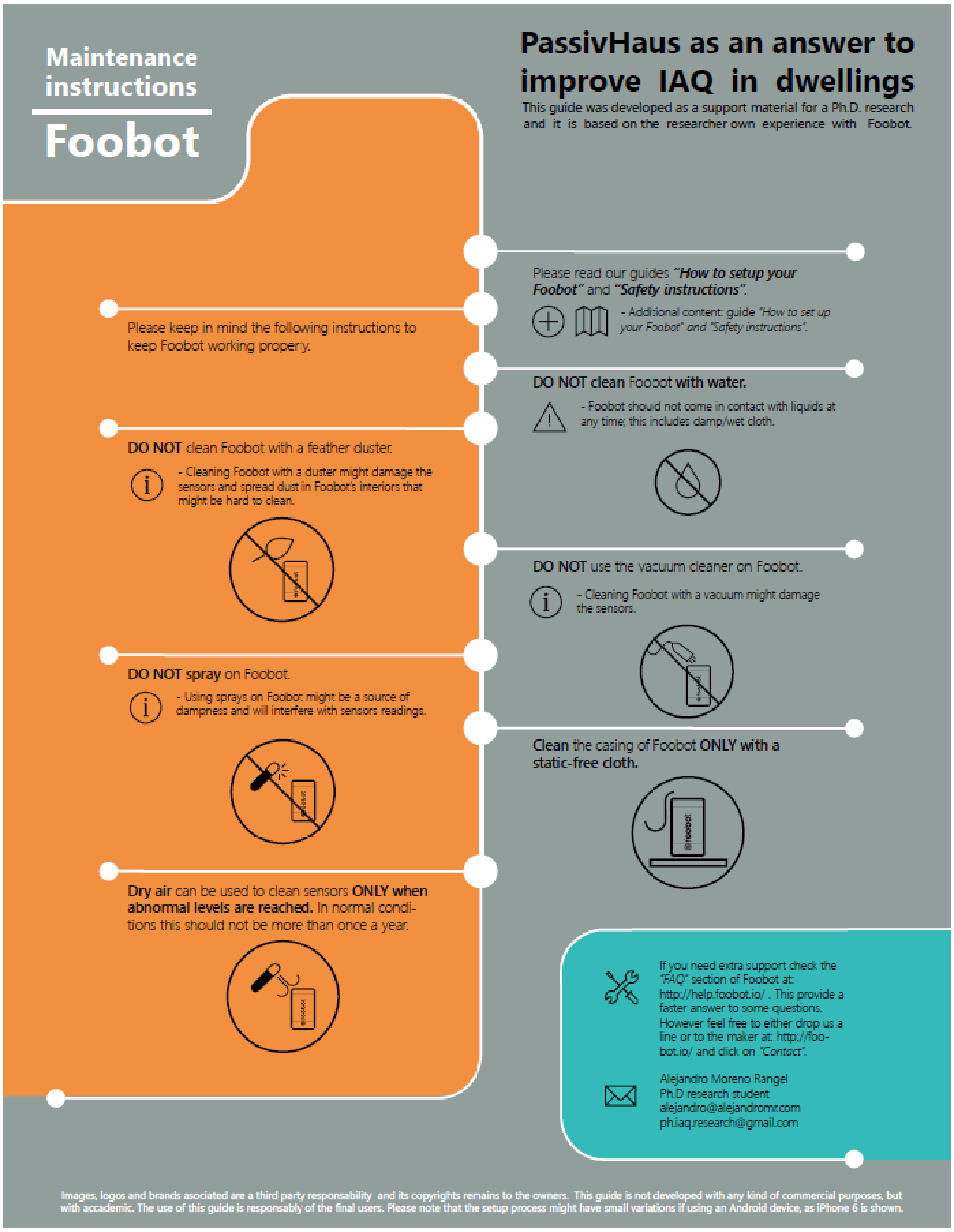
Maintenance instructions
Foobot
PassivHaus as an answer to improve IAQ in dwellings
This guide was developed as a support material for a Ph.D. research and it is based on the researcher own experience with Foobot.
Please keep in mind the following instructions to keep Foobot working properly.
Please read our guides "How to setup your Foobot" and "Safety instructions".
- Additional content: guide "How to set up your Foobot" and "Safety instructions".
DO NOT clean Foobot with water.
- Foobot should not come in contact with liquids at any time; this includes damp/wet cloth.
DO NOT clean Foobot with a feather duster.
- Cleaning Foobot with a duster might damage the sensors and spread dust in Foobot's interiors that might be hard to clean.
DO NOT use the vacuum cleaner on Foobot.
- Cleaning Foobot with a vacuum might damage the sensors.
DO NOT spray on Foobot.
- Using sprays on Foobot might be a source of dampness and will interfere with sensors readings.
Clean the casing of Foobot ONLY with a static-free cloth.
Dry air can be used to clean sensors ONLY when abnormal levels are reached. In normal conditions this should not be more than once a year.
If you need extra support check the "FAQ" section of Foobot at: http://help.foobot.io/ . This provide a faster answer to some questions. However feel free to either drop us a line or to the maker at: http://foobot.io/ and click on "Contact".
Alejandro Moreno Rangel
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ph.iaq.research@gmail.com
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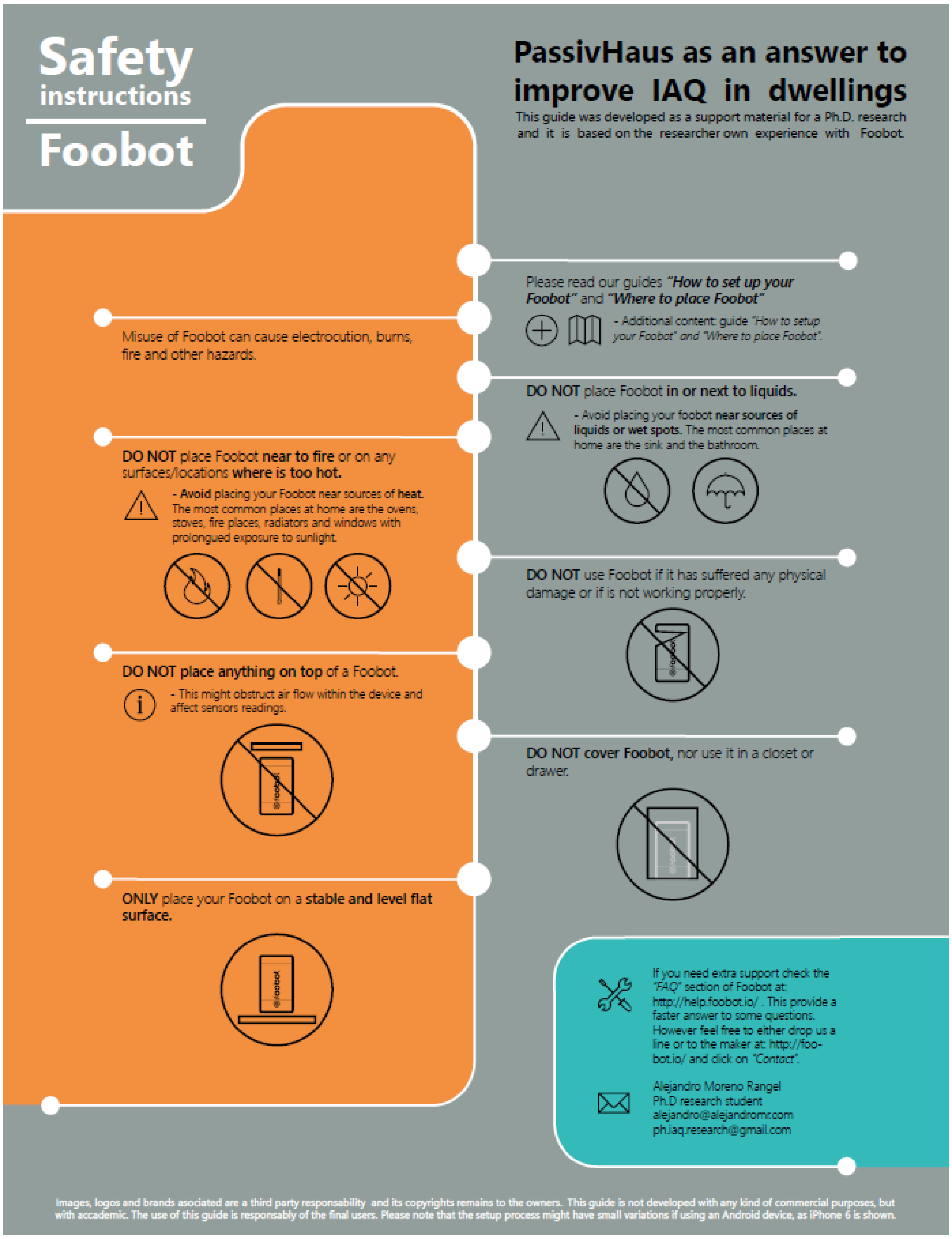
Safety instructions
Foobot
PassivHaus as an answer to improve IAQ in dwellings
This guide was developed as a support material for a Ph.D. research and it is based on the researcher own experience with Foobot.
Misuse of Foobot can cause electrocution, burns, fire and other hazards.
DO NOT place Foobot near to fire or on any surfaces/locations where is too hot.
- Avoid placing your Foobot near sources of heat. The most common places at home are the ovens, stoves, fire places, radiators and windows with prolongued exposure to sunlight.
DO NOT place anything on top of a Foobot.
- This might obstruct air flow within the device and affect sensors readings.
ONLY place your Foobot on a stable and level flat surface.
Please read our guides "How to set up your Foobot" and "Where to place Foobot"
- Additional content: guide "How to setup your Foobot" and "Where to place Foobot".
DO NOT place Foobot in or next to liquids.
- Avoid placing your foobot near sources of liquids or wet spots. The most common places at home are the sink and the bathroom.
DO NOT use Foobot if it has suffered any physical damage or if is not working properly.
DO NOT cover Foobot, nor use it in a closet or drawer.
If you need extra support check the "FAQ" section of Foobot at: http://help.foobot.io/ . This provide a faster answer to some questions. However feel free to either drop us a line or to the maker at: http://foobot.io/ and click on "Contact".
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Annex 2 – Building information survey

[Survey title] Building characteristics 01/04

Thanks [Participant] for helping us with this study, we really appreciate the time you are taking to answer this questionnaire. This should not take more than 5 minutes of your time, or 15 minutes if you are taking the three parts of this "Building characteristics questionnaire" at the same time. This survey is to be filled only one time.
ALL ANSWERS WILL BE COMPLETELY ANONYMOUS.

[Page title] General building information

*1. How long have you been living in this PassivHaus? *(Specify YY years and MM months)*

*2. In average, how many hours is your house occupied during WEEKDAYS?

*3. In average, how many hours is your house occupied during WEEKEND?

*4. What is the primary cooking fuel? *Please, mark the one that apply.*

- Gas
- Electricity
- Oil
- If other, please specify

*5. What is the primary heating fuel? *Please, mark the one that apply.*

- Gas
- Electricity
- Oil
- If other, please specify

*6. What is the ventilation strategy used in your home? *Please, mark the one that apply.*

- Natural ventilation
- Hybrid ventilation
- Mechanical ventilation
- Mechanical ventilation with heat recovery
- If other, please specify

1 / 2	[progress bar]	50%
	[Next button]	
--	[End of page]	--

*7. How many people currently live in your household? and what is the age of them? *Mark the age group of each of the occupants or N/A for the extra occupants once you have marked each of the occupants.*

	Under 16	More than 16, but less than 25	More than 25, but less than 35	More than 35, but less than 45	45 or older	N/A
Occupant 1						
Occupant 2						
Occupant 3						
Occupant 4						
Occupant 5						

Please, indicate the age of any other occupant. Please, indicate if you do have a pet.

*8. Does anyone in your household currently smoke cigarettes, or not? *Please, mark the one that apply.*

- Yes, someone does
- No, no one does
- Not sure

If yes, how many occupants smoke?

*9. Are cigarettes ever smoked at home? *Please, mark the one that apply.*

- Yes
- No

2 / 2	[progress bar]	100 %

[Back button] [Done (thanks for your participation) button]
-- [End of page] --

[Survey title] Building characteristics 02/04

Thanks [Participant] for helping us with this study, we really appreciate the time you are taking to answer this questionnaire. This should not take more than 5 minutes of your time, or 15 minutes if you are taking the three parts of this "Building characteristics questionnaire" at the same time. This survey is to be filled only one time.
ALL ANSWERS WILL BE COMPLETELY ANONYMOUS.

[Page title] Ventilation

*1. How often do you open the windows during SUMMER? *Please, mark the one that describes better your behaviour; only one answer per row is admitted.*

	Never	Rarely	Occasionally	Regularly	Constantly
Morning	☐	☐	☐	☐	☐
Afternoon	☐	☐	☐	☐	☐
Evening	☐	☐	☐	☐	☐
Night	☐	☐	☐	☐	☐

*2. How often do you open the windows during WINTER? *Please, mark the one that describes better your behaviour; only one answer per row is admitted.*

	Never	Rarely	Occasionally	Regularly	Constantly
Morning	☐	☐	☐	☐	☐
Afternoon	☐	☐	☐	☐	☐
Evening	☐	☐	☐	☐	☐
Night	☐	☐	☐	☐	☐

*3. How often do you use the extraction fan/cooker hood? *Please, mark the one that describes better your behaviour; only one answer per row is admitted.*

	Never	Rarely	Occasionally	Regularly	Constantly
During cooking	☐	☐	☐	☐	☐
After cooking	☐	☐	☐	☐	☐

1 / 4 [progress bar] 25%
[Next button]
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[Page title] Mechanical ventilation

*4. Is there a boost function for the mechanical ventilation system? *Please, mark the one that apply.*

☐ Yes

☐ No

5. If yes, how often do you use it? *Please, mark the one that describes better your behaviour; only one answer per row is admitted.*

	Never	Rarely	Occasionally	Regularly	Constantly
Overall	◻	◻	◻	◻	◻
During showering	◻	◻	◻	◻	◻
After showering	◻	◻	◻	◻	◻
During cooking	◻	◻	◻	◻	◻
After cooking	◻	◻	◻	◻	◻

*6. Have you ever adjusted the supply or extract vents of the ventilation system? *Please, mark the one that apply.*

◻ Yes

◻ No

If yes, could you explain the reason why and what adjustment you did?

[ ]

2 / 4 [progress bar] 50%

[Back button] [Next button]

-- [End of page] --

[Page title] Heating

*7. Do you have a thermostat, which controls the heating system? Please, mark the one that apply.

◻ Yes

◻ No

If yes, could you indicate the temperature settings?

[ ]

8. What time during different seasons are you more likely to use any form of heating (either heating system or additional appliances) in the home? *Please complete with hours, i.e. 6:00 am to 10:00 am and 18:00 pm to 23:30 pm.*

Spring [ ]

Summer [ ]

Autumn [ ]

Winter [ ]

3 / 4 [progress bar] 75%

[Back button] [Next button]

-- [End of page] --

[Page title] Cleaning

*9. How often do you clean your house... *Please, mark the one that describes better your behaviour; only one answer per row is admitted.*

	Never / I don't have	Once a month	Once a week	Several times a week	Daily
...using a brush?	○	○	○	○	○
...using a vacuum?	○	○	○	○	○
...using a duster?	●	○	○	○	○

*10. What kind of cleaning products do you use? *Please, mark the one that apply.*

○ Chemical cleaning products

○ Chemical and biological products

○ Biological products

○ I'm not sure

4 / 4	[progress bar]	100 %
	[Back button] [Done (thanks for your participation) button]	
--	[End of page]	--

[Survey title] Building characteristics 03/04

Thanks [Participant] for helping us with this study, we really appreciate the time you are taking to answer this questionnaire. This should not take more than 5 minutes of your time, or 15 minutes if you are taking the three parts of this "Building characteristics questionnaire" at the same time. This survey is to be filled only one time.

ALL ANSWERS WILL BE COMPLETELY ANONYMOUS.

[Page title] Kitchen habits

*1. Is there any dishwasher at home? *Please, mark the one that apply.*

- Yes
- No

2. If yes, how often do you use it? *Please, mark the one that apply.*

Never	Once a month	Once a week	Several times a week	Daily
☐	☐	☐	☐	☐

*3. In average, how much time do you spend cooking each day?

[ ]

1 / 2 [progress bar] 50%

[Next button]

-- [End of page] --

[Page title] Washing habits

4. Is there a washing machine at home? *Please, mark the one that apply.*

- Yes
- No

5. If yes, how often do you use it?

Never	Once a month	Once a week	Several times a week	Daily
☐	☐	☐	☐	☐

*6. Do you have a tumble drier at home? *Please, mark the one that apply.*

- Yes
- No

If yes, is it vented outdoors? [ ]

7. If yes, how often do you use it? *Please, mark the one that apply.*

Never	Once a month	Once a week	Several times a week	Daily
☐	☐	☐	☐	☐

*8. Are clothes ever drier indoors WITHOUT the use of a tumble drier? *Please, mark the one that apply*.

- Yes
- No
- If yes, could you describe under which circumstances and how?

9. If yes, how often do you use this method? *Please, mark the one that apply.*

Never	Once a month	Once a week	Several times a week	Daily
(selected)				

2 / 2 [progress bar] 100 %

[Back button] [Done (thanks for your participation) button]

-- [End of page] --

[Survey title] Building characteristics 04/04

Thanks [Participant] for helping us with this study, we really appreciate the time you are taking to answer this questionnaire. This should not take more than 5 minutes of your time, or 15 minutes if you are taking the three parts of this "Building characteristics questionnaire" at the same time. This survey is to be filled only one time.
ALL ANSWERS WILL BE COMPLETELY ANONYMOUS.

[Page title] Pets

*1. Is there any pets at home? *Please, mark the one that apply.*

- ☐ Yes
- ☐ No
- ☐ If yes, could you provide us with details?

[ ]

1 / 2	[progress bar]	50%
	[Next button]	
--	[End of page]	--

[Page title] Indoor environmental quality

*2. At home, how often do you... *Please, mark the one that describes better your behaviour; only one answer per row is admitted.*

	Never / I don't use	Once a month	Once a week	Several times a week	Daily
...use of cleaning products?	☐	☐	☐	☐	☐
...use pesticides?	☐	☐	☐	☐	☐
...use air fresheners?	☐	☐	☐	☐	☐
...use candles or incidences?	☐	☐	☐	☐	☐
...smoke?	☐	☐	☐	☐	☐
...hygiene/cosmetic products?	☐	☐	☐	☐	☐
...light a fire? (not for cooking)	☐	☐	☐	☐	☐
...use paints or glues?	☐	☐	☐	☐	☐

*3. Have you observed damp on walls or ceilings? *Please, mark the one that apply.*

- ☐ Yes
- ☐ No

If yes, could you state where?

*4. Have you observed mould on walls or ceilings? *Please, mark the one that apply.*

- Yes
- No

If yes, could you state where?

*5. Do you keep plants inside of your home? *Please, mark the one that apply.*

- Yes
- No

If yes, could you state where?

2 / 2	[progress bar]	100 %
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--	[End of page]	--

Annex 3 – Occupants perception survey

[Survey title] Occupants perception 01/03
[Page title] Environmental conditions

Thanks [Participant] for helping us with this study, we really appreciate the time you are taking to answer this questionnaire. This should not take more than 5 minutes of your time, or 15 minutes if you are taking the three parts of this "Occupants perception questionnaire" at the same time. This survey is to be filled by three of the home occupants, if it is to be completed by a child (16 years old or younger) it can be completed by a parent/guardian on her/his behalf with input from the child.
ALL ANSWERS WILL BE COMPLETELY ANONYMOUS.

[Page title] Background information

*1. Completed by: *Please, mark the one that apply*

- Occupant
- On behalf of an occupant

Could you write your initials, so we can follow your answers on the next surveys? This will be used only for this reason. ______

*2. What is your age? *Please, mark the one that apply*

- 16 years or younger
- More than 16, but less than 25 years
- More than 25, but less than 35 years
- More than 35, but less than 45 years
- More than 45, but less than 55 years
- 75 years or older

*3. What is your gender? *Please, mark the one that apply*

- Female
- Male

*4. In average, how much time do you spend a day at home (including the hours you are sleeping) during... *Please, complete the details of the hours, i.e. 14*

...weekdays? ______

...weekends? ______

*5. What do you think indoor air quality is?

*6. Do you currently smoke? *Please, mark the one that apply*

- (selected) Yes, I do
- ( ) No, I do not

1 / 2	[progress bar]	50%
	[Next button]	
--	[End of page]	--

[Page title] Background information

*7. Have you ever experienced at home... *Please, mark the one that apply.*

	In the last 12 months	Any time in your life	Never
...asthma?	(selected)	( )	( )
...bronchitis/pneumonia?	( )	( )	( )
...hay fever?	( )	( )	( )
...air obstruction in the chest?	( )	( )	( )
...allergic rhinitis?	( )	( )	( )
...conjunctivitis?	( )	( )	( )
...allergies?	( )	( )	( )
...sinusitis?	( )	( )	( )
...emphysema?	( )	( )	( )
...laryngitis?	( )	( )	( )
...other chest conditions	( )	( )	( )

Any other illness(es) you suspect might be related to the quality of the indoor air in your home?

*8. In the past 12 months have you had more than two episodes of:

Please tick the box representing the answer to the symptoms you had. If you are undecided about your answer to any question, then please tick "No" for that symptom.
If you answer "Yes" to any of the symptoms, please indicate the frequency for that symptom. You do not need to report the frequency of a symptom unless it was better (symptoms disappeared or decreased) on days away from home.

	Yes	No	Every day spent at home	3 - 4 days each week	1 - 2 days each week	Every 2 or 3 weeks	Less often or never	Better away from home?

								(tick if yes)
Dryness of eyes	☐	☐	☐	☐	☐	☐	☐	☐
Itchy or watery eyes	☐	☐	☐	☐	☐	☐	☐	☐
Blocked or stuffy nose	☐	☐	☐	☐	☐	☐	☐	☐
Runny nose	☐	☐	☐	☐	☐	☐	☐	☐
Dry throat	☐	☐	☐	☐	☐	☐	☐	☐
Lethargy and/or tiredness	☐	☐	☐	☐	☐	☐	☐	☐
Headache	☐	☐	☐	☐	☐	☐	☐	☐
Dry, itching or irritated skin	☐	☐	☐	☐	☐	☐	☐	☐

Since you moved in, have you experienced any other symptoms which, in your opinion, might be related to the home environment?

2 / 2	[progress bar]	100 %
	[Back button] [Done (thanks for your participation) button]	
--	[End of page]	--

Occupants perception 02/03

[Survey title] Environmental conditions

Thanks [Participant] for helping us with this study, we really appreciate the time you are taking to answer this questionnaire. This should not take more than 5 minutes of your time, or 15 minutes if you are taking the three parts of this "Occupants perception questionnaire" at the same time. This survey is to be filled by three of the home occupants, if it is to be completed by a child (16 years old or younger) it can be completed by a parent/guardian on her/his behalf with input from the child.

ALL ANSWERS WILL BE COMPLETELY ANONYMOUS.

*1. Completed by: *Please, mark the one that apply.*

☐ Occupant

☐ On behalf of an occupant

Could you write your initials, so we can follow your answers on the next surveys? This will be used only for this reason. [ ]

1 / 3	[Progress bar]	33%
	[Next button]	
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[Page title] Indoor air quality and environmental comfort

*2. How fresh/stuffy is the air in your home/flat? *Please, mark the most appropriate rate in the scale; only one answer per row is admitted.*

	Too fresh			Neither fresh, nor stuffy			Too stuffy
Summer	☐	☐	☐	☐	☐	☐	☐
Winter	☐	☐	☐	☐	☐	☐	☐

*3. How dry/humid is the air in your home/flat? Please, mark the most appropriate rate in the scale; only one answer per row is admitted.

	Too dry			Neither dry, nor humid			Too humid
Summer	☐	☐	☐	☐	☐	☐	☐
Winter	☐	☐	☐	☐	☐	☐	☐

*4. How still/draughty is the air in your home/flat? Please, mark the most appropriate rate in the scale; only one answer per row is admitted.

	Too still			Neither still, nor draughty			Too draughty
Summer	☐	☐	☐	☐	☐	☐	☐
Winter	☐	☐	☐	☐	☐	☐	☐

*5. How smelly is the air in your home/flat? Please, mark the most appropriate rate in the scale; only one answer per row is admitted.

	Odourless			Neither odourless, nor smelly			Smelly
Summer	☐	☐	☐	☐	☐	☐	☐

Winter	◯	◯	◯	◯	◯	◉	◯

*6. How satisfied are you with the overall air quality of your home/flat? Please, mark the most appropriate rate in the scale; only one answer per row is admitted.

	Satisfactory overall						Unsatisfactory overall
Summer	◯	◯	◯	◯	◯	◯	◯
Winter	◯	◯	◯	◯	◯	◯	◯

2 / 3 [progress bar] 67%

[Back button] [Next button]

-- [End of page] --

[Page title] Indoor air quality and environmental comfort

*7. Since you moved, have you ever experienced condensation on... *Please, mark the one that apply; only one answer per row is admitted.*

	Yes	No	I'm not sure
...windows?	◯	◯	◯
...doors?	◯	◯	◯

*8. Do you often notice smells that you do not like at home from the any of the following? *Please, mark all that apply.*

- ☐ Furnishing
- ☐ Kitchen
- ☐ Toilets
- ☐ Stairway
- ☐ Outdoors
- ☐ Other flats
- ☐ If somewhere else, could you tell us where?

[ ]

*9. Which of the following ventilation strategies are you more likely to use? *Please, mark the one that apply.*

- ◯ Natural ventilation, open/close windows
- ◯ Hybrid ventilation, open/close windows and mechanical ventilation
- ◯ Mechanical ventilation
- ◯ I'm not sure

Could you explain why and under which circumstances?

3 / 3	[progress bar]	100 %
	[Back button] [Done (thanks for your participation) button]	
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Occupants perception 03/03
[Survey title] Environmental conditions

Thanks [Participant] for helping us with this study, we really appreciate the time you are taking to answer this questionnaire. This should not take more than 5 minutes of your time, or 15 minutes if you are taking the three parts of this "Occupants perception questionnaire" at the same time. This survey is to be filled by three of the home occupants, if it is to be completed by a child (16 years old or younger) it can be completed by a parent/guardian on her/his behalf with input from the child.

ALL ANSWERS WILL BE COMPLETELY ANONYMOUS.

*1. Completed by: *Please, mark the one that apply.*

- ◉ Occupant
- ○ On behalf of an occupant

Could you write your initials, so we can follow your answers on the next surveys? This will be used only for this reason. [ ]

1 / 3	[Progress bar]	33%
	[Next button]	
--	[End of page]	--

[Page title] Thermal comfort

Having in mind ONLY the time you spend inside the home/flat, describe the typical environmental conditions. How would you describe typical living conditions in the flat?

*2. How comfortable is the temperature in your home/flat? *Please, mark the most appropriate rate in the scale; only one answer per row is admitted.*

	Comfortable			Neither comfortable, nor uncomfortable			Uncomfortable
Summer	○	○	○	○	○	○	○
Winter	○	○	○	○	○	○	○

*3. How hot/cold is the temperature at your home/flat? *Please, mark the most appropriate rate in the scale; only one answer per row is admitted.*

	Too hot			Neither hot, nor cold			Too cold
Summer	○	○	○	○	○	○	○
Winter	○	○	○	○	○	○	○

*4. How much does the temperature varies in your home/flat? *Please, mark the most appropriate rate in the scale; only one answer per row is admitted.*

	Stable						Varies during the day
Summer	○	○	○	○	○	○	○
Winter	○	○	○	○	○	○	○

*5. How satisfied are you with the overall thermal comfort of your home/flat? *Please, mark the most appropriate rate in the scale; only one answer per row is admitted.*

	Satisfactory overall						Unsatisfactory overall
Summer	☐	☐	☐	☐	☐	☐	☐
Winter	☐	☐	☐	☐	☐	☐	☐

2 / 3 [progress bar] 67%

[Back button] [Next button]

-- [End of page] --

6. Inside your home, are you bothered by draughts from any of the following? *Please, mark all that apply.*

☐ Open windows

☐ Cold window panes

☐ Mechanical ventilation

☐ Door to the outside

☐ Doors within the flat

☐ Stairways or landing

☐ If other, please specify

*7. Which of the following heating strategies are you more likely to use? *Please, mark the one that apply.*

☐ Radiant heating, such as radiators or radiant floors

☐ Air heating

☐ Fire places

☐ I'm not sure

Could you explain why and under which circumstances?

3 / 3 [progress bar] 100 %

[Back button] [Done (thanks for your participation) button]

-- [End of page] --

Annex 4 – Occupant diary

Dear Participant, We ask you to fill this occupant diary as detailed as possible. This should not take you more than 15 minutes and it will retrofit a lot our research. We really value your input and interest.

Occupants diary

Week date: ____________ Address: ____________

BEDROOM	Example	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Time got up	8:30 AM							
Time went to bed	22:15 PM							
Bedroom occupancy	2 adults							
Door open at day/night?	Yes - completely from 09:00 -23:00							
Window open day/night?	Yes - slightly from 12:00 - 17:30							

Dining	Example	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
When was the flat occupied and by how many people?	Home all day, 2 people. Went out 14-16.							
Door open at day/night?	No							
Window open day/night?	Yes - slightly							

Activity	Example	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Drying clothes indoors	11:00 to 20:00							
Cleaning	10:00 to 10:30							
Smooking indoors	In living room 11:00 and 16:00							
Ventilation Heating/cooling	Cooling / 14:00 - 23:00							

Please fill as appropriate and send a picture/scan to alejandromorenorangel@gmail.com with the subject "Occupants diary"

Best Regards,

The Research Team

Annex 5 – Participant information and consent form

[Survey title] Participant Information Form

Dear [Participant's name],

Thank you very much for the interest shown in this research. You will find here some useful information about the study and the participation consent form. Once you complete this, we will be ready to start. Meanwhile, I'll be preparing the material and ordering the monitors.

Best Regards,

Alejandro Moreno Rangel

[End of section]

What is the aim of this study?

This research seeks to improve the indoor air quality (IAQ) of homes by following the PassivHaus building certification recommendations. For this reason, we are undertaking a 6-8 months study of houses. During this time we will gather information on the performance of the buildings. This will be through the monitoring of the air quality and environmental conditions using equipment, which will be installed on the houses. We will also be conducting some interviews and ask you to keep a diary of the activities you realise at home during this period(s).

What is Indoor Air Quality (IAQ)?

Acceptable IAQ is defined by ASHARE 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".*

When air quality exceeds, the acceptable levels could lead to health problems, from cold to cancer, causing even death. Buildings play a significant role in providing acceptable IAQ. Therefore, this study seeks to improve building practices to provide safer environments.

What is PassivHaus?

PassivHaus is a building concept[1] developed by Dr Feist in 1988, whom later in 1996 founded in Darmstadt, Germany the Passive House Institute (PHI). It based on a scientific design tool, known as PassivHaus Planning Package (PHPP), which seeks more comfortable, healthier, economical, affordable and environmentally friendly buildings. The concept opts to achieve extreme low-energy demands[2], and therefore a reduction in CO2 emissions to accomplish its goals (PHI, 2015). PassivHaus principle is based on providing thermal comfort, as defined in the ISO 7730, by post-heating or post-cooling of fresh air flows are required for healthy IAQ, as described in the DIN1946, without recirculating used air (J. Bere, 2013).

The PassivHaus solution for warm climates is based on 6 fundamental principles (insulation, thermal mass, thermal bridges, high-performance doors and windows, airtightness, and ventilation) to achieve a very high level of indoor comfort and health using very little as a maximum of 15kWh/m2/yr for specific heat/cooling[3] demand and as much as 120kWh/ m2/yr as a primary energy demand. The PHPP software contains detailed requirements that must be fulfilled, and that should lead to the mandatory comfort, health and energy standards.

Why have I invited?

You have asked to take part of this research either because you live in a PassivHaus or because you live near to one of the PassivHaus identified. This study is conducted with the population that meet any of the two requirements above.

Do I have to take part?

It is up to you to decide to join our research. We would provide enough information so you can make your mind and decide. If you agree to take part of our study, the next step is to sign our consent form. Please be advised that in case you choose to continue you are free to withdraw at any time and without giving a reason. This would not affect our confidentiality agreements either your legal rights.

What will I do if I take part?

This investigation aims to record and monitor IAQ levels at your home. However, other data will be needed to support our research. Therefore, a researcher with whom you can discuss all your concerns might visit your home to gather some information about your neighbourhood and your home.

To do this study, we need to gain access to the house at the start of the project to install the monitoring equipment. We will agree on a suitable date for this – it should take a morning or afternoon to do the actual installation, and then we need to visit to check that everything is working properly. Various sets of small transmitters and sensors will be plugged and/or fit to the walls of some rooms.

We would also like to collect some information on how people use the houses. This will be through a visit to the property where we will conduct an interview, and we will also be conducting a survey of all residents of the site. We are also asking occupants to keep a note of general activities in the home. This will be in the form of a very simple diary about how the house is being used.

This interview is a brief questionnaire on which your concerns about possible IAQ problems at your place will be gathered, followed by a walk-through of your neighbourhood and your home. The information collected will help to characterise your house. The information include, but not limited to: building typology, number of bedrooms and type of major appliances, household characteristics and their health problems (related to IAQ issues), qualitative characteristics about the building and its context, possible pollution sources, building or maintenance flaws, building envelope, qualitative information about the indoor spaces, building systems, appliances and IAQ-related features, as well as mechanisms and activities that could cause IAQ problems.

Finally, the monitoring phase of our investigation will take 6-8 months at your home. They are divided into two parts. The first one is conducted during summer and the second during winter; however, we will still collect information of the season in between. During this time, we might ask you to change some building parameters on how your home is used, but we will give precise information when the time comes, it should not affect your comfort, security nor normal activities. The information that will be collected with the samplers is temperature, relative humidity and levels of the following chemicals CO, PM2.5, CO2, and tVOCs.

Photographs may be taken from inside and outside of your home, but they will remain anonym. Our team will make an effort to treat each of the photos, so information that might breach confidentiality, family or mementoes will be blurred as appropriate on all publications.

There are no disadvantages, risk or economic cost involved in your participation.

What are the possible benefits of taking part?

The personal benefit for taking part of this investigation is that you might be able to know from the report of our investigation the IAQ performance of your house and possible causes that might detriment the air quality in your home without any cost to you. Moreover, your participation will contribute to other non-personal benefits, the final output of this research may lead to causes and effects on buildings that could help to improve dwelling.

Please be advised that you are not responsible for any cost that this investigation might cause to the researchers.

What are the possible disadvantages and risks of taking part?

There is not any direct risk for taking part on our investigation, all responses and information provided by you will be anonymised, and photographs taken will be treated so they might not be linked to you. Only members of the research team will have access to the information you will provide to us.

Additional information and data protection:

Will my participation be kept confidential?

All the information you provide to us, or we obtain from you, as all the information collected about you or your place will be held strictly confidential. It will be stored anonymously, and only members of the research team will have access to it. All data We don't have separate Trustees, we have Directors (who are the Trustees) and potentially co-opted Directors (who might not be but we don't have any of right now).collection, storage will comply with the principles of the Data Protection Act 1998 (United Kingdom). Under no circumstances will identifiable responses or information collected will be shared or provided to any other third party unless the last clause of this agreement happens. Information emanating from the evaluation will only be made public in an entirely un-attributable format or at the aggregate level in ensuring that any participant will be identified, your name and exact address will be removed so that you cannot be recognised. However, the zone/location of your home will be provided. The information of the household will be characterised, so no personal or characteristics information is divulged.
Photographs from or at your property might be taken, either from indoor and outdoor spaces. Therefore, all pictures will be treated, and information that might breach confidentiality will be blurred before any publication.
Copies of the participants' data will be stored securely and retained until one year after the publication of the results of this study.
Participants' are aware that the researcher may break the confidentiality agreement if during the study any suspicious, abuse, neglect or criminal activities come across. In which case, the researcher or the research team will inform of it to the appropriate authorities.

Why my information could be shared with the authorities?

If any criminal, suspicious, abuse or neglect activity happens during the study, it is a legal obligation to the researcher and the research team to report it to the appropriate authorities. Therefore, it is for your safety and protection as well.

What will happen to the results of the research study?

The results of this study will be available, but not limited to one or more of the following sources: peer-reviewed academic journals, technical reports, conference publications, website publications, exhibitions and books. You will not be identified in any report/publication unless you have prior given your written consent on the consent form.

Who is organising and funding this research?

This investigation is undertaken as a part of PhD studies in Architecture and is organised by Alejandro Moreno Rangel at the Mackintosh School of Architecture of the Glasgow School of Art, under the supervision of Prof Tim Sharpe and Dr Filbert Musau at the Mackintosh Environment Architecture Research Unit. This investigation is partially funded by the CONACyT, Mexico's

National Council for Science and Technology. Therefore, this does not affect any of your legal rights and the agreements made by the research team.

Who has reviewed the study?

There is subject to the Glasgow School of Art ethical policy and has been examined and approved by the Glasgow School of Art Research Ethics Sub-Committee.

Contact for further Information

For further information, please communicate with the research team members:
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[1] Note that the PHI prefers to be defined as a build concept, rather than a building standard, as the concept requires technical design methods based on building physics' science throughout the PHPP as a design tool.
[2] The CEPHEUS programme found that PassivHaus consumed less heat energy than the low-energy buildings (as described by the German Building Codes) (Schnieders and Hermelink, 2006; Schnieders, 2003).
[3] Cooling demand could be higher as a supplementary latent demand for specific climatic conditions (i.e. humid climates) is added.

*1. Have you read and understand the information above?

☐ Yes

☐ No

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[Section title] Consent Form

Dear [Participant's name],

This research is conducted for a PhD research. However, the information and results of this work might be used for other academic purposes which are, but not limited to publications in conferences, scientific journals, lectures and books.

This research is conducted by Alejandro Moreno Rangel at the Mackintosh School of Architecture at the Glasgow School of Art and supervised by Prof Tim Sharpe and Dr Filbert Musau at the Mackintosh Environment Architecture Research Unit at the Glasgow School of Art.

Before taking part of this research, we ask you to read and tick the following statements to continue our studies. We agree that by answering completely to this questionnaire you agree to participate in this study and by clicking "Done" at the end of this survey will serve as proof of signature.

*2. Mark the boxes that you agree/understand.

☐ I confirm that I have read and understood the information sheet for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.

☐ I can confirm I have the internet and a WiFi network and grant access to it at the place where the monitoring will be held. This is essential due to the methodology used.

☐ I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason.

☐ I agree to be interviewed and that photographs might be taken on my property (inside and outside) and for the photos to be used in publications and presentations (including online platforms) but understand that my name will not appear.

☐ I agree that any information given by me may be used in publications and presentations but understand that my name/address will not appear.

☐ I agree to the results being used for future research or teaching purposes.

☐ I agree to take part in the above study.

☐ I need/want a hard copy of the Participant Information Form and Participant Consent Form

*3. What is your complete name?

[ ]

*4. What is the date?

Date / Time

*5. What are your contact details (home address and email)? if this is a different address from where you want us to send any material, please let us know.

You will soon receive a confirmation email to participate and further instructions for the research project.

If any issues arise concerning about this investigation, please refer to:

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References

Abdulsalam, H.M., Bader, A.A., Anwar, A. & Eman, S.A., 2014. Deploying a LEACH data aggregation technique for air quality monitoring in wireless sensor network. *Procedia Computer Science*, 34, pp.499–504. DOI: 10.1016/j.procs.2014.07.055.

Abu Al-Haija, Q., Al-Qadeeb, H. & Al-Lwaimi, A., 2013. Case Study: Monitoring of AIR quality in King Faisal University using a microcontroller and WSN. *Procedia Computer Science*, 21, pp.517–521. DOI: 10.1016/j.procs.2013.09.072.

Ackers, J.G. Den Boer, J.F., De Jong, P. & Wolschrijn, R.A., 1985. Radioactivity and radon exhalation rates of building materials in The Netherlands. *Science of the Total Environment*, 45, pp.151–156. DOI: 10.1016/0048-9697(85)90215-3.

Adamson, B., 2011. *Towards Passive Houses in Cold Climates as in Sweden*, Lund: Lund University.

Ahlbom, A., Backman, A., Bakke, J., Foucard, T., Halken, S., Kjellman, N.I.M., Malm, L., Skerfving, S., Sundell, J. & Zetterstrom, O., 1998. "NORDPET" pets indoors - A risk factor for or protection against sensitisation/allergy. *Indoor Air*, 8(4), pp.219–235. DOI: 10.1111/j.1600-0668.1998.00003.x.

Alarie, Y. Alarie, Y. Schaper, M. Nielsen, G.D. & Abraham, M.H., 1996. Estimating the sensory irritating potency of airborne nonreactive volatile organic chemicals and their mixtures. *SAR and QSAR in Environmental Research*, 5(3), pp.151–165.

Alders, E.E., 2017. Adaptive heating, ventilation and solar shading for dwellings. *Architectural Science Review*, 60(3), pp.150–166. DOI: 10.1080/00038628.2017.1300132.

Ali, A.S., Zanzinger, Z., Debose, D. & Stephens, B., 2016. Open Source Building Science Sensors (OSBSS): A low-cost Arduino-based platform for long-term indoor environmental data collection. *Building and Environment*, 100, pp.114–126. DOI: 10.1016/j.buildenv.2016.02.010.

Allard, F. & Alvarez, S., 1998. *Natural Ventilation in Buildings: A Design Handbook* 1st ed., London: Taylor & Francis Ltd.

Allen, J.G., MacNaughton, P. Satish, U. Santanam, S. Vallarino, J. & Spengler, J.D., 2016. Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: A controlled exposure study of green and conventional office environments. *Environmental Health Perspectives*, 124(6), pp.805–812. DOI: 10.1289/ehp.1510037.

Allen, M., Arlian, L.G., Bernstein, I.L., Friedman, S., Grant, A., Liberman, P., Lopez, M., Metzger, J., Schatz, M., Spector, S. & Wasserman, S., 1988. Prevalence of dust mites in the homes of asthmatics in several US geographical regions. *Journal of Allergy and Clinical Immunology*, 81, p.270.

Amaratunga, D., Baldry, D., Sarshar, M. & Newton, R., 2002. Quantitative and qualitative research in the built environment: application of “mixed” research approach. *Work Study*, 51(1), pp.17–31. DOI: 10.1108/00438020210415488.

Amato, G.D., Cecchi, L., Amato, M.D. & Liccardi, G., 2010. Urban Air Pollution and Climate Change as Environmental Risk Factors of Respiratory Allergy: An Update. , 20(2), pp.95–102.

American Lung Association, 2018. *State of the Air 2018*, DOI: 10.1017/CBO9781107415324.004.

Amouei Torkmahalleh, M., Gorjinezhad, S., Unluevcek, H.S. & Hopke, P.K., 2017. Review of factors impacting emission/concentration of cooking generated particulate matter. *Science of the Total Environment*, 586, pp.1046–1056. DOI 10.1016/j.scitotenv.2017.02.088.

AMS, 2015. Indoor Air Quality Sensor Module., pp.1–22.

An, M. & Kang, D., 2014. Development of Weather Condition Observation System for Wind Turbine Based on Integrated Sensor Module Gateway. In *Advanced Science and Technology Letters*. SERSC, pp. 238–241.

Anderson, J.E., Wulfhorst, G. & Lang, W., 2015. Energy analysis of the built environment - A review and outlook. *Renewable and Sustainable Energy Reviews*, 44, pp.149–158. DOI: 10.1016/j.rser.2014.12.027.

Andersson, K. & Stridth, G., 1992. The use of standarized questionnaires in Building-Related Illness (BRI) and Sick Building Syndrome (SBS) surveys. In *NATO/CCMS Pilot Study on Indoor Air Quality*. pp. 47–64.

Anon, 2011. Air Pollution in Mexico City, facts and stats. Available at: http://www.mexicocityvibes.com/air-pollution-in-mexico-city/ [Accessed May 1, 2015].

Appleby, A., 1990. Indoor air quality and ventilation in warm climates. In *Buildings and health, the Rosehaugh guide to the design, construction, use and management of buildings*. Lisbon, Portugal: Selper Ltd, pp. 167–193. Available at: http://www.aivc.org/resource/ventilation-criteria-and-design-good-indoor-air-quality.

Appleton, J., 2007. Radon: Sources, Health Risks, and Hazard Mapping. *AMBIO: A Journal of the Human Environment*, 36(1), pp.85–89. DOI: 10.1579/0044-7447(2007)36[85:RSHRAH]2.0.CO;2.

AQEG, 2012. *Fine Particulate Matter in the United Kingdom*, London. Available at: http://uk-air.defra.gov.uk/assets/documents/reports/cat11/1212141150_AQEG_Fine_Particulate_Matter_in_the_UK.pdf.

Ares, B.E., 2016. Zero Carbon Homes. House of Commons Library No. 6678.

Arhami, M., Polidori, A., Delfino, R.J., Tjoa, T. & Sioutas, C., 2009. Associations between personal, indoor, and residential outdoor pollutant concentrations: Implications for exposure assessment to size-fractionated particulate matter. *Journal of the Air and Waste Management Association*, 59(4), pp.392–404. DOI: 10.3155/1047-3289.59.4.392.

Arlian, L.G., 1981. Reevaluation of the Humidity Requirements of the House Dust Mite Dermatophagoides Farinae (Acari: Pyroglyphidae). *J. Med. Entomol*, 18(4), pp.351–352.

Arlian, L.G., 1992. Water balance and humidity requirements of house dust mites. *Experimental and Applied Acarology*, 16(1–2), pp.15–35. DOI 10.1007/BF01201490.

Arlian, L.G., Bernstein, I.L. & Gallagher, J.S., 1982. The prevalence of house dust mites, Dermatophagoides spp, and associated environmental conditions in homes in Ohio. *The Journal of Allergy and Clinical Immunology*, 69(6), pp.527–532. DOI: 10.1016/0091-6749(82)90178-6.

Arundel, A. V., Arundel, A.V., Sterling, E.M., Biggin, J.H. & Sterling, T D., 1986. Indirect health effects of relative humidity in indoor environments. *Environmental Health Perspectives*, VOL. 65(3), pp.351–361. DOI: 10.1289/ehp.8665351.

ASHRAE, 2007. *ASHRAE standard 62.1-2007 Ventilation for Acceptable Indoor Air Quality*, Atlanta, GA.

ASHRAE, 2017. ASHRAE Standard 55-2017 Thermal Environmental Conditions for Human Occupancy. Available at: https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy.

ASTM, 2014. *ASTM Volume 11.07 Air Quality - D7297-14 - Standard Practice for Evaluating Residential Indoor Air Quality*, Available at: http://www.astm.org/BOOKSTORE/BOS/1107.htm.

Awbi, H., 1991. *Ventilation of Buildings* 1st ed., London: Routledge.

Baek, S.O., Kim, Y.S. & Perry, R., 1997. Indoor air quality in homes, offices and restaurants in Korean urban areas - Indoor/outdoor relationships. *Atmospheric Environment*, 31(4), pp.529–544. DOI: 10.1016/S1352-2310(96)00215-4.

Badescu, V. & Sicre, B., 2003. Renewable energy for passive house heating: Part I. Building description. *Energy and Buildings*, 35, pp.1077–1084. DOI:

10.1016/j.enbuild.2003.10.001.

Bakker, a & Huijsing, J.H., 1999. A low-cost high-accuracy CMOS smart temperature sensor, pp.302–305.

Balter, K.A., 2005. Web-based and Mailed Questionnaires. *Epidemiology*, 16(4), pp.577–590. DOI: 10.1097/01.ede.0000164553.16591.4b.

Balvers, J., Bogers, R., Jongeneel, R., van Kamp, I., Boerstra, A. & , van Dijken, F., 2012. Mechanical ventilation in recently built Dutch homes: technical shortcomings, possibilities for improvement, perceived indoor environment and health effects. *Architectural Science Review*, 55(2), pp.4-14. DOI: 10.1080/00038628.2012.664938.

Barraza-Villarreal, A., Sunyer, J., Hernandez-Cadena, L., Escamilla-Nunñez, M.C., Sienra-Monge, J.J., Ramírez-Aguilar, M., Cortez-Lugo, M., Holguin, F., Diaz-Sánchez, D., Olin, A.C. & Romieu, I., 2008. Air pollution, airway inflammation, and lung function in a cohort Study of Mexico City Schoolchildren. *Environmental Health Perspectives*, 116(6), pp.832–838. DOI: 10.1289/ehp.10926.

Bay Area Air Quality Management District, 2018. About Air Quality. *Interactive Data Maps*. Available at: http://www.baaqmd.gov/about-air-quality/interactive-data-maps [Accessed August 22, 2018].

Beamer, M., Duluk, S., Kwok, A., Bisers, D. & Hogard, D., 2003. Comfort and indoor air quality in passive houses in the US. pp.1–8.

BEIS, 2019. *Digest of United Kingdom Energy Statistics 2018*, London. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/736148/DUKES_2018.pdf.

Bell, M.L., Davis, D.L., Gouveia, N., Borja-Aburto, V.H. & Cifuentes, L.A., 2006. The avoidable health effects of air pollution in three Latin American cities: Santiago, São Paulo, and Mexico City. *Environmental Research*, 100(3), pp.431–440. DOI: 10.1016/j.envres.2005.08.002.

Bere, J., 2013. *Introduction to passive house* First Edit., London: RIBA Publishing.

Berge, M. & Mathisen, H.M., 2015. The suitability of air-heating in residential passive house buildings from the occupants' point of view - a review. *Advances in Building Energy Research*, 9(2), pp.175–189. DOI: 10.1080/17512549.2015.1040069..

Berglund, B., Brunekreef, B., Knöppe, H., Lindvall, T., Maroni, M., Mølhave, L. & Skov, P., 1992. Effects of Indoor Air Pollution on Human Health. *Indoor Air*, 2(1), pp.2–25. DOI: 10.1111/j.1600-0668.1992.02-21.x.

Berglund, B., Clausen, G., Kettrup, A, Lindvall, T., & Maroni, M., 1997. *Total Volatile Organic Compounds (TVOC) in Indoor Air Quality Investigation (EUR 17675 EN)*, European Commision Joint Research Centre. DOI: 10.1111/j.1600-0668.1997.00002.x.

Bernal, S.M., 2015. Assesment of the implications of natural and mechanical ventilation on human health in the residential sector. In University of Colorado, ed. *PROCEEDINGS HEALTHY BUILDINGS 2015 AMERICA Innovation in a Time of Energy Uncertainty and Climate Adaptation*. Boulder, Colorado: ISIAQ, pp. 126–129.

Bernnan, T., 2015. PM2.5: AN EMERGING ISSUE FOR STANDARD OF CARE IN INDOOR SPACES. In U. of Colorado, ed. *PROCEEDINGS HEALTHY BUILDINGS 2015 AMERICA - Innovation in a Time of Energy Uncertainty and Climate Adaptation*. Boulder, Colorado: International Society of Indoor Air Quality and Climate, pp. 261–264.

Bernstein, J., Alexis, N., Bacchus, H., Bernstein, I.L., ,Fritz, P. Horner, E., Li, N., Mason, S., Nel, A., Oullette, J. ,Reijula, K., Reponen, T., Seltzer, J., Smith, A. & Tarlo, S.M., 2008. The health effects of nonindustrial indoor air pollution. *Journal of Allergy and Clinical Immunology*, 121(3), pp.585–591. DOI: 10.1016/j.jaci.2007.10.045.

Berry, D., 2004. Internet research: privacy, ethics and alienation: an open source approach. *Internet Research*, 14(4), pp.323–32. DOI: 10.1108/10662240410555333.

Berry, R., Crump, D., Brown, V. & Coward, S.K.D., 1996. *Indoor air quality in homes, part 1*, Watford: BRE press.

Berry, R., Crump, D., Brown, V. & Coward, S.K.D., 1996. *Indoor air quality in homes, part 2: Annexes*, Watford: BRE press.

BéruBé, K.A., Sexton, K.J., Jones, T.P., Moreno, T., Anderson, S. & Richards, R.J., 2004. The spatial and temporal variations in PM10 mass from six UK homes. *Science of the Total Environment*, 324(1–3), pp.41–53. DOI: 10.1016/j.scitotenv.2003.11.003.

Bland, J.M. & Altman, D.G., 2010. Statistical methods for assessing agreement between two methods of clinical measurement. *International Journal of Nursing Studies*, 47(8), pp.931–936. DOI: 10.1016/j.ijnurstu.2009.10.001.

Blight, T.S. & Coley, D.A., 2013. Sensitivity analysis of the effect of occupant behaviour on the energy consumption of passive house dwellings. *Energy and Buildings*, 66, pp.183–192. DOI: 10.1016/j.enbuild.2013.06.030.

Bluyssen, P.M., Cox, C., Seppänen, O., Oliveira Fernandes, E., Clausen, G., Müller, B. & Roulet, C.A., 2003. Why, when and how do HVAC-systems pollute the indoor environment and what to do about it? The European AIRLESS project. *Building and Environment*, 38(2), pp.209–225. DOI: 10.1016/S0360-1323(02)00058-6.

de Boer, R. & Kuller, K., 1997. Mattresses as a winter refuge for house-dust mite populations. *Allergy*, 52(14), pp.299–305. DOI: 10.1111/j.1398-9995.1997.tb00994.x.

Bone, A., Murray, V., Myers, I., Dengel, A. & Crump, D., 2010. Will drivers for home energy efficiency harm occupant health? *Perspectives in public health*, 130(5), pp.233–238. DOI: 10.1177/1757913910369092.

Bonfigli, C., Chorafa, M., Diamond, S., Eliades, C., Mylona, A., Taylor, B. & Virk, D., 2017. *Design methodology for the assessment of overheating risk in homes TM59:2017*, UK. Available at: https://www.cibse.org/knowledge/knowledge-items/detail?id=a0q0O00000DVrTdQAL#. Bordass, B., Cohen, R., Standeven,

M. & Leaman, A., 2001a. Assessing building performance in use 2: technical performance of the Probe buildings. *Building Research & Information*, 29(2), pp. 103–113. DOI: 10.1080/09613210010008027.

Bordass, B., Cohen, R., Standeven, M. & Leaman, A., 2001b. Assessing building performance in use 3: energy performance of the Probe buildings. *Building Research & Information*, 29(2), pp. 114–128. DOI: 10.1080/09613210010008036.

Bordass, B., Leaman, A. and Ruyssevelt, P., 2001. Assessing building performance in use 5: conclusions and implications. *Building Research & Information*, 29(2), pp. 144–157. DOI: 10.1080/09613210010008054.

Bornehag, C.G., Sundell, J., Hägerhed-Engman, L. & Sigsgaard, T., 2005. Association between ventilation rates in 390 Swedish homes and allergic symptoms in children. *Indoor Air,* 15(4), pp.275–280. DOI: 10.1111/j.1600-0668.2005.00372.x.

Bornehag, C.G., Sundell, J. & Sigsgaard, T., 2004. Dampness in buildings and health (DBH): Report from an ongoing epidemiological investigation on the association between indoor environmental factors and health effects among children in Sweden. *Indoor Air, Supplement,* 14(SUPPL. 7), pp.59–66. DOI: 10.1111/j.1600-0668.2004.00274.x.

Bossew, P. & Lettner, H., 2007. Investigations on indoor radon in Austria, Part 1: Seasonality of indoor radon concentration. *Journal of Environmental Radioactivity*, 98, pp. 329-345. DOI: 10.1016/j.jenvrad.2007.06.006.

BRE Global, 2015. BREEAM. Available at: http://www.breeam.com/ [Accessed January 1, 2015].

BRE Global, 2014. *BREEAM New Construction, technical manual* 4th ed., Watford: BRE bookshop.

Brimblecombe, R. & Rosemeier, K., 2017. *Positive Energy Homes* 1st ed. Peter Storer Editorial Services, ed., Clayton South: CSIRO Publishing.

Brook, R.D. et al., 2010. Particulate Matter Air Pollution and Cardiovascular Disease An Update to the Scientific Statement From the American. *Circulation*, 121(21), pp.2231–2378. DOI: 10.1161/CIR.0b013e3181dbece1.

Bros-Williamson, J., Garnier, C. & Currie, J.I., 2016. A longitudinal building fabric and energy performance analysis of two homes built to different energy principles. *Energy and Buildings*, 130, pp.578–591. DOI: 10.1016/j.enbuild.2016.08.052.

Brown-Saracino, J., Thurk, J. & Fine, G.A., 2008. Beyond groups: seven pillars of peopled ethnography in organizations and communities. *Qualitative Research*, 8(5), pp.547–567. DOI: 10.1177/1468794108094865.

Brown, C. & Gorgolewski, M., 2015. Understanding the role of inhabitants in innovative mechanical ventilation strategies. *Building Research and Information*, 43(2), pp.210–221. DOI: 10.1080/09613218.2015.963350.

Brown, N., New small, low-power MOX VOC sensors: how might they be used for indoor air quality monitoring? *AMS*. Available at: http://ams.com/eng/Support/Technical-Papers/VOCs-and-IAQ [Accessed September, 2017].

Brown, S.K., Sim, M.R., Abramson, M.J. & Gray, C.N., 1994. Concentrations of volatile organic compounds in indoor air–a review. *Indoor Air*, 4(2), pp.123-134. DOI: 10.1111/j.1600-0668.1994.t01-2-00007.x.

Bruce, N., Perez-Padilla, R. & Albalak, R., 2000. Indoor air pollution in developing countries: a major environmental and public health challenge. *Bulletin of the World Health Organization*, 78(9), pp.1078–1092. DOI: 10.1590/S0042-96862000000900004.

Brunekreef, B. & Holgate, S.T., 2002. Air pollution and health. *Lancet*, 360(9341), pp.1233–1242. DOI: 10.1016/S0140-6736(02)11274-8.

Brunsgaard, C., Heiselberg, P., Knudstrup, M.A. & Larsen, T.S., 2012. Evaluation of the Indoor Environment of Comfort Houses: Qualitative and Quantitative Approaches. *Indoor and Built Environment*, 21(3), pp.432–451. DOI:

10.1177/1420326X11431739.

Brunsgaard, C., Knudstrup, M.A. & Heiselberg, P., 2012. Occupant Experience of Everyday Life in Some of the First Passive Houses in Denmark. *Housing, Theory and Society*, 29(3), pp.223–254. DOI: 10.1080/14036096.2011.602718.

Bryman, A., 2006. Integrating quantitative and qualitative research: How is it done? *Qualitative Research*, 6(1), pp.97–113. DOI: 10.1177/1468794106058877.

Bryman, A., 2012. *Social Research Methods* Fourth Ed., Oxford: Oxford University Press.

Buchanan, E.A., 2010. Internet research ethics: past, present, and future. In R. Burnett, M. Consalvo, & C. Ess, eds. *The Handbook of Internet Studies*. Wiley-blackwell, pp. 83–108. Available at: https://books.google.co.uk/books?hl=en&lr=&id=3CakiQW_GVAC&oi=fnd&pg=PA83&dq=ethics+E-Research&ots=7kMuWuOUmG&sig=NKniN1d59MhzSm4bSjhkprutJww#v=onepage&q=ethics E-Research&f=false [Accessed January 2017].

Budde, M., Busse, M. & Beigl, M., 2012. Investigating the use of commodity dust sensors for the embedded measurement of particulate matter. *2012 Ninth International Conference on Networked Sensing Systems (INSS)*, pp.1–4. DOI: 10.1109/INSS.2012.6240545.

de Buen, O., 2009. Greenhouse Gas Emission Baselines and Reduction Potentials from Buildings in Mexico (a disussion document). *Sustainable United Nations.*

Burge, P.S., 2004. Sick building syndrome. *Occup Environ Med*, 61(2), pp.185–190. DOI: 10.1136/oem.2003.008813.

Burton, J., 1962. Effects of dry anaesthetic gases on the respiratory mucous membrane. *The Lancet*, 279(7223), pp.235–238. DOI: 10.1016/S0140-6736(62)91187-X.

Cablé, A., Hammer, H.L. & Mysen, M., 2016. Comparison of Two Ventilation

Control Strategies in the First Passive House Standard Norwegian School. *International Journal of Ventilation*, 14(4), pp.371–382. DOI: 10.1080/14733315.2016.11684094.

California Building Standards Commission (CBSC), 2016a. *2016 California Mechanical Code, entire code with errata pages*, US: Department of Building Inspection. Available at: https://sfdbi.org/codes.

California Building Standards Commission (CBSC), 2016b. *2016 California Mechanical Code, entire code with errata pages*, US: Department of Building Inspection.

Carrer, P., Fanetti, A.C., Forastiere, F., Holcatova, I., Sundell, J., Viegi, G. & Simoni, M., 2009. *EnVIE - Co-ordination Action on Indoor Air Quality and Health Effects - Final report*.

Carrer, P., Wargocki, P., Fanetti, A., Bischof, W., Oliveira, E.De, Hartmann, T. & Kephalopoulos, S., 2015. What does the scientific literature tell us about the ventilation–health relationship in public and residential buildings? *Building and Environment*, 94(1), pp.273–286. DOI: 10.1016/j.buildenv.2015.08.011.

Castell, N., Dauge, F.R., Schneider, P., Vogt, M., Lerner, U., Fishbain, B., Broday, D. & Bartonova, A., 2017. Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates? *Environment International*, 99, pp.293–302. DOI: 10.1016/j.envint.2016.12.007.

Cavazos Galvan, M., Guerrero Nuñez, B. & Ramirez Aragon, D., 2008. Comparative mites and cockroaches sensitization study in three cities of Mexico. *Revista Alergia Mexico*, 55(6), pp.234–239. Available at: https://www.ncbi.nlm.nih.gov/pubmed/19157220.

Cayre, E., Allibe, B., Laurent, M-H. & Osso, D., 2011. There are people in the house! How the results of purely technical analysis of residential energy consumption are misleading for energy policies. In *Proceedings of the ECEEE 2011 Summer Study on Energy Efficiency First: The Foundation of a Low-Carbon Society*. Belambra Presqu'île de Giens, France: ECEEE, pp. 1675–1683.

CEC, 2007. California Energy Commission. *Energy Policy*.

CEC, 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings, Brussels: Commision of the European Communities.

CEN (European Committee for Standardization), 2005. Ventilation for non-residential buildings - Performance requirements for ventilation and room conditioning systems. *BRITISH STANDARD*, pp.1–75.

CEN EN (2008) EN 15251:2007 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Brussels.

Cerny, S.D., 2007. *An Architectural Guide to San Francisco and the Bay Area* First. G. Smith, 1st ed., Utha.

Champion, W.M. et al., 2015. Comparison of Indoor and outdoor air quality in Latino communities in Peru, Chile and USA. In University of Colorado, ed. *PROCEEDINGS HEALTHY BUILDINGS 2015 AMERICA - Innovation in a Time of Energy Uncertainty and Climate Adaptation*. Boulder, Colorado: International Society of Indoor Air Quality and Climate, pp. 33–36.

Chan, C.S., Ostertag, M.H., Akyürek, A.S. & Šimunić Rosing, T., 2017. Context-aware system design. In T. George, ed. *Micro- and Nanotechnology Sensors, Systems, and Applications IX*. SPIE, pp. 1-17. DOI: 10.1117/12.2263232.

Chapman, L., Bell, C. & Bell, S., 2016. Can the crowdsourcing data paradigm take atmospheric science to a new level? A case study of the urban heat island of London quantified using Netatmo weather stations. *International Journal of Climatology*, 3605(December 2016), pp.3597–3605. DOI: 10.1002/joc.4940

Chatoutsidou, S., Ondracek, J., Tesar, O., Torseth, K., Zdímal, V. & Lazaridis, M., 2015. Indoor/outdoor particulate matter number and mass concentration in modern offices. *Building and Environment*, 92, pp.462–474. DOI: 10.1016/j.buildenv.2015.05.023.

Chen, C. & Zhao, B., 2011. Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor. *Atmospheric Environment*, 45(2), pp.275–288. DOI: 10.1016/j.atmosenv.2010.09.048.

Chen, H., Kwong, J.C., Copes, R., Tu, K., Villeneuve, P.J., Donkelaar, A.V., Hystad, P., Martin, R.V., Murray, B.J., Jessiman, B., Wilton, A.S., Kopp, A. & Burnett, R.T., 2017. Living near major roads and the incidence of dementia, Parkinson's disease, and multiple sclerosis: a population-based cohort study. *The Lancet*, 389(10070), pp.718–726. DOI: 10.1016/S0140-6736(16)32399-6.

Cheng, K.C., Park, H.K., Tetteh, A.O., Zheng, D., Ouellette, N.T., Nadeau, K.C. & Hildemann, L.M., 2016. Mixing and sink effects of air purifiers on indoor PM2.5 concentrations: A pilot study of eight residential homes in Fresno, California. *Aerosol Science and Technology*, 50(8), pp.835–845. DOI: 10.1080/02786826.2016.1197375.

Chong, C.Y. & Kumar, S.P., 2003. Sensor networks: Evolution, opportunities, and challenges. *Proceedings of the IEEE*, 91(8), pp.1247–1256. DOI: 10.1109/JPROC.2003.814918.

Chou, J., 2000a. Chapater 1 - Introduction. In *Hazardous Gas Monitors: A Pratical Guide to Selection, Operation and Applications*. New York: McGraw-Hill Professional, pp. 1–24. Available at: http://www.intlsensor.com/pdf/Intro_Chap01.pdf.

Chou, J., 2000b. Chapter 4 - Solid-State Gas Sensors. In *Hazardous Gas Monitors: A Practical Guide to Selection, Operation and Applications*. McGraw-Hill Professional, pp. 47–53. Available at: http://wrap.warwick.ac.uk/23761/.

CIBSE, 2005. *CIBSE Applications Manual AM10 - Natural ventilation in non-domestic buildings*, London.

CIBSE, Humphreys, M., Nicol, F., Levermore, G., Muneer, T., Page, J., Sanders, C., Anderson, B., Liddament, M., Holmes, M., Britton, C., Wright, A. & Arnold, D., 2006. *CIBSE Guide A: Environmental Design* 7th edition. K. Butcher, ed., Norwich: CIBSE Publications.

CIBSE, Humphreys, M., Nicol, F., Levermore, G., Muneer, T., Page, J., Sanders, C., Anderson, B., Liddament, M., Holmes, M., Britton, C., Wright, A. & Arnold, D., 2015. *CIBSE Guide A: Environmetnal Desing* 8th Editio., Norwich: CIBSE Publications.

CIBSE, 2011. *CIBSE KS17 Indoor Air Quality and Ventilation*, Available at: http://www.cibse.org/Knowledge/CIBSE-KS/KS17-Indoor-Air-Quality-Ventilation.

CIBSE, 2012. Practical psychrometry CIBSE Knowledge Series KS20. Edited by K. Butcher. CIBSE.

CIBSE, 2013. *The limits of thermal comfort: avoiding overheating in European buildings TM52b*, UK. Available at: http://www.cibse.org/Knowledge/knowledge-items/detail?id=a0q20000008I7f5AAC.

CIBSE, 2016. *Guide B2: 2016 - Ventilation and ductwork*. 1st edn. London: CIBSE Publications

City and County of San Francisco, 2017. City and County of San Francisco Housing Code. Available at: http://library.amlegal.com/alpscripts/get-content.aspx.

Ciuzas, D., Prasauskas, T., Krugly, E., Sidaraviciute, R., Jurelionis, A., Seduikyte, L., Kauneliene, V., Wierzbicka, A. & Martuzevicius, D., 2015. Characterization of indoor aerosol temporal variations for the real-time management of indoor air quality. *Atmospheric Environment*, 118, pp.107–117. DOI: 10.1016/j.atmosenv.2015.07.044.

Cohen, A.J., 2000. Outdoor Air Pollution and Lung Cancer Exposures to Carcinogens in Outdoor Air. *Environmental Health Perspectives*, 108(August), pp.743–750. DOI: 10.1289/ehp.00108s4743.

Cohen, A.J. et al., 2004. Chapter 17 - Urban air pollution. In M. Ezzati et al., eds. *Comparative quantification of health risks 2*. WHO, pp. 1353–1433.

Cohen, R., Standeven, M., Bordass, B, & Leaman, A., 2001. Assessing building performance in use 1: the Probe process. *Building Research & Information*, 29(2), pp. 85–102. DOI: 10.1080/09613210010008018.

Colloff, M.J., 1987. Mites from house dust in Glasgow. *Medical and Veterinary Entomology*, 1(2), pp.163–168. DOI: 10.1111/j.1365-2915.1987.tb00338.x.

Commission, E., 2015. Air Quality Standards. *Air Quality*, p.2. Available at: http://ec.europa.eu/environment/air/quality/standards.htm [Accessed September 10, 2015].

CONAVI, 2010. *Código de Edificación de Vivienda*, Mexican Government.

Cook, D.J., Guyatt, G.H., Juniper, E., Griffith, L., McIlroy, W., Willan, A., Jaeschke, R. & Epstein, R., 1993. Interviewer versus self-administered questionnaires in developing a disease-specific, health-related quality of life instrument for asthma. *Journal of Clinical Epidemiology*, 46(6), pp.529–534. DOI: 10.1016/0895-4356(93)90125-K.

Corsi, R.L., Siegel, J.A. & Chiang, C., 2008. Particle Resuspension During the Use of Vacuum Cleaners on Residential Carpet. *Journal of Occupational and Environmental Hygiene Volume 5, 2008 - Issue 4*, 5(4), pp.232–238. DOI: 10.1080/15459620801901165.

Cortez-Lugo, M., Moreno-Macias, H., Holguin-Molina, F., Chow, J.C., Watson, J.G., Gutiérrez-Avedoy, V., Mandujano, F., Hernández-Ávila, M. & Romieu, I., 2008. Relationship between indoor, outdoor, and personal fine particle concentrations for individuals with COPD and predictors of indoor-outdoor ratio in Mexico city. *Journal of Exposure Science and Environmental Epidemiology*, 18(1), pp.109–115. DOI: 10.1038/sj.jes.7500557.

Cotterell, J. & Dadeby, A., 2012. *The PassivHaus handbook: a practical guide to contructing and retrofitting buildings for ultra-low energy performance* First., Cambridge: Green Books.

Council, F.F. & National Research Council, 2002. *Learing from our buildings: A State-of-the-Practive summary of post-occupancy evaluation Vol. 145* 1st ed., Washington, DC: The National Academies Press.

Coward, S.K.D., Llewellyn, J.W., Raw, G.J., Brown, V., Crump, D. & Ross, D., 2001. *Indoor Air Quality in Homes in England* First Edit., London: BRE bookshop.

Crandall, M., Sieber, W. & Malkin, R., 1996. HVAC and building environmentl findings and health symptoms associations in 80 office buildings. In *Proceedings of IAQ 1996*. pp. 103–108.

Crowther, D., Horwood, J., Baker, N., The Martin Centre & Thomson, D., 2000. House Dust Mites and the Built Environment: A Literature Review.

Crowther, D., Wilkinson, T., Biddulph, P., Oreszczyn, T., Pretlove, S. & Ridley, I., 2006. A simple model for predicting the effect of hygrothermal conditions on populations of house dust mite Dermatophagoides pteronyssinus (Acari: Pyroglyphidae). *Experimental and Applied Acarology*, 39(2), pp. 127–148. DOI: 10.1007/s10493-006-9003-8.

Crump, D., Raw, G.J., Upton, S., Scivyer, C., Hunter, C. & Hartless, R., 2002. *A protocol for the assessment of indoor air quality in homes and office buildings* First Edit., London: BRE bookshop.

Crump, D., Dengel, A. & Swainson, M., 2009. *Indoor air quality in highly energy efficient homes—a review*, BRE press.

Cuce, P.M. & Riffat, S., 2015. A comprehensive review of heat recovery systems for building applications. *Renewable and Sustainable Energy Reviews*, 47, pp.665–682. DOI: 10.1016/j.rser.2015.03.087.

Cunningham, M.J., 1996. Controlling dust mites psychrometrically-a review for building scientists and engineers. *Indoor Air*, 6, pp.249–258. DOI: 10.1111/j.1600-0668.1996.00004.x.

Curto, A., Donaire-Gonzalez, D., Barrera-Gomez, J., Nieuwenhuijsen, M.J., Wellenius, G.A., Tonne, C. & Marshall, J.D., 2018. Performance of low-cost monitors to assess household air pollution. *Environmental Research*, 163, pp.53–63. DOI: 10.1016/j.envres.2018.01.024.

Curwell, S.R., March, C. & Venables, R., 1990. *Buildings and Health: The Rosehaugh Guide to the Design, Construction, Use and Management of Buildings*, RIBA Publ.

Dan, D., Tanasa, C., Stoian, V., Brata, S., Stoian, D., Nagy Gyorgy, T. & Florut, S.C., 2016. Passive house design-An efficient solution for residential buildings in Romania. *Energy for Sustainable Development*, 32, pp.99–109. DOI: 10.1016/j.esd.2016.03.007.

Davies, I. & Harvey, V., 2008. *Zero carbon: what does it mean to homeowners and housebuilders?*, NHBC Foundation.

DEFRA, 2016. *Local Air Quality Management*, UK: Available at: http://www.scottishairquality.co.uk/assets/documents/LAQM-TG16-April-16-v1.pdf.

DEFRA, 2007. The Air Quality Strategy for England , Scotland , Wales and Northern Ireland: Volume 1. Available at: http://archive.defra.gov.uk/environment/quality/air/airquality/strategy/documents/air-qualitystrategy-vol1.pdf.

Delia, A., 2012. Total Volatile Organic Compounds (Total VOCs) in the air. *State of Knowledge Report*, (March), pp.1–4. Available at: http://www.environment.gov.au/atmosphere/airquality/publications/sok/vocs.html.

Denscombe, M., 2008. The Length of Responses to Open-Ended Questions: A Comparison of Online and Paper Questionnaires in Terms of a Mode Effect. *Social Science Computer Review*, 26(3), pp.359–368. DOI: 10.1177/0894439307309671.

Dentz, J., Varshney, K. & Henderson, H., 2014. Overheating in multifamily residential buildings in New York. *Energy Efficiency*, 7(3), pp.401–415. DOI: 10.1007/s12053-013-9228-4.

Derbez, M., Berthineau, B., Cochet, V., Lethrosne, M., Pignon, C., Riberon, J. & Kirchner, S., 2014. Indoor air quality and comfort in seven newly built, energy-efficient houses in France. *Building and Environment*, 72, pp.173–187. DOI: 10.1016/j.buildenv.2013.10.017.

Derudi, M., Gelosa, S., Sliepcevich, A., Cattaneo, A., Rota, R., Cavallo, D. & Nano, G., 2012. Emissions of air pollutants from scented candles burning in a test chamber. *Atmospheric Environment*, 55, pp.257–262. DOI: 10.1016/j.atmosenv.2012.03.027.

Deutsches Institut für Normung e. V, 2012. *DIN 1946 Ventilation and air conditioning – Part 6: Ventilation for residential Buildings – General requirements, requirements fro measuring, performance and labeling, delivery/acceptance (certification) and maintenance*, Germany.

Dillman, D.A. & Tortora, R.D., 1992. The Web Questionnaire Challenge to Survey Methodologists. In *World Bank Discussion Papers*. pp. 159–178. DOI: 10.1097/00000433-198206000-00020.

Dillman, D.A., Tortora, R.D. & Bowker, D., 1998. Principles for Constructing Web Surveys. *Joint Meetings of the American Statistical Association*, pp.1–16. DOI: 10.1017/CBO9781107415324.004.

Dimitroulopoulou, C., Crump, D., Coward, S.K.D., Brown, V., Squire, R., Mann, H., White, M., Pierce, B. & Ross, D., 2005. *Ventilation, air tightness and indoor air quality in new homes* First., Watford: IHS BRE Press.

Dimitroulopoulou, C., 2012. Ventilation in European dwellings: A review. *Building and Environment*, 47(1), pp.109–125. DOI: 10.1016/j.buildenv.2011.07.016.

Dodoo, A., Gustavsson, L. & Sathre, R., 2011. Primary energy implications of ventilation heat recovery in residential buildings. *Energy and Buildings*, 43(7), pp.1566–1572. DOI: 10.1016/j.enbuild.2011.02.019.

Doty, R.L., Cometto-Muñiz, J.E., Jalowayski, A., Dalton, P., Kendal-Reed, M. & Hodgson, M., 2004. Assessment of upper respiratory tract and ocular irritative effects of volatile chemicals in humans. *Critical reviews in toxicology,* 34(2) pp. 85-142. DOI 10.1080/10408440490269586.

Easterby-Smith, M., Thorpe, R. & Jackson, P., 2012. *Managment Research* 4th ed. K. Smy, ed., London: SAGE.

ECA, 1992. *European collaborative action Indoor air quality & its impact on man: Report No.11: Guidelines for ventilation requirements in buildings*, Available at: http://www.inive.org/medias/ECA/ECA_Report11.pdf.

Edgerton, S., Bian, X., Doran, J.C., Fast, J.D., Hubbe, J.M., Malone, E.L., Shaw, W.J., Whiteman, C.D. & Zhong, S., 2000. Particulate Air Pollution in Mexico City : A Collaborative Research Project. Journal of the Air & Waste Management Association, 49(10), pp.1221–1229. DOI: 10.1080/10473289.1999.10463915.

EHSO EMORY University, 2012. Indoor Air Quality Questionnaire.

Eicker, U., 2010. Cooling strategies, summer comfort and energy performance of a rehabilitated passive standard office building. *Applied Energy*, 87(6), pp.2031–2039. DOI: 10.1016/j.apenergy.2009.11.015.

Emmerich, S.J., Howard-reed, C. & Gupte, A., 2005. Modeling the IAQ Impact of HHI Interventions in Inner-city Housing. *Report for the U.S. Department of Housing and Urban Development Office of Healthy Homes and Lead Hazard Control*, p.102.

Emmerich, S.J. & Persily, A.K., 2011. Indoor air quality in Sustainable, energy efficient buldings. *HVAC&R Research*, 18(1–2), pp.4–20. DOI: 10.1080/10789669.2011.592106.

Energy Saving Trust, 2006. Energy efficient ventilation in dwellings – a guide for specifiers Contents.

Engineering ToolBox, 2004. Carbon Dioxide Concentrations in Rooms with People. Available at: https://www.engineeringtoolbox.com/pollution-concentration-rooms-d_692.html [Accessed May 23, 2018].

National Environmental Protection Council, 2003. *National Environment Protection (Ambient Air Quality) Measure*. Office of Legislative Drafting, Attorney-General's Department, Canberra; Australia.

EPA, 2003. *A Standardized EPA Protocol for Characterizing Indoor Air Quality in Large Office Buildings*. Washington, DC: EPA. Available at: https://www.epa.gov/sites/production/files/2016-04/documents/standardized_iaq_base_protocol_for_characterizing_iaq_in_large_buildings-pdf.pdf

EPA, 2012. *A brief guide to mold moisture and your home EPA 402-K-02-003*, Washington, DC: EPA.

EPA, 2018. *U.S. Greenhouse Gas Emissioms and Sinks, 1990-2016*, Washington, DC: EPA.

Erickson, F., 1986. Qualitative methods. In M. C. Wittrick, ed. *Handbook of Research on Teaching*. New York: Macmillan, pp. 119–161.

Escobedo, L.E. et al., 2014. Indoor air quality in Latino homes in Boulder, Colorado. *Atmospheric Environment*, 92, pp.69–75. DOI: 10.1016/j.atmosenv.2014.03.043.

Eze, I.C., Hemkens, L.G., Bucher, H.C., Hoffmann, B., Schindler, C., Künzli, N., Schikowski, T. & Probst-Hensch, N.M., 2015. Review Association between Ambient Air Pollution and Diabetes Mellitus in Europe. *Environmental Health Perspectives*, 123(5), pp.381–389. DOI: 10.1289/ehp.1307823.

Fang, L., Clausen, G. & Fanger, P.O., 1998. Impact of temperature and humidity on the perception of indoor air quality. *Indoor air*, 8(2), pp.80–90. DOI: 10.1111/j.1600-0668.1998.t01-2-00003.x.

Fanger, P.O., 2000. Indoor Air Quality in the 21st Century: Search for Excellence. *Indoor Air*, 10, pp.68–73. DOI: 10.1034/j.1600-0668.2000.010002068.x

Fanger, P.O., 2006. What is IAQ? *Indoor Air*, 16(5), pp.328–334. DOI: 10.1111/j.1600-0668.2006.00437.x.

Federal-Provincial Advisory Committee on Environmental and Occupational

Health, 1989. *Exposure Guidelines for Residential Indoor Air Quality*, Canada. Available at: http://www.hc-sc.gc.ca/ewh-semt/pubs/air/exposure-exposition/index-eng.php [Accessed February 9, 2015].

Fehrm, M., Reiners, W. & Ungemach, M., 2002. Exhaust air heat recovery in buildings. *International Journal of Refrigeration*, 25(4), pp.439–449. DOI: 10.1016/S0140-7007(01)00035-4.

Feist, W. et al., 2015. *Passive House Planning Package Version 9, The energy balance and design tool for efficent buildings and retrofits* 1st ed., Darmstadt, Germany: Passive House Institute.

Feist, W., Schnieders, J., Dorer, V. & Haas, A., 2005. Re-inventing air heating: Convenient and comfortable within the frame of the Passive House concept. *Energy and Buildings*, 37(11 SPEC. ISS.), pp.1186–1203. DOI: 10.1016/j.enbuild.2005.06.020.

Feist, W., 2012. *Technical Annex : Evaluation of social housing building types in Mexico: Study of energy efficiency, additional costs and CO2 mitigation as basis for the preparation of the "Supported NAMA for Sustainable Housing in Mexico - Mitigation Actions and Finance*, Durban.

Fellows, R. & Liu, A., 2015. *Research Methods for Construction* 4th ed., John Wiley & Sons, Inc.

Ferdoush, S. & Li, X., 2014. Wireless sensor network system design using Raspberry Pi and Arduino for environmental monitoring applications. *Procedia Computer Science*, 34, pp.103–110. DOI: 10.1016/j.procs.2014.07.059.

Fernández-Seara, J. et al., 2011. Experimental analysis of an air-to-air heat recovery unit for balanced ventilation systems in residential buildings. *Energy Conversion and Management*, 52(1), pp.635–640. DOI: 10.1016/j.enconman.2010.07.040.

Field, A., 2016. *An Adventure in Statistics* 1st ed., London: SAGE Publications Ltd.

Figueiredo, A., Figueira, J., Romeu, V. & Maio, R., 2016. Thermal comfort and energy performance: Sensitivity analysis to apply the Passive House concept to the Portuguese climate. *Building and Environment*, 103, pp.276–288. DOI: 10.1016/j.buildenv.2016.03.031.

Figueroa-Villamar, C., Figueroa-Castrejon, A. and Bojorquez-Morales, G., 2014. Thermal comfort in housing of the metropolitan area of the valley of mexico, in *PLEA 2014 - Sustainable habitat for developing societies*. Ahmedabad: PLEA, pp. 1–7.

Firestone, W.A., 1987. Meaning in Method : The Rhetoric of Quantitative and Qualitative Research. *Education Researcher*, 16(7), pp.16–21. DOI: 10.3102/0013189X016007016.

Firląg, S. & Zawada, B., 2013. Impacts of airflows, internal heat and moisture gains on accuracy of modeling energy consumption and indoor parameters in passive building. *Energy and Buildings*, 64, pp.372–383. DOI: 10.1016/j.enbuild.2013.04.024.

Fischer, a, Langer, S. & Ljungström, E., 2014. Chemistry and indoor air quality in a multi-storey wooden passive (low energy) building: Formation of peroxyacetyl nitrate. *Indoor and Built Environment*, 23(3), pp.485–496. DOI: 10.1177/1420326X13487917.

Fisk, W.J., Mendell, M.J., Daisey, J.M., Faulkner, D., Hodgson, A.T., Nematollahi, M. & Macher, J.M., 1993. Phase 1 of the California Healthy Building Study: A Summary. *Indoor Air*, 3(4), pp.246–254. DOI: 10.1111/j.1600-0668.1993.00005.x.

Flyvbjerg, B., 2006. Five Misunderstandings About Case-Study Research. *Qualitative Inquiry*, 12(2), pp.219–245. DOI: 10.1177/1077800405284363.

Foddy, W., 1993. *Constructing Questions for Interviews and Questionnaires: Theory and Practice in Social Research* C. Turner & E. Martin, eds., Cambridge: Cambridge University Press.

Fokaides, P.A., Christoforou, E., Ilic, M. & Papadopoulos, A., 2016. Performance of a Passive House under subtropical climatic conditions. *Energy & Buildings*, 133, pp.14–31. DOI: 10.1016/j.enbuild.2016.09.060.

Fortmann, R., Kariher, P. & Clayton, R., 2001. *Indoor Air Quality: Residential Cooking Exposures.*, Sacramento.

Foster, J. et al., 2016. Scottish Passive House: Insights into environmental conditions in monitored Passive Houses. *Sustainability (Switzerland)*, 8(5), pp.1–24. DOI: 10.3390/su8050412

Von Frankenberg und Ludwigsdorff, N., Peters, S., Brugge, B., Loftness, V. & Aziz, A., 2016. Effective visualization and control of the indoor environmental quality in smart buildings. *CEUR Workshop Proceedings*, 1559, pp.124–129.

Frey, S.E., Destaillats, H., Cohn, S., Ahrentzen, S. & Fraser, M.P., 2014. Characterization of indoor air quality and resident health in an Arizona senior housing apartment building. *Journal of the Air and Waste Management Association*, 64(11), pp.1251–1259. DOI: 10.1080/10962247.2014.937513.

Fromme, H., Twardella, D., Dietrich, S., Heitmann, D., Schierl, R., Liebl, B. & Rüden, H., 2007. Particulate matter in the indoor air of classrooms-exploratory results from Munich and surrounding area. *Atmospheric Environment*, 41(4), pp.854–866. DOI: 10.1016/j.atmosenv.2006.08.053.

Fu, X., Qian, X. & Wang, L., 2017. Energy efficiency for airtightness and exteriorwall insulation of passive houses in hot summer and cold winter zone of China. *Sustainability (Switzerland)*, 9(7). DOI: 10.3390/su9071097.

Fu, Y. & Hallberg, B., 2010. A Personal Environment Monitoring System for Pulmonary Disease Management. *2010 4th International Conference on Bioinformatics and Biomedical Engineering*, pp.1–4. DOI: 10.1109/ICBBE.2010.5516510.

George AC., 2008. *World history of radon research and measurement from the early 1900's to today*. In: AIP Conference Proceedings. pp.20–33. DOI: 10.1063/1.2991210.

Georges, L., Berner, M. & Mathisen, H.M., 2014. Air heating of passive houses in cold climates: Investigation using detailed dynamic simulations. *Building and Environment*, 74, pp.1–12. DOI: 10.1016/j.buildenv.2013.12.020.

Gillham, B., 2000. *Case Study Research Methods* First., London: Continum.

Giordano, J., Reilly, M.O., Taylor, H. & Dogra, N., 2007. Confidentiality and Autonomy : The Challenge (s) of Offering Research Participants. *Qualitative Health Research*, (2004). DOI: 10.1177/1049732306297884.

GIZ, 2014. NAMA facility - Implementation of the New Housing NAMA Mexico. Available at: http://www.nama-facility.org/projects/mexico.html [Accessed May 20, 2009].

Gobierno del Distrito del Distrito Federal, 2004a. *Normas técnicas complementarias para el proyecto arquitectónico*, Mexico.

Gobierno del Distrito del Distrito Federal, 2004b. *Reglamento de Construcciones para el Distrito Federal*, Mexico.

Godish, T., Spengler, D., Godishi, T. & Spengler~, J.D., 1996. Relationship Between Ventilation and Indoor Air Quality: A Review. *Indoor Air*, 6, pp.135–145. DOI: 10.1111/j.1600-0668.1996.00010.x.

Gram-hanssen, K., 2010. Residential heat comfort practices: understanding users. *Building Research & Information*, 38(2), pp. 175-186. DOI: 10.1080/09613210903541527.

GrayWolf, 2017. Sensor heating effects in still air - GrayWolf Tech Note.

Greene, J.C., Caracelli, V.J. & Graham, W.F., 1989. Toward a Conceptual Framework for Mixed-Method Evaluation Designs. *Educational Evaluation and Policy Analysis*, 11(3), pp.255–274. DOI: 10.3102/01623737011003255.

Groat, L. & Wang, D., 2013. *Architectural Research Methods* Second., Hoboken, New Jersey: John Wiley & Sons, Inc.

Guardino Solá, X., 1998. Calidad del aire interior. *Enciclopedia de salud y* *seguridad en el trabajo*, p.44.1-44.33. DOI: 10.1590/S1020-49891998001200018

Guarnieri, M. & Balmes, J.R., 2014. Outdoor air pollution and asthma. *The Lancet*, 383(9928), pp.1581–1592. DOI: 10.1016/S0140-6736(14)60617-6.

Guba, E.G., 1990. The Alternative Paradigm Dialog. In *The paradigm dialog*. Newbury Park, California: SAGE, pp. 17–27.

Guba, E.G. & Lincoln, Y.S., 1989. *Fourth Generation Evaluation* 1st ed. E. G. Guba, ed., SAGE.

Guerra-Santin, O., Tweed, C., Jenkins, H. & Jiang, S., 2013. Monitoring the performance of low energy dwellings: Two UK case studies. *Energy and Buildings*, 64, pp.32–40. DOI: 10.1016/j.enbuild.2013.04.002.

Guerra-Santin, O. & Itard, L., 2010. Occupants' behaviour: Determinants and effects on residential heating consumption. *Building Research and Information*, 38(3), pp.318–338. DOI: 10.1080/09613211003661074.

Guillén-Lambea, S., Rodríguez-Soria, B. & Marín, J.M., 2017. Control strategies for Energy Recovery Ventilators in the South of Europe for residential nZEB—Quantitative analysis of the air conditioning demand. *Energy and Buildings*, 146, pp.271–282. DOI: 10.1016/j.enbuild.2017.04.058.

Guillén-Lambea, S., Rodríguez-Soria, B. & Marín, J.M., 2016. Review of European ventilation strategies to meet the cooling and heating demands of nearly zero energy buildings (nZEB)/Passivhaus. Comparison with the USA. *Renewable and Sustainable Energy Reviews*, 62, pp.561–574. DOI: 10.1016/j.rser.2016.05.021.

Guo, H. et al., 2004. Risk assessment of exposure to volatile organic compounds in different indoor environments. *Environmental Research*, 94(1), pp.57–66. DOI: 10.1016/S0013-9351(03)00035-5.

Guo, Z. et al., 2000. Fine Particulate Matter Emissions. In *Engineering Solutions to Indoor Air Quality Problems Symposium*. Raleigh, NC, pp. 1–21.

Gupta, R., Kapsali, M. & Howard, A., 2018. Evaluating the influence of building fabric, services and occupant related factors on the actual performance of low energy social housing dwellings in UK. *Energy & Buildings*, 174(1), pp.548–562. DOI: 10.1016/j.enbuild.2018.06.057.

Hadjri, K. & Crozier, C., 2009. Post-occupancy evaluation: purpose, benefits and barriers. *Facilities*, 27(1/2), pp.21–33. DOI: 10.1108/02632770910923063.

Hady, M., van Ginkel, J.T., Hasselaar, E., Schrijvers, G., IJssel-Vecht, G.G.D. & Region, T., 2008. The relationship between health complaints, the quality of indoor air and housing characteristics, In: *Indoor Air 2008: Proceedings of the 11th International Conference on Indoor Air Quality and Climate*, (August), pp.17–22.

Haghighat, F. & De Bellis, L., 1998. Material emission rates: Literature review, and the impact of indoor air temperature and relative humidity. *Building and Environment*, 33(5), pp.261–277. DOI: 10.1016/S0360-1323(97)00060-7.

Hanoune, B. & Carteret, M., 2015. Impact of kerosene space heaters on indoor air quality. *Chemosphere*, 134, pp.581–587. DOI: 10.1016/j.chemosphere.2014.10.083.

Harrison, R.M., Giorio, C., Beddows, D.C.S. & Dall'Osto, M., 2010. Size distribution of airborne particles controls outcome of epidemiological studies. *Science of the Total Environment*, 409(2), pp.289–293. DOI: 10.1016/j.scitotenv.2010.09.043.

Hart, B.J., 1998. Life cycle and reproduction of house-dust mites: environmental factors influencing mite populations. *Allergy*, 53, pp.13–17. DOI: 10.1111/j.1398-9995.1998.tb04990.x.

Hart, C., 1998. *Doing a literature review: releasing the social science reserach imagination* 1st ed., London: SAGE.

Harvie-clark, J., Conlan, N., Wei, W. & Siddall, M., 2016. How loud is too loud ? Noise from domestic mechanical ventilation systems.

Hasenfratz, D., Saukh, O., Sturzenegger, S. & Thiele, L., 2012. Participatory Air Pollution Monitoring Using Smartphones. *2nd International Workshop on Mobile Sensing*, pp.1-5.

He, C., Morawska, L., Hitchins, J. & Gilbert, D., 2004. Contribution from indoor sources to particle number and mass concentrations in residential houses. *Atmospheric Environment*, 38(21), pp.3405–3415. DOI: 10.1016/j.atmosenv.2004.03.027.

Health and Safety Executive, 2011. *EH40 / 2005 Workplace exposure limits EH40 / 2005 Workplace exposure limits* Second Edi., HSE Books.

Hedge, A., 2004. Indoor Air Quality. *Handbook of Human Factors and Ergonomics Methods*, 1414, pp.11–64. DOI: 10.1201/9780203489925.ch64.

Heffernan, E., Pan, W., Liang, X. & Wilde, P.De, 2016. Zero carbon homes : Perceptions from the UK construction industry. *Energy Policy*, 79(2015), pp.23–36. DOI: 10.1016/j.enpol.2015.01.005.

Hekmat, D., Feustel, H.E. & Modera, M.P., 1986. Impacts of ventilation strategies on energy consumption and indoor air quality in single-family residences. *Energy and Buildings*, 9(3), pp.239–251. DOI: 10.1016/0378-7788(86)90024-1.

Hens, H., Parijs, W. & Deurinck, M., 2010. Energy consumption for heating and rebound effects. *Energy and Buildings*, 42(1), pp.105–110. DOI: 10.1016/j.enbuild.2009.07.017.

Herberger, S., Herold, M., Ulmer, H., Burdack-Freitag, A. & Mayer, F., 2010. Detection of human effluents by a MOS gas sensor in correlation to VOC quantification by GC/MS. *Building and Environment*, 45(11), pp.2430–2439. DOI: 10.1016/j.buildenv.2010.05.005.

Hernandez, G. et al., 2014. Smart Nest Thermostat : A Smart Spy in Your Home. *Black Hat USA*, pp.1–8.

Herring, H. & Roy, R., 2007. Technological innovation, energy efficient design and the rebound effect. *Technovation*, 27(4), pp.194–203. DOI:

10.1016/j.technovation.2006.11.004.

Herriott, R.E. & Firestone, W.A., 1983. Multisite Qualitative Policy Research: Optimizing Description and Generalizability. *Educational Researcher*, 12(2), pp.14–19. DOI: 10.3102/0013189X012002014.

Hill, D., 1998. *Field Survey of Heat Recovery Ventilation Systems Final Report*, Ottawa.

Hill, M.K., 1997. Undestanding pollution. In *Undestanding environmental pollution*. Cambridge: Cambridge University Press, pp. 1–33.

HM Government, 2013. Ventilation - Approved Document F. *The Building Regulation 2010*, (October), p.61.

Hodgson, M.J., Frohliger, J., Permar, E., Tidwell, C., Traven, N.D., Olenchock, S.A. & Karpf, M., 1991. Symptoms and Microenvironmental Measures in Nonproblem Buildings. *Journal of Occupational Medicine*, 33(4).

Holguín, F., Téllez-Rojo, M.M., Hernández, M., Cortez, M., Chow, J.C., Watson, J.G., Mannino, D. & Romieu, I., 2003. Air pollution and heart rate variability among the elderly in Mexico City. *Epidemiology (Cambridge, Mass.)*, 14(5), pp.521–527. DOI: 10.1097/01.ede.0000081999.15060.ae.

Hopfe, C.J. & McLeod, R.S., 2015. *The PassivHaus designer's manual: A technical guide to low and zero energy buildings* 1st ed. C. J. Hopfe & R. S. McLeod, eds., London: Routledge.

Al horr, Y., Arif, M., Katafygiotou, M., Mazroei, A., Kaushik, A. & Elsarrag, E., 2016. Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature. *International Journal of Sustainable Built Environment*, 5(1), pp.1–11. DOI: 10.1016/j.ijsbe.2016.03.006.

Howden-Chapman, P., Matheson, A., Crane, J., Viggers, H., Cunningham, M., Blakely, T., Cunningham, C., Woodward, A., Saville-Smith, K., O'Dea, D., Kennedy, M., Baker, M., Waipara, N., Chapman, R. & Davie, G., 2007. Effect of insulating existing houses on health inequality: Cluster randomised study in the community. *British Medical Journal*, 334(7591), pp.460–464. DOI: 10.1136/bmj.39070.573032.80.

Howe, K.R., 1988. Against the Quantitative-Qualitative Incompatibility Thesis or Dogmas Die Hard. *Educational Researcher*, 17(8), pp.10–16. DOI: 10.3102/0013189X017008010.

Howieson, S., Sharpe, T. & Farren, P., 2013. Building tight - ventilating right? How are new air tightness standards affecting indoor air quality in dwellings? *Building Services Engineering Research and Technology*, 35(5), pp.475–487. DOI: 10.1177/0143624413510307.

IBO, 2017. *Details for Passive Houses: Renovation : A Catalogue of Ecologically Rated Constructions for Renovation* 1st ed. IBO OEsterreichisches Institut fur Baubiologie und -oekologie, ed., Basel, Switzerland: Birkhauser.

IEA, 2017a. Monthly Oil Price Statistics. *International Energy Agency*, (Feburary), pp.5–6. Available at: https://www.iea.org/media/statistics/surveys/prices/mps.pdf.

IEA, 2008. *World Energy Outlook 2008*, Available at: https://www.iea.org/media/weowebsite/2008-1994/WEO2008.pdf.

IEA, 2015. *World Energy Outlook 2015*, Available at: www.iea.org/t&c.

IEA, 2017b. *World Energy Outlook 2017*, Available at: http://www.iea.org/bookshop/750-World_Energy_Outlook_2017.

Institute of Medicine, 2000. *Clearing the Air: Asthma and Indoor Air Exposures*, Available at: https://www.nap.edu/catalog/9610/clearing-the-air-asthma-and-indoor-air-exposures.

International Well Building Institute, 2019. *WELL v1 Revolutionizing buildings, WELL v1 features within each WELL concept*. Available at: https://www.wellcertified.com/certification/v1/standard (Accessed: 24 July 2019).

Iordache, V., Teodosiu, C., Teodosiu, R. & Catalina, T., 2016. Permeability Measurements of a Passive House during Two Construction Stages. *Energy Procedia*, 85(November 2015), pp.279–287. DOI: 10.1016/j.egypro.2015.12.253.

IPCC, 2013. *Climate Change 2013*.

IPCC, 2007. *Mitigation of climate change: Contribution of working group III to the fourth assessment report of the Intergovernmental Panel on Climate Change*.

IPCC, 2014. *Summary for Policymakers*,

iPHA, 2017. International Passive House Associaition. *The global Passive House platform*. Available at: https://passivehouse-international.org/index.php?page_id=65 [Accessed March 26, 2018].

ISO, 2001. BS EN ISO 7726:2001 Ergonomics of the thermal environment — Instruments for measuring physical quantities.

ISO, 2006. BS EN ISO 16000-1:2006 Indoor air. General aspects of sampling strategy.

Jablotron, 2014. Air Pohoda iERV-240 technical sheet. , p.9. Available at: https://www.jablotronlt.com/en.

Jack, M., Currie, J., Bros-Williamson, J. & Stinson, J., 2013. Housing Innovation Showcase 2012: Building Performance Evaluation, Phase 1-Part 1. , p.180. DOI: 10.14297/enr.2013.000001.

Jacobs, D.E., Kelly, T. & Sobolewski, J., 2007. Linking Public Health, Housing, and Indoor Environmental Policy: Successes and Challenges at Local and Federal Agencies in the United States. *Environmental Health Perspectives*, 115(6), pp.976–982. DOI: 10.1289/ehp.8990.

Jang, W.-S., Healy, W.M. & Skibniewski, M.J., 2008. Wireless sensor networks as part of a web-based building environmental monitoring system. *Automation in Construction*, 17(6), pp.729–736. DOI: 10.1016/j.autcon.2008.02.001.

Janssen, N.A.H., Hoek, G., Brunekreef, B., Harssema, H., Mensink, I. & Zuidhof, A., 1998. Personal Sampling of Particles in Adults : Relation among Personal, Indoor, and Outdoor Air Concentrations. *American Journal of Epidemiology*, 147(6), pp.537–547. DOI 10.1093/oxfordjournals.aje.a009485.

Ji, W. & Zhao, B., 2015. Contribution of outdoor-originating particles, indoor-emitted particles and indoor secondary organic aerosol (SOA) to residential indoor PM2.5 concentration: A model-based estimation. *Building and Environment*, 90, pp.196–205. DOI: 10.1016/j.buildenv.2015.04.006.

Jia, C., Batterman, S. & Godwin, C., 2008. VOCs in industrial, urban and suburban neighborhoods, Part 1: Indoor and outdoor concentrations, variation, and risk drivers. *Atmospheric Environment*, 42(9), pp.2083–2100. DOI: 10.1016/j.atmosenv.2007.11.055.

Johansson, P., Svensson, T. & Ekstrand-Tobin, A., 2013. Validation of critical moisture conditions for mould growth on building materials. *Building and Environment*, 62, pp.201–209. DOI: 10.1016/j.buildenv.2013.01.012.

Johnson, B. & Onwuegbuzie, A.J., 2004. Mixed Methods Research: A Research Paradigm Whose Time Has Come. *Educational Researcher*, Vol. 33 No, pp.14–26. DOI: 10.3102/0013189X033007014.

Jones, A.P., 1999. Indoor air quality and health. *Atmospheric Environment*, 33(28), pp.4535–4564. DOI 10.1016/S1352-2310(99)00272-1.

Jones, N.C., Thornton, C.A., Mark, D. & Harrison, R.M., 2000. Indoor/outdoor relationships of particulate matter in domestic homes with roadside, urban and rural locations. *Atmospheric Environment*, 34(16), pp.2603–2612. DOI: 10.1016/S1352-2310(99)00489-6.

De Jong, P., Van Dijk, W., Van Der Graaf, E.R. & De Groot, T.J.H., 2006. National survey on the natural radioactivity and 222 Rn exhalation rate of building materials in the Netherlands. *Health Physics*, 91(3), pp.200–210. DOI: 10.1097/01.HP.0000205238.17466.1c.

Kadosaki, M., Sakai, Y., Tamura, I., Matsubara, I. & Itoh, T., 2010. Development of an oxide semiconductor thick film gas sensor for the detection of total volatile organic compounds. *Electronics and Communications in Japan*, 93(10), pp.34–41. DOI: 10.1002/ecj.10190.

Kaineg, R. et al., 2012. *NAMA Apoyada para la Vivienda Sustentable en México – Acciones de Mitigación y Paquetes Financieros*, Mexico.

Kaiser, K., 2009. Protecting respondent confidentiality in qualitative research. *Qualitative Health Research*, 19(11), pp.1632-1641. DOI: 10.1177/1049732309350879.

Kajtar, L., Herczeg, L., Lang, E., Hrustinszky, T. & Banhidi, L., 2006. Influence of Carbon-dioxide Pollutant on Human Well-being and Work Intensity. In *HB 2006 - Healthy Buildings: Creating a Healthy Indoor Environment for People, Proceedings*. pp. 85–90.

Kampa, M. & Castanas, E., 2008. Human health effects of air pollution. *Environmental Pollution*, 151(2), pp.362–367. DOI: 10.1016/j.envpol.2007.06.012.

Kang, J. & Hwang, K. Il, 2016. A comprehensive real-time indoor air-quality level indicator. *Sustainability (Switzerland)*, 8(9), pp.1–15. DOI: 10.3390/su8090881.

Katafygiotou, M.C. & Serghides, D.K., 2015. Bioclimatic chart analysis in three climate zones in Cyprus. *Indoor and Built Environment*, 24(6), pp.746–760. DOI: 10.1177/1420326X14526909.

Katsouyanni, K., Part, P., Andersson, I., Autrup, H., Baños de Guisasola, E., Bjerregaard, P., Mette, B., Bert, B., Calheiros, J., Casse, F.F., Castaño, A., Cochet, C. & Eisenreich, S., 2004. *Baseline Report on Needs in the framework of the European Environmetn and Helath Strategy ((COM 2003)338 final)*.

Kaunelienė, V., Prasauskas, T., Krugly, E., Stasiulaitienė, I., Čiužas, D., Šeduikytė, L. & Martuzevičius, D., 2016. Indoor air quality in low energy residential buildings in Lithuania. *Building and Environment*, 108, pp.63–72. DOI: 10.1016/j.buildenv.2016.08.018.

Kelle, U., 2005. Sociological Explanations between Micro and Macro and the Integration of Qualitative and Quantitative Methods. *Historical Social Research/Historische Sozialforschung*, 30(1), pp.95–117. DOI: 10.1007/s13398-014-0173-7.2.

Kelly, S., 2011. *Do Homes that are More Energy Efficient Consume Less Energy?: A Structural Equation Model for England's Residential Sector*, Cambridge.

Kelly, S., Crawford-brown, D. & Pollitt, M.G., 2012. Building performance evaluation and certification in the UK : Is SAP fit for purpose ? *Renewable and Sustainable Energy Reviews*, 16(9), pp.6861–6878. DOI: 10.1016/j.rser.2012.07.018.

Khan, F.I. & Kr. Ghoshal, A., 2000. Removal of Volatile Organic Compounds from polluted air. *Journal of Loss Prevention in the Process Industries*, 13(6), pp.527–545. DOI: 10.1016/S0950-4230(00)00007-3.

Kim, D.S., Jin Ching, B. & Son, S.-Y., 2017. Implementation of a Low-Cost Energy and Environment Monitoring System Based on a Hybrid Wireless Sensor Network. *Journal of Sensors*, 2017(Article ID 5957082), pp.461–462. DOI: 10.1155/2017/5957082.

Kim, J.-J., Jung, S.K. & Kim, J.T., 2010. Wireless monitoring of indoor air quality by a sensor network. *Indoor and Built Environment*, 19(1), pp.145–150. DOI: 10.1177/1420326X09358034.

Kim, K.H., Kim, Y.H., Kim, B.W., Ahn, J.H., Bae, M.S. & Brown, R.J.C., 2014. The reproducibility of indoor air pollution (IAP) measurement: A test case for the measurement of key air pollutants from the pan frying of fish samples. Scientific World Journal, 2014. DOI: 10.1155/2014/236501.

Kim, M.J., Liu, H., Kim, J.T. & Yoo, C.K., 2014. Evaluation of passenger health risk assessment of sustainable indoor air quality monitoring in metro systems based on a non-Gaussian dynamic sensor validation method. *Journal of Hazardous Materials*, 278(X), pp.124–133. DOI: 10.1016/j.jhazmat.2014.05.098.

Kim, Y.-S., Walker, I. & Delp, W.W., 2018. Development of a standard capture efficiency test method for residential kitchen ventilation. *Science and Technology for the Built Environment*, 24(2), pp.176–187. DOI: 10.1080/23744731.2017.1416171.

Kinnane, O., Sinnott, D. & Turner, W.J.N., 2016. Evaluation of passive ventilation provision in domestic housing retrofit. *Building and Environment*, 106, pp.205–218. DOI: 10.1016/j.buildenv.2016.06.032.

Kintner-Meyer, M., 2002. Vol.7; Information and Electronic Technologies; Promises and Pitfalls - Wireless sensors: technology and cost-savings for commercial buildings. In *Teaming for Efficiency: Proceedings, 2002 ACEEE Summer Study on Energy Efficiency in Buildings.* August 2002, pp.121–134.

Kleiven, T., 2003. *Natural Ventilation in Buildings, Architectural concepts, consequences and possibilities*. Norwegian University of Science and Technology.

Klepeis, N.E., Nelson, W.C., Ott, W.R., Robinson, J.P., Tsang, A.M., Switzer, P., Behar, J.V., Hern, C. & Engelmann, W.H., 2001. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *Journal of Exposure Analysis and Environmental Epidemiology*, 11, pp.231–252. DOI: 10.1038/sj.jea.7500165.

Knopf, J.W., 2006. Doing a Literature Review. *Journal of Business-to-Business Marketing*, (January), pp.127–132. DOI: 10.1017/S1049096506060264.

Koistinen, K., Kotzias, D., Kephalopoulos, S., Schlitt, C., Carrer, P., Jantunen, M., Kirchner, S., McLaughlin, J., Molhave, L., Fernandes, E. O. & Seifert, B., 2008. The INDEX project: Executive summary of a European Union project on indoor air pollutants. *Allergy: European Journal of Allergy and Clinical Immunology*, 63(7), pp.810–819. DOI: 10.1111/j.1398-9995.2008.01740.x.

Kolokotsa, D. & Santamouris, M., 2015. Review of the indoor environmental quality and energy consumption studies for low income households in Europe. *Science of the Total Environment*, 536, pp.316–330. DOI: 10.1016/j.scitotenv.2015.07.073.

Korsgaard, J., 1983. House-dust mites and absolute indoor humidity. *Allergy*, 38, pp.85–92. DOI: 10.1111/j.1398-9995.1983.tb01591.x.

Korsgaard, J. & Hallas, T.E., 1979. Tarsonemid mites in Danish house dust. *Allergy*, 34, pp.225–232. DOI: 10.1111/j.1398-9995.1979.tb01703.x.

Kovesi, T., Zaloum, C., Stocco, C., Fugler, D., Dales, R.E., Ni, A., Barrowman, N., Gilbert, N.L. & Miller, J.D., 2009. Heat recovery ventilators prevent respiratory disorders in Inuit children. *Indoor Air*, 19(6), pp.489–499. DOI: 10.1111/j.1600-0668.2009.00615.x.

Kubba, S., 2010. *LEED Practices, Certification, and Accreditation Handbook* 1st ed., Butterworth Heinemann. Available at: http://www.sciencedirect.com.ezproxy.lib.gla.ac.uk/science/book/9781856176910.

Kularatna, N. & Sudantha, B.H., 2008. An Environmental Air Pollution Monitoring System Based on the IEEE 1451 Standard for Low Cost Requirements. *IEEE Sensors Journal*, 8(4), pp.415–422.

Kumar, P., Skouloudis, A.N., Bell, M., Viana, M., Carotta, M.C., Biskos, G. & Morawska, L., 2016. Real-time sensors for indoor air monitoring and challenges ahead in deploying them to urban buildings. *Science of the Total Environment*, 560–561(April), pp.150–159. DOI: 10.1016/j.scitotenv.2016.04.032.

Kumar, P., Morawska, L., Martani, C., Biskos, G., Neophytou, M., Di Sabatino, S., Bell, M., Norford, L. & Britter, R., 2015. The rise of low-cost sensing for managing air pollution in cities. *Environment International*, 75, pp.199–205. DOI: 10.1016/j.envint.2014.11.019.

Kuo, H.W. & Shen, H.Y., 2010. Indoor and outdoor PM2.5 and PM10 concentrations in the air during a dust storm. *Building and Environment*, 45(3), pp.610–614. DOI: 10.1016/j.buildenv.2009.07.017.

Kurnitski, J., Eskola, L., Palonen, J. & Seppänen, O., 2007. Use of mechanical ventilation in Finnish houses. In *Proceedings of 2nd European blowerdoor-symposium*, May 2014, pp.152–161.

Lai, A.C.K. & Chen, F.Z., 2007. Modeling of cooking-emitted particle dispersion and deposition in a residential flat: A real room application. *Building and Environment*, 42(9), pp.3253–3260. DOI: 10.1016/j.buildenv.2006.08.015.

Lai, H.K., Kendall, M., Ferrier, H., Lindup, I., Alm, S., Hänninen, O., Jantunen, M., Mathys, P., Colvile, R., Ashmore, M. R., Cullinan, P. & Nieuwenhuijsen, M.J., 2004. Personal exposures and microenvironment concentrations of $PM_{2.5}$, VOC, NO_2 and CO in Oxford, UK. *Atmospheric Environment*, 38(37), pp.6399–6410. DOI: 10.1016/j.atmosenv.2004.07.013.

Landsberger, H.A., 1958. Hawthorne revisited: Managment and the worker, its Critics and Developments in Human Relations in Industry. , 9, p.132.

Langer, S., Bekö, G., Bloom, E., Widheden, A. & Ekberg, L., 2015. Indoor air quality in passive and conventional new houses in Sweden. *Building and Environment*, 93(P1), pp.92–100. DOI: 10.1016/j.buildenv.2015.02.004.

Langer, S., amalho, O., Derbez, M., Ribéron, J., Kirchner, S. & Mandin, C., 2016. Indoor environmental quality in French dwellings and building characteristics. *Atmospheric Environment*, 128, pp.82–91. DOI: 10.1016/j.atmosenv.2015.12.060.

Larsen, T.S. & Heiselberg, P., 2008. Single-sided natural ventilation driven by wind pressure and temperature difference. *Energy and Buildings*, 40, pp.1031–1040. DOI: 10.1016/j.enbuild.2006.07.012.

Laxen, D., Moorcroft, S., Marner, B., Laxen, K., Boulter, P., Barlow, T., Harrison, R. & Heal, M., 2010. PM 2.5 in the UK.

Leaman, A., 2011. BUS occupant survey method, The building Use Studies (BUS) occupant survey: Origins and aproach. Available at: https://www.usablebuildings.co.uk/UsableBuildings/Unprotected/BUSOccupantSurveyQ&A.pdf.

Leaman, A. and Bordass, B., 2001. Assessing building performance in use 4 : the Probe occupant surveys and their implications, *Building Research & Information*, 29(2), pp. 129–143. DOI: 10.1080/09613210010008045.

Leary, C.O., Lofthouse, S. & Jones, B., 2015. Mitigating Occupant Exposure to PM2.5 Emitted by Cooking in High Occupancy Dwellings Using Natural Ventilation Strategies. In *36th Air Infiltration and Ventilation Center Conference*. Madrid, pp. 549–558.

Lee, D.D., 2001. Environmental gas sensors. *IEEE Sensors Journal*, 1(3), pp.214–224. DOI: 10.1109/JSEN.2001.954834.

Less, B., Mullen, N., Singer, B. & Walker, I., 2015. Indoor air quality in 24 California residences designed as high-performance homes. *Science and Technology for the Built Environment*, 21(1), pp.14–24. DOI: 10.1080/10789669.2014.961850.

Liang, X., Wang, Y., Royapoor, M., Wu, Q. & Roskilly, T., 2017. Comparison of building performance between Conventional House and Passive House in the UK. In *Energy Procedia*. Elsevier B.V., pp. 1823–1828. DOI: 10.1016/j.egypro.2017.12.570.

Lichtenbelt, W.V.M., Hanssen, M., Pallubinsky, H., Kingma, B. & Schellen, L., 2017. Healthy excursions outside the thermal comfort zone. *Building Research & Information*, 45(7), pp.819–827. DOI: 10.1080/09613218.2017.1307647.

Lincoln, Y.S., Lynham, S.A. & Guba, E.G., 2011. Paradigmatic controversies, contradictions, and emerging confluences, revisited. In N. K. Denzin & Y. S. Lincoln, eds. *The SAGE Handbook of Qualitative Research*. Thousand Oaks, California: SAGE, pp. 97–128.

Litvak, a, Gadgil, a J. & Fisk, W.J., 2000. Hygroscopic fine mode particle deposition on electronic circuits and resulting degradation of circuit performance: an experimental study. *Indoor air*, 10(1), pp.47–56. DOI: 10.1016/S0021-8502(98)90800-X.

Liu, D., Zhao, F.Y. & Tang, G.F., 2010. Active low-grade energy recovery potential for building energy conservation. *Renewable and Sustainable Energy Reviews*, 14(9), pp.2736–2747. DOI: 10.1016/j.rser.2010.06.005.

Liu, X., Cheng, S., Liu, H., Hu, S., Zhang, D. & Ning, H., 2012. A Survey on Gas

Sensing Technology. *Sensors*, 12(7), pp.9635–9665. DOI: 10.3390/s120709635

Lohr, V.I. & Pearson-Mims, C.H., 1996. Particulate matter accumulation on horizontal surfaces in interiors: Influence of foliage plants. *Atmospheric Environment*, 30(14), pp.2565–2568. DOI: 10.1016/1352-2310(95)00465-3.

Lomas, K.J. & Porritt, S.M., 2017. Overheating in buildings: lessons from research. *Building Research & Information*, 45(1-2), pp. 1-18. DOI: 10.1080/09613218.2017.1256136.

Macnaughton, P., Spengler, J., Vallarino, J., Santanam, S., Satish, U. & Allen, J., 2016. Environmental perceptions and health before and after relocation to a green building. *Building and Environment*, 104, pp.138–144. DOI: 10.1016/j.buildenv.2016.05.011.

Mahdavi, A. & Doppelbauer, E.M., 2010. A performance comparison of passive and low-energy buildings. *Energy and Buildings*, 42(8), pp.1314–1319. DOI: 10.1016/j.enbuild.2010.02.025.

Manikonda, A., Zikova, N., Hopke, P.K. & Ferro, A.R., 2016. Laboratory assessment of low-cost PM monitors. *Journal of Aerosol Science*, 102, pp.29–40. DOI: 10.1016/j.jaerosci.2016.08.010.

Manz, H., Huber, H., Schälin, A., Weber, A., Ferrazzini, M. & Studer, M., 2000. Performance of single room ventilation units with recuperative or regenerative heat recovery. *Energy and Buildings*, 31(1), pp.37–47. DOI: 10.1016/S0378-7788(98)00077-2.

Mardiana-Idayu, A. & Riffat, S.B., 2011. An experimental study on the performance of enthalpy recovery system for building applications. *Energy and Buildings*, 43(9), pp.2533–2538. DOI: 10.1016/j.enbuild.2011.06.009.

Mardiana-Idayu, A. & Riffat, S.B., 2012. Review on heat recovery technologies for building applications. *Renewable and Sustainable Energy Reviews*, 16(2), pp.1241–1255. DOI: 10.1016/j.rser.2011.09.026.

Mardiana, A. & Riffat, S.B., 2013. Review on physical and performance parameters of heat recovery systems for building applications. *Renewable and Sustainable Energy Reviews*, 28, pp.174–190. DOI: 10.1016/j.rser.2013.07.016.

Markham, A. & Buchanan, E.A., 2012. *Ethical Decision-Making and Internet Research: Recommendations from the AOIR Ethics Committee*.

Maroni, M., Seifert, B. & Lindvall, T., 1995. *Indoor air quality a comprehensive reference book* First., Amsterdam: Elsevier Science BV.

Marques, G. & Pitarma, R., 2016. Health informatics for indoor air quality monitoring | Sistema de Monitorizacao da Qualidade do Ar Interior. *Iberian Conference on Information Systems and Technologies, CISTI*, 2016–July. DOI: 10.1109/CISTI.2016.7521375.

Marszal, A.J., Heiselberg, P., Bourrelle, J.S., Musall, E., Voss, K., Sartori, I. & Napolitano, A., 2011. Zero Energy Building - A review of definitions and calculation methodologies. *Energy and Buildings*, 43(4), pp.971–979. DOI: 10.1016/j.enbuild.2010.12.022.

Martinez Jimenez, N.E., Aguilar Angeles, D. & Rojas Ramos, E., 2010. Prevalencia de la sensibilización a Blomia tropicalis y Dermatophagoides pteronyssinus, farinae y siboney en pacientes con rinitis o asma alérgica (o ambas) en una población de la zona metropolitana de la Ciudad de México. *Revista Alergia Mexico*, 57(1), pp.3–10.

Masoso, O.T. & Grobler, L.J., 2010. The dark side of occupants' behaviour on building energy use. *Energy and Buildings*, 42(2), pp.173–177. DOI: 10.1016/j.enbuild.2009.08.009.

Matsuoka, Y. & Fisher, E.J., 2017. Context adaptive cool-to-dry feature for HVAC controller. p.A thermostat and a method include using occupancy.

McGill, G., Sharpe, T., Robertson, L., Gupta, R. & Mawditt, I., 2016. Meta-analysis of indoor temperatures in new-build housing. *Building Research & Information*, 0(0), pp.1–21. DOI: 10.1080/09613218.2016.1226610.

McGill, G., Oyedele, L.O. & Keeffe, G., 2015. Indoor air-quality investigation in code for sustainable homes and passivhaus dwellings. *World Journal of Science, Technology and Sustainable Development*, 12(1), pp.39–60. DOI: 10.1108/WJSTSD-08-2014-0021.

McGill, G., Oyedele, L.O. & McAllister, K., 2015. Case study investigation of indoor air quality in mechanically ventilated and naturally ventilated UK social housing. *International Journal of Sustainable Built Environment*, 4(1), pp.58–77. DOI: 10.1016/j.ijsbe.2015.03.002.

McGill, G., Qin, M. & Oyedele, L., 2014. A case study investigation of indoor air quality in UK Passivhaus dwellings. *Energy Procedia*, 62, pp.190–199. DOI: 10.1108/WJSTSD-08-2014-0021.

McLeod, R., Jaggs, M., Cheeseman, B., Tilford, A. & Mead, K., 2014. Passivhaus primer: airtightness guide; airtightness and air pressure testing in accordance with the Passivhaus Standard. *BRE Trust*.

McLeod, R.S., Hopfe, C.J. & Kwan, A., 2013. An investigation into future performance and overheating risks in Passivhaus dwellings. *Building and Environment*, 70, pp.189–209. DOI: 10.1016/j.buildenv.2013.08.024.

Mcnutt, M., 2013. Climate Change Impacts. *Science*, 341(6145), p.435. DOI: 10.1126/science.1243256.

Mead, M.I., Popoola, O.A.M., Stewart, G.B., Landshoff, P., Calleja, M., Hayes, M., Baldovi, J.J., McLeod, M.W., Hodgson, T. F., Dicks, J., Lewis, A., Cohen, J., Baron, R., Saffell, J.R. & Jones, R.L., 2013. The use of electrochemical sensors for monitoring urban air quality in low-cost, high-density networks. *Atmospheric Environment*, 70, pp.186–203. DOI: 10.1016/j.atmosenv.2012.11.060.

Meadow, J.F., Altrichter, A.E., Kembel, S.W., Kline, J., Mhuireach, G., Moriyama, M., Northcutt, D., O'Connor, T.K., ,Womack, A.M. Brown, G.Z., Green, J.L. & Bohannan, B.J.M., 2014. Indoor airborne bacterial communities are influenced by ventilation, occupancy, and outdoor air source. *Indoor Air*, 24(1), pp.41–48. DOI: 10.1111/ina.12047.

MEARU, 2014. *Domestic Buildings Phase 2: In-use performance & post occupancy evaluation (Final report).* In Scotland's Housing Expo. Innovate UK.

Meier, F., Fenner, D., Grassmann, T., Otto, M. & Scherer, D., 2017. Crowdsourcing air temperature from citizen weather stations for urban climate research. *Urban Climate*, 19, pp.170–191. DOI: 10.1016/j.uclim.2017.01.006.

Mendell, M., 2013. Do we Know Much about Low Energy Buildings and Health? In *ASHRAE IAQ: Environmental Health in Low Energy Buildings*. Vancouver.

Mendell, M.J., 1993. Non-specific Symptoms in Ofice Workers: A Review and Summary of the Epidemiologic Literature. *Indoor Air*, 3, pp.227–236. DOI: 10.1111/j.1600-0668.1993.00003.x.

Miguez, J.L., Porteiro, J., Lopez-Gonzalez, L.M., Vicuna, J.E., Murillo, S., Moran, J.C. & Granada, E., 2006. Review of the energy rating of dwellings in the European Union as a mechanism for sustainable energy. *Renewable and Sustainable Energy Reviews*, 10, pp.24–45. DOI: 10.1016/j.rser.2004.08.003.

Mihai, M., Tanasiev, V., Dinca, C., Badea, A. & Vidu, R., 2017. Passive house analysis in terms of energy performance. *Energy and Buildings*, 144, pp.74–86. DOI: 10.1016/j.enbuild.2017.03.025.

Militello-hourigan, R.E. & Miller, S.L., 2018. The impacts of cooking and an assessment of indoor air quality in Colorado passive and tightly constructed homes. *Building and Environment*, 144(August), pp.573–582. DOI: 10.1016/j.buildenv.2018.08.044.

Miller, S.L., Scaramella, P., Campe, J., Goss, C.W., Diaz-Castillo, S., Hendrikson, E., DiGuiseppi, C. & Litt, J., 2009. An assessment of indoor air quality in recent Mexican immigrant housing in Commerce City, Colorado. *Atmospheric Environment*, 43(35), pp.5661–5667. DOI: 10.1016/j.atmosenv.2009.07.037.

Milner, J., Milner, J., Shrubsole, C., Das, P., Jones, B., Ridley, I., Chalabi, Z., Hamilton, I., Armstrong, B., Davies, M. & Wilkinson, P., 2014. Home energy efficiency and radon related risk of lung cancer: modelling study. *BMJ*, 348(7496), pp.1-12. DOI: 10.1136/bmj.f7493.

Mittal, R. & Bhatia, M.P.S., 2010. Wireless sensor networks for monitoring the environmental activities. *2010 IEEE International Conference on Computational Intelligence and Computing Research*, pp.1-5. DOI: 10.1109/ICCIC.2010.5705791.

Mlakar, J. & Štrancar, J., 2011. Overheating in residential passive house: Solution strategies revealed and confirmed through data analysis and simulations. *Energy and Buildings*, 43, pp.1443–1451. DOI: 10.1016/j.enbuild.2011.02.008.

Mlecnik, E., Schütze, T., Jansen, S.J.T., De Vries, G., Visscher, H.J. & Van Hal, A., 2012. End-user experiences in nearly zero-energy houses. *Energy and Buildings*, 49, pp.471–478. DOI: 10.1016/j.enbuild.2012.02.045.

Molhave, L., 1991. Volatile organic compounds, indoor air quality and health. *Indoor Air*, 1(4), pp.357–376. DOI: 10.1111/j.1600-0668.1991.00001.x

Mølhave, L., Clausen, G., Berglund, B., Ceaurriz, J., Kettrup, A., Lindvall, T., Maroni, M., Pickering, A.C., Risse, U., Rothweiler, H., Seifert, B. & Younes, M., 1997. Total Volatile Organic Compounds (TVOC) in Indoor Air Quality Investigations. *Indoor Air*, 7(19), pp.225–240. DOI: 10.1111/j.1600-0668.1997.00002.x.

Molhave, L., Jensen, J.G. & Larsen, S., 1991. Subjective Reactions To Volatile Organic Compounds As Air Pollutants. *Atmospheric Environment*, 25(7), pp.1283–1293. DOI: 10.1016/0960-1686(91)90240-8.

Montoya, T., Gurian, P.L., Velázquez-Angulo, G., Corella-Barud, V., Rojo, A. & Graham, J.P., 2008. Carbon monoxide exposure in households in Ciudad Juárez, México. *International Journal of Hygiene and Environmental Health*, 211(1–2), pp.40–49. DOI: 10.1016/j.ijheh.2006.12.001.

Moran, T.K., 1987. Research and managerial strategies for integrating evaluation research into agency decision making. *Evaluation Review*, 11(5), pp.612–630.

Moreno-Rangel, A., Sharpe, T., Musau, F. & McGill, G., 2018. Field evaluation of a low-cost indoor air quality monitor to quantify exposure to pollutants in residential environments. *Journal of Sensors and Sensor Systems*, 7, pp.373–

388. DOI: 10.5194/jsss-7-373-2018.

Moreno-Rangel A, Sharpe T, Musau F, McGill G. Indoor Fine Particle (PM2.5) Pollution and Occupant Perception of the Indoor Environment During Summer of the First Passivhaus Certified Dwelling in Latin America. *Journal of Natural Resources and Development*. 2018;8:78–90. DOI: 10.5027/jnrd.v8i0.08.

Morgan, C., Foster, J.A., Poston, A. & Sharpe, T., 2017. Overheating in Scotland: contributing factors in occupied homes. *Building Research & Information*, 45(1–2), pp.143–156. DOI: 10.1080/09613218.2017.1241472.

Morgan, D.L., 2007. Paradigms Lost and Pragmatism Regained: Methodological Implications of Combining Qualitative and Quantitative Methods. *Journal of Mixed Methods Research*, 1(1), pp.48–76. DOI: 10.1177/2345678906292462.

Mott, L., Fore, D., Curtis, J. & Solomon, G., 1997. Chapter 4 - Air Pollution. In *Our Children at Risk, the five worst environment threats to their health.* Available at: http://www.nrdc.org/health/kids/ocar/ocarinx.asp.

Mukaka, M.M., 2012. A guide to appropriate use of Correlation coefficient in medical research. *Malawi Medical Journal*, 24(3), pp.69–71. DOI: 10.1016/j.cmpb.2016.01.020.

Mulla, M., Harkrider, J.R., Galant, S.P. & Amin, L., 1975. Some House-Dust Control Measures and Abundance of Dermatophagoides Mites in Southern California (Acari: Pyroglyphidae). *Journal of Medical Entomology*, 12(1), pp.5–9. DOI: 10.1093/jmedent/12.1.5.

Murray, A.B., Ferguson, A.C. & Morrison, B.J., 1985. Sensitization to house dust mites in different climatic areas. *The Journal of Allergy and Clinical Immunology*, 76(1), pp.108–112. DOI: 10.1016/0091-6749(85)90812-7.

Myles, P.S. & Cui, J., 2007. Using the Bland-Altman method to measure agreement with repeated measures. *British Journal of Anaesthesia*, 99(3), pp.309–311. DOI: 10.1093/bja/aem214.

De Nazelle, A., Seto, E., Donaire-Gonzalez, D., Mendez, M., Matamala, J., Nieuwenhuijsen, M.J. & Jerrett, M., 2013. Improving estimates of air pollution exposure through ubiquitous sensing technologies. *Environmental Pollution*, 176, pp.92–99. DOI: 10.1016/j.envpol.2012.12.032.

Neill, M.S.O. & Ebi, K.L., 2009. Temperature Extremes and Health: Impacts of Climate Variability and Change in the United States. *Journal of Occupational and Environmental Medicine*, 51(1), pp.13–25. DOI: 10.1097/JOM.0b013e318173e122.

Ng, L., Poppendieck, D., Dols, W.S. & Emmerich, S.J., 2018. Evaluating indoor air quality and energy impacts of ventilation in a net-zero energy house using a coupled model. *Science and Technology for the Built Environment*, 24(2), pp.124–134. DOI: 10.1080/23744731.2017.1401403.

NHBC Foundation, 2009. *A practical guide to building airtight dwellings*, Available at: http://www.zerocarbonhub.org/sites/default/files/resources/reports/A_Practical_Guide_to_Building_Air_Tight_Dwellings_NF16.pdf.

Nicol, F., 2004. Adaptive thermal comfort standards in the hot-humid tropics. *Energy and Buildings*, 36(7), pp.628–637. DOI: 10.1016/j.enbuild.2004.01.016.

Nicol, J.F. & Humphreys, M. A., 2002. Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings*, 34(6), pp.563–572. DOI: 10.1016/S0378-7788(02)00006-3.

Nicol, J. F. & Wilson, M., 2011. A critique of European Standard EN 15251: strengths , weaknesses and lessons for future standards. *Building Research & Information*, 39(2), pp. 183–193. DOI: 10.1080/09613218.2011.556824.

Nielsen, K.F., Holm, G., Uttrup, L.P. & Nielsen, P.A., 2004. Mould growth on building materials under low water activities. Influence of humidity and temperature on fungal growth and secondary metabolism. *International Biodeterioration and Biodegradation*, 54(4), pp.325–336. DOI: 10.1016/j.ibiod.2004.05.002.

Niven, R., Fletcher, M., Pickering, C., Custovic, A., Sivour, J.B., Preece, R., Oldham, L. & Francis, H.C., 1999. Attempting to control mite allergens with mechanical ventilation and dehumidification in British houses. *The Journal of allergy and clinical immunology*, 103(5 Pt 1), pp.756–62.DOI: 10.1016/S0091-6749(99)70416-1.

Northcross, A.L., Edwards, R.J., Johnson, M.A., Wang, Z-M., Zhu, K., Allen, T. & Smith, K.R., 2013. A low-cost particle counter as a realtime fine-particle mass monitor. *Environ. Sci.: Processes Impacts*, 15(2), pp.433–439. DOI: 10.1039/C2EM30568B.

Offerman, F.J., 2009. *Ventilation and Indoor Air Quality in New Homes*, San Francisco. Available at: http://www.arb.ca.gov/research/apr/past/04-310.pdf.

Orecchio, S., 2011. Polycyclic aromatic hydrocarbons (PAHs) in indoor emission from decorative candles. *Atmospheric Environment*, 45(10), pp.1888–1895. DOI: 10.1016/j.atmosenv.2010.12.024.

Othman, M.F. & Shazali, K., 2012. Wireless sensor network applications: A study in environment monitoring system. *Procedia Engineering*, 41, pp.1204–1210. DOI: 10.1016/j.proeng.2012.07.302.

Paliouras, P., Matzaflaras, N., Peuhkuri, R.H. & Kolarik, J., 2015. Using Measured Indoor Environment Parameters for Calibration of Building Simulation Model - A Passive House Case Study. *Energy Procedia*, 78, pp.1227–1232. DOI: 10.1016/j.egypro.2015.11.209.

Park, C., 2003. In other (People's) words: Plagiarism by university students-literature and lessons. *Assessment and Evaluation in Higher Education*, 28(5), pp.471–488. DOI: 10.1080/02602930301677.

Parkinson, T., Parkinson, A. and Dear, R. De, 2019a. 'ontinuous IEQ monitoring system : Context and development. *Building and Environment*, 149, pp. 15–25. DOI: 10.1016/j.buildenv.2018.12.010.

Parkinson, T., Parkinson, A. and Dear, R. De, 2019b. Continuous IEQ monitoring system : Performance specifications and thermal comfort classification. *Building and Environment*, 149, pp. 241–252. DOI: 10.1016/j.buildenv.2018.12.016.

Parkinson, T. & Dear, R.De, 2015. Thermal pleasure in built environments: physiology of alliesthesia. *Building Research & Information*, 43(3), pp.288–301. DOI: 10.1080/09613218.2015.989662.

Patel, S., Li, J., Pandey, A., Pervez, S., Chakrabarty, R.K. & Biswas, P., 2017. Spatio-temporal measurement of indoor particulate matter concentrations using a wireless network of low-cost sensors in households using solid fuels. *Environmental Research*, 152(July 2016), pp.59–65. DOI: 10.1016/j.envres.2016.10.001.

Peacock, A.D., Jenkins, D.P. & Kane, D., 2010. Investigating the potential of overheating in UK dwellings as a consequence of extant climate change. *Energy Policy*, 38(7), pp.3277–3288. DOI: 10.1016/j.enpol.2010.01.021.

Pears, R. & Shields, G., 2005. *Cite them right: the essential guide to referencing and plagarism* 2nd ed., Newcastle upon Tyne: Northumbria University Press.

Peretti, C. and Schiavon, S., 2011. Indoor environmental quality surveys. A brief literature review. In *Indoor Air 2*. Dallas, pp. 1331–1336.

Pérez-Lombard, L., Ortiz, J. & Pout, C., 2008. A review on buildings energy consumption information. *Energy and Buildings*, 40(3), pp.394–398. DOI: 10.1016/j.enbuild.2007.03.007.

Persily, A. & Levin, H., 2011. Ventilation Measurements in IAQ Studies : Problems and Opportunities. In *The 12th International Conference on Indoor Air Quality and Climate*. Austin, TX: ISIAQ.

Persily, A. & Wargocki, P., 2016. How to Evaluate Ventilation in IAQ Studies. In *Indoor Air*. ISIAQ, p. 573.

Persily, A.K., 1997. Evaluating building IAQ and ventilation with indoor carbon dioxide. *ASHRAE Transactions*, 103(pt 2), pp.193–204.

Persily, A.K., 2014. Indoor Air Quality in High Performance Buildings: What is and isn't in ASHRAE/IES/USGBC Standard 189.1. *13th International Conference on Indoor Air Quality and Climate.* Hong Kong.

Persily, A.K., 1996. The relationship between indoor air qualiti and carbon dioxide.pdf. *Indoor Air '96: The 7th International Conference on Indoor Air Quality and Climate*, pp.961–966.

Petersdorff, C., Boermans, T. & Harnisch, J., 2006. Mitigation of CO2 Emissions from the EU-15 Building Stock Beyond the EU Directive on the Energy Performance of Buildings. *Environmental Science and Pollution Research*, 13(5), pp.350–358. DOI: 10.1065/espr2005.12.289.

Petersen, J., Kristensen, J., Elarga, H., Andersen, R. & Midtstraum, A., 2018. Accuracy and Air Temperature Dependency of Commercial Low-cost NDIR CO2 Sensors: An Experimental Investigation. In *4th International Conference On Building Energy & Environment*. Melbourne, Australia, pp. 203–207.

PHE, 2014. Minimum home temperature thresholds for health in winter: a systematic literature review. , pp.1–69.

Phelps, A.F. & Horman, M.J., 2010. Ethnographic Theory-Building Research in Construction. *Journal of Construction Engineering and Management*, 136(1), pp.58–65. DOI: 10.1061/%28ASCE%29CO.1943-7862.0000104.

PHI, 2016. *Handbook for step-by-step retrofits with Passive House Components* 1st ed. Z. Bastian, ed., Darmstadt, Germany: Passive House Institute.

PHI, 2017a. Passipedia: The Passive House Resourse. *Basics*, p.1. Available at: https://passipedia.org/basics [Accessed March 23, 2018].

PHI, 2017b. Passipedia. Available at: http://www.passipedia.org/ [Accessed March 29, 2018].

PHI, 2014. Passive House Database. Available at: http://www.passivhausprojekte.de/index.php?lang=en [Accessed March 26, 2018].

PHI, 2015. Requirements and testing procedures for energetuc and acoustical assessment of Passive House ventilation systems for Certification as 'Passive house suitable component', Small ventilation systems (capacity > 600m3/h). Available at: https://passiv.de/downloads/03_Reqs_and_testing_procedures_ventilation_en.pdf [Accessed: July 23, 2019].

PHI, 2015a. Passive House Institute. Available at: http://www.passiv.de/en/index.php [Accessed May 20, 2009].

PHI, 2015b. *Passive House Regions with renewable Energies (Final Report)*, Darmstadt, Germany.

PHI, 2011. *Passive Houses for different climate zones* 1st ed., Darmstadt: Passive House Institute.

Piedrahita, R. et al., 2014. The next generation of low-cost personal air quality sensors for quantitative exposure monitoring. *Atmospheric Measurement Techniques*, 7(10), pp.3325–3336. DOI: 10.5194/amt-7-3325-2014.

Pluijm, W. Van Der, 2010. *The robustness and effectiveness of mechanical ventilation in airtight dwellings: A study to the residential application of mechanical ventilation with heat recovery in the Netherlands*. Eindhoven University of Technology.

Porteous, C.D.A., 2011. Sensing a Historic Low-CO 2 Future. In D. N. Mazzeo, ed. *Chemistry, Emission Control, Radioactive Pollution and Indoor Air Quality*. InTech, pp. 213–246..

Porteous, C.D.A., Sharpe, T.R., Menon, R.A., Shearer, D., Musa, H., Baker, P.H., Sanders, C.H., Strachan, P.A., Kelly, N.J. & Markopoulos, A., 2012. Energy and environmental appraisal of domestic laundering appliances. *Building Research and Information*, 40(6), pp.679–699. DOI: 10.1080/09613218.2012.708599.

Porteous, C. D. A., Sharpe, T. R., Menon, R., Strachan, P. A., Kelly, N. J. & Markopoulos, A., 2014. Domestic laundering: Environmental audit in Glasgow with emphasis on passive indoor drying and air quality. *Indoor and Built Environment*, 23(3), pp. 373–392. DOI: 10.1177/1420326X13508145.

Postolache, O. a, Pereira, J.M.D. & Girao, P.M.B.S., 2009. Smart Sensors Network for Air Quality Monitoring Applications. *Ieee Transactions On Instrumentation And Measurement*, 58(9), pp.3253–3262. DOI 10.1109/TIM.2009.2022372.

Poulhet, G., Dusanter, S., Crunaire, S., Locoge, N., Kaluzny, P. & Coddeville, P., 2015. Recent developments of passive samplers for measuring material emission rates: Toward simple tools to help improving indoor air quality. *Building and Environment*, 93(P1), pp.106–114. DOI: 10.1016/j.buildenv.2015.02.034.

Pretlove, S., Oreszczyn, T., Ridley, I., Wilkinson, T. & Crowther, D., 2005. A steady-state model for predicting hygrothermal conditions in beds in relation to house dust mite requirements. *Building Services Engineering Research and Technology*, 26(4), pp. 301–314. DOI: 10.1191/0143624405bt137oa.

Prieto Ursula, L., Sienra Monge, J.J., del Rio Navarro, B.E. & Mercado Ortiz, V.M., 1995. Skin tests for different species of acari in asthmatic children from Mexico City. *Revista Alergia Mexico*, 42(3), pp.49–53.

Ragazzi, M., Rada, E.C., Zanoni, S., Passamani, G. & Dalla Valle, L., 2017. Particulate matter and carbon dioxide monitoring in indoor places. *International Journal of Sustainable Development and Planning*, 12(6), pp.1032–1042. DOI: 10.2495/SDP-V12-N6-1032-1042.

Raw, G.J., 1995. *A Questionnaire for Studies of Sick Building Syndrome: a Report To the Royal Society of Health* Building Research Research, 1st ed., Watford: BRE press.

Raw, G.J., Roys, M.S, Whitehead, C. & Tong, D., 1995. Questionnaire desing for sick building syndrome: an empirical comparison of options. *Environment International*, 22(1), pp.61–72.

Redlich, C.A., Sparer, J. & Cullen, M.R., 1997. Sick-building syndrome. *The Lancet*, 349(9057), pp.1013–1016. Available at:

https://www.sciencedirect.com/science/article/pii/S0140673696072200 [Accessed August 9, 2018].

Rehwagen, M., Schlink, U. & Herbarth, O., 2003. Seasonal cycle of VOCs in apartments. *Indoor Air*, 13(3), pp.283–291. DOI: 10.1034/j.1600-0668.2003.00206.x.

Reja, U., Manfreda, K.L., Hlebec, V. & Vehovar, V., 2003. Open-ended vs. Close-ended Questions in Web Questionnaires. *Developments in Applied Statistics*, 19, pp.159–177.

Ridley, D., 2012. *The literature review: A step-by-step guide for students* 2nd ed. K. Metzler, ed., Los Angeles, CA: SAGE.

Ridley, I., Clarke, A., Bere, J., Altamirano, H., Lewis, S., Durdev, M. & Farr, A., 2013. The monitored performance of the first new London dwelling certified to the Passive House standard. *Energy and Buildings*, 63, pp.67–78. DOI: 10.1016/j.enbuild.2013.03.052.

Ridley, I., Bere, J., Clarke, A., Schwartz, Y. & Farr, A., 2014. The side by side in use monitored performance of two passive and low carbon Welsh houses. *Energy and Buildings*, 82, pp.13–26. DOI: 10.1016/j.enbuild.2014.06.038.

Rodolfo-Sosa, E., Humberto-Bravo, A., Violeta-Mugica, A., Pablo-Sanchez, A., Emma-Bueno, L. & Krupa, S., 2009. Levels and source apportionment of volatile organic compounds in southwestern area of Mexico City. *Environmental Pollution*, 157(3), pp.1038–1044. DOI: 10.1016/j.envpol.2008.09.051.

Rodrigues, L.T., Gillott, M. & Tetlow, D., 2013. Summer overheating potential in a low-energy steel frame house in future climate scenarios. *Sustainable Cities and Society*, 7, pp.1–15. DOI: 10.1016/j.scs.2012.03.004.

Rojas, G., Wagner, W., Suschek-Berger, J., Pfluger, R. & Feist, W., 2016. Applying the passive house concept to a social housing project in Austria – evaluation of the indoor environment based on long-term measurements and user surveys. *Advances in Building Energy Research*, 10(1), pp.125–148. DOI:

10.1080/17512549.2015.1040072.

Rojas, L., 2014. Implications of air pollution on health in Mexico City's Metropolitan Area and the potential benefits of applying control measures. , pp.1–13. Available at: http://centromariomolina.org/english/wp-content/uploads/2014/07/Oportunidades-calidad-del-aire-y-salud-para-ZMVM-final_LeonoraRojas_eng.pdf.

Rosseau, D., Bowser, D. & Mattock, C., 2001. *A Guide to Mechanical Equipment for Healthy Indoor Environments*, Canda. Available at: https://www.cmhc-schl.gc.ca/odpub/pdf/62015.pdf.

Rossman, G., & & Wilson, B., 1994. Numbers and Words Revisited: Being "Shamelessy Eclectic." *Quality and quantity*, 28, pp.315–327.

Royal College of Physicians, 2016. *Every breath we take: the lifelong impact of air pollution. Report of a working party*, London: RCP.

Royal College of Physicians, 2018. *Reducing air pollution in the UK: Progress report 2018*, London.

Rutgherford, S., 2000. Indoor air quality and the influence of house dust mites, cockraches and pets. In *Indoor air qulity a report on health impacts and management Options*. Canberra, pp. 59–69. Available at: https://www.researchgate.net/profile/Michael_Moore4/publication/43482403_Health_Risk_Assessment_and_Management/links/02bfe510066c65cdf3000000.pdf#page=60.

Sabouri, V. & Femenias, P., 2012. Two Case Studies in Energy Efficient Renovation of Multi-family Housing; Explaining Robustness as a Characteristic to Assess Long-Term Sustainability. In A. Hakansson, M. Höjer, R.J. Howlett & L.C Jain eds. *4th International Conference on Sustainability in Energy and Buildings (SEB'12)*. Stokholm: Sringer, pp. 45–57.

Sadineni, S.B., Madala, S. & Boehm, R.F., 2011. Passive building energy savings: A review of building envelope components. *Renewable and Sustainable Energy Reviews*, 15(8), pp.3617–3631. DOI: 10.1016/j.rser.2011.07.014.

Samet, J.M., 1993. Indoor air pollution: a public health perspective. *Science*, 3(4), pp.219–226. DOI: 10.1126/science.6857273.

Santin, O.G., Itard, L. & Visscher, H., 2009. The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock. *Energy & Buildings* , 41, pp.1223–1232. DOI: 10.1016/j.enbuild.2009.07.002.

Sassi, P., 2013. A Natural Ventilation Alternative to the Passivhaus Standard for a Mild Maritime Climate. *Buildings*, 3, pp.61–78. DOI: 10.3390/buildings3010061.

Sassi, P., 2006. *Strategies for Sustainable Architecture*, 1st ed. Abingdon, Taylor & Francis.

Satish, U., Mendell, M.J., Shekhar, K., Hotchi, T., Sullivan, D., Streufert, S. & Fisk, W.J., 2012. Is CO_2 an indoor pollutant? Direct effects of low-to-moderate CO_2 concentrations on human decision-making performance. *Environmental Health Perspectives*, 120(12), pp.1671–1677. DOI: 10.1289/ehp.1104789.

Schellnhuber, H.J., Cramer, W., Nakicenovic, N., Wigley, T. & Yohe, G., 2006. *Avoiding Dangerous Climate Change*, 1st ed. Cambridge, Cambridge Press.

SCHER, 2007. *Opinion on risk assessment on indoor air quality*.

Schieweck, A., Uhde, E., Salthammer, T., Salthammer, L.C., Morawska, L., Mazaheri, M. & Kumar, P., 2018. Smart homes and the control of indoor air quality. *Renewable and Sustainable Energy Reviews*, 94, pp.705–718. DOI: 10.1016/j.rser.2018.05.057.

Schlink, U., Rehwagen, M., Damm, M., Richter, M., Borte, M. & Herbarth, O., 2004. Seasonal cycle of indoor-VOCs: Comparison of apartments and cities. *Atmospheric Environment*, 38(8), pp.1181–1190. DOI: 10.1016/j.atmosenv.2003.11.003.

Schnieders, J., 2003. CEPHEUS – measurement results from more than 100 dwelling units in passive houses. In *ECEEE 2003 Summer Study*, pp.341–351.

Schnieders, J., 2009. *Passive Houses in South West Europe. A quantitative investigation of some passive and active space conditioning techniques for highly energy efficient dwellings in the South West European region* 2nd ed., Darmstadt: Passive House Institute.

Schnieders, J., Feist, W. & Rongen, L., 2015. Passive Houses for different climate zones. *Energy & Buildings*, 105, pp.71–87. DOI: 10.1016/j.enbuild.2015.07.032.

Schnieders, J. & Hermelink, A., 2006. CEPHEUS results: Measurements and occupants' satisfaction provide evidence for Passive Houses being an option for sustainable building. *Energy Policy*, 34(2 SPEC. ISS.), pp.151–171. DOI: 10.1016/j.enpol.2004.08.049.

Schrauwen, P. & Lichtenbelt, W.D.V.M., 2016. Combatting type 2 diabetes by turning up the heat. *Diabetologia*, 59, pp.2269–2279. DOI: 10.1007/s00125-016-4068-3.

Scottish Government, 2017. *Domestic Technical Handbook 2017*, Scotland. Available at: http://www.gov.scot/Resource/0039/00397457.pdf.

Sears, M.R., Herbison, G.P., Holdaway, M.D., Hewitt, C.J., Flannery, E.M. & Silva, P.A., 1989. The relative risks of sensitivity to grass pollen, house dust mite and cat dander in the development of childhood asthma. *Clinical and Experimental Allergy*, 19(19), pp.419–424. DOI: 10.1111/j.1365-2222.1989.tb02408.x.

Seasay, H. & Dobson, R., 1972. Studies on the mite fauna of house dust in Scotland with special reference to that of bedding. *Acarologia*, 14(3), pp.384–92.

Seawright, J. & Gerring, J., 2008. Case Selection Techniques in A Menu of Qualitative and Quantitative Options. *Political Research Quarterly*, (1975), pp.294–308.

Sechrest, L. & Sidani, S., 1999. Quantitative and qualitative methods:: Is There an Alternative? *Evaluation and Program Planning*, 12, pp.6–13.

Secretaria de Economía, 2013. *NMX-AA-164-SCFI-2013 - Edificación sustentable - criterios y requerimientos ambientales mínimos*, Mexico. Available at: http://biblioteca.semarnat.gob.mx/janium/Documentos/Ciga/agenda/DOFsr/DO3156.pdf.

Secretaria de Salud, 2014. *NOM-025-SSA1-2014*, Mexico. Available at: http://www.inecc.gob.mx/calaire-informacion-basica/559-calaire-nom-cal-aire.

SEMARNAT & INECC, 2015. Primer Informe Bienal de Actualización ante la Convención Marco de las Naciones Unidas sobre el Cambio Climático. p.287.

Semple, S., Garden, C., Coggins, M., Galea, K.S., Whelan, P., Cowie, H., Sánchez-Jiménez, A., Thorne, P.S., Hurley, J.F. & Ayres, J.G., 2012. Contribution of solid fuel, gas combustion, or tobacco smoke to indoor air pollutant concentrations in Irish and Scottish homes. *Indoor Air*, 22(3), pp.212–223. DOI: 10.1111/j.1600-0668.2011.00755.x.

Semple, S., Ibrahim, A.E., Apsley, A., Steiner, M. & Turner, S., 2013. Using a new, low-cost air quality sensor to quantify second-hand smoke (SHS) levels in homes. *Tobacco Control*, 24(2), pp.153–158. DOI: 10.1136/tobaccocontrol-2013-051188.

SENSIRION, 2014. *Datasheet SHT20 Humidity and Temperature Sensor IC*, Available at: https://www.sensirion.com/fileadmin/user_upload/customers/sensirion/Dokumente/2_Humidity_Sensors/Sensirion_Humidity_Sensors_SHT20_Datasheet_V4.pdf.

Sensor Business Digest, 2002. SENSOR INDUSTRY DEVELOPMENTS AND TRENDS. *Nov*. Available at: http://archives.sensorsmag.com/resources/businessdigest/sbd1102.shtml [Accessed July 19, 2017].

Seppänen, O., 2008. Ventilation strategies for good indoor air quality and energy efficiency. *International Journal of Ventilation*, 6(4), pp.297–306. DOI: 10.1080/14733315.2008.11683785.

Seppänen, O. & Fisk, W.J., 2002. Association of ventilation system type with SBS symptoms in office workers. *Indoor air*, 12, pp.98–112. DOI: 10.1034/j.1600-0668.2002.01111.x.

Seppänen, O. & Fisk, W.J., 2004. Summary of human responses to ventilation. *Indoor Air, Supplement*, 14(SUPPL. 7), pp.102–118. DOI: 10.1111/j.1600-0668.2004.00279.x.

Seppänen, O., Fisk, W.J. & Mendell, M.J., 1999. Association of ventilation rates and CO2 concentrations with health and other responses in commercial and institutional buildings. *Indoor air*, 9, pp.226–252. DOI: 10.1111/j.1600-0668.1999.00003.x.

SHARP, Application note of Sharp dust sensor GP2Y1010AU0F - Sheet No.: OPI3024EN. , pp.0–6.

Sharpe, R.A., Thornton, C.R., Nikolaou, V. & Osborne, N.J., 2015. Fuel poverty increases risk of mould contamination, regardless of adult risk perception & ventilation in social housing properties. *Environment International*, 79, pp.115–129. DOI: 10.1016/j.envint.2015.03.009.

Sharpe, T., McGill, G., Gregg, M. & Mawditt, I., 2016. *Characteristics and performance of MVHR systems A meta study of MVHR systems used in the Innovate UK Building Performance Evaluation*, MEARU.

Sharpe, T., 2018. Ethical issues in domestic building performance evaluation studies. *Building Research & Information*, 47(3), pp. 318-329. DOI: 10.1080/09613218.2018.1471868.

Sharpe, T., Farren, P., Howieson, S., Tuohy, P. & McQuillan, J., 2015. Occupant interactions and effectiveness of natural ventilation strategies in contemporary new housing in Scotland, UK. *International Journal of Environmental Research and Public Health*, 12(7), pp.8480–8497. DOI: 10.3390/ijerph120708480.

Sharpe, T., Mcquillan, J., Howieson, S., Farren, P. & Tuohy, P., 2014. *Research Project To Investigate Occupier Influence On Indoor Air Quality In Dwellings*, Livingston. Available at: https://www2.gov.scot/Resource/0046/00460968.pdf.

Sharpe, T.R., Porteous, C. D.A., Foster, J. & Shearer, D., 2014. An assessment of environmental conditions in bedrooms of contemporary low energy houses in Scotland. *Indoor and Built Environment*, 23(0), pp.1–24. DOI: 10.1177/1420326X14532389.

Shenton, A.K., 2010. This Problem of Plagiarism … Just What Can We Do About It? *The school Librarian*, 58(2), pp.73–76.

Sherin, A. & Li, X., 2014. A cost-effective wireless sensor network system for indoor air quality monitoring applications. *Procedia Computer Science*, 34, pp.165–171. DOI: 10.1016/j.procs.2014.07.090.

Sherman, M.H., 2008. Trend in the US ventilation market and drivers for change. In *Ventilation Information Paper* (May).

Sherman, M.H. & Chan, R., 2004. Building Airtightness: Research and Practice. *Lawrence Berkeley National Laboratory*, (January), pp.1–46.

Shiue, I. & Shiue, M., 2014. Indoor temperature below 18°C accounts for 9% population attributable risk for high blood pressure in Scotland. *International Journal of Cardiology*, 171(1), pp.e1–e2. DOI: 10.1016/j.ijcard.2013.11.040.

Short, C. A. Cook, M. & Lomas, K. J., 2009. Delivery and performance of a low-energy ventilation and cooling strategy. *Building Research & Information*, 37(1), pp. 1–30. DOI: 10.1080/09613210802607841.

Short, C. A., 2018. The recovery of natural environments in architecture : Delivering the recovery. *Journal of Building Engineering*. Elsevier Ltd, 15, pp. 328–333. DOI: 10.1016/j.jobe.2017.11.014.

Shrubsole, C., 2017. Changes in exposure to PM2.5 in English dwellings: an unintended consequence of energy efficient refurbishment of the housing stock. University College London. Available at: http://discovery.ucl.ac.uk/10026085/

Silverman, D., 1998. Qualitative research: meanings or practices? *Information Systems Journal*, 8(1), pp.3–20. DOI: 10.1046/j.1365-2575.1998.00002.x.

Singh, J., Wah Francis Yu, C. & Tai Kim, J., 2010. Building Pathology, Investigation of Sick Buildings —Toxic Moulds. *Indoor and Built Environment*, 19(1), pp.40-47. DOI: 10.1177/1420326X09358808.

Smith, J.K., 1983. Quantitative versus Qualitative Research: An Attempt to Clarify the Issue. *Educational Researcher*, 12(3), pp.6–13. DOI: 10.3102/0013189X012003006.

Smith, J.K., 1984. The Problem of Criteria for Judging Interpretive Inquiry. *Educational Evaluation and Policy Analysis*, 6(4), pp.379–391. DOI: 10.3102/01623737006004379.

Smith, K.R. & Mehta, S., 2003. The burden of disease from indoor air pollution in developing countries: comparison of estimates. *International journal of hygiene and environmental health*, 206(4–5), pp.279–289. DOI: 10.1078/1438-4639-00224.

Sousan, S., Koehler, K., Hallett, L. & Peters, T.M., 2017. Evaluation of consumer monitors to measure particulate matter. *Journal of Aerosol Science*, 107, pp.123–133. DOI: 10.1016/j.jaerosci.2017.02.013.

Sousan, S., Koehler, K., Thomas, G., Park, J.H., Hillman, M., Halterman, A. & Thomas M., P., 2016. Inter-comparison of low-cost sensors for measuring the mass concentration of occupational aerosols. *Aerosol Science and Technology*, 50(5), pp.462–473. DOI: 10.1080/02786826.2016.1162901.

Spachos, P., Song, L. & Hatzinakos, D., 2013. Prototypes of opportunistic wireless sensor networks supporting indoor air quality monitoring. In *Consumer Communications and Networking Conference (CCNC), 2013 IEEE*. Demos: IEEE, pp. 851–852.

Spengler, J. & Sexton, K., 1987. Indoor air pollution: a public health perspective. *Science*, 221(4605), pp.9–17. DOI: 10.1126/science.6857273.

Spengler, J.D., 2012. Climate change, indoor environments, and health. *Indoor Air*, 22(2), pp.89–95. DOI: 10.1111/j.1600-0668.2012.00768.x.

Stake, R.E., 1995. *The art of case study research*, SAGE.

Steiger, S., Hellwing, R. & Junker, E., 2008. Distribution of carbon dioxide in a naturally ventilated room with high internal heat load. In C. Rode, ed. *Symposium on Building Physics in the Nordic Countries*. Copenhagen, Denmark, pp. 377–384.

Steinle, S., Reis, S., Sabel, C.E., Semple, S., Twigg, M.M., Braban, C.F., Leeson, S.R., Heal, M.R., Harrison, Da., Lin, C. & Wu, H., 2015. Personal exposure monitoring of PM2.5 in indoor and outdoor microenvironments. *Science of the Total Environment*, 508, pp.383–394. DOI: 10.1016/j.scitotenv.2014.12.003.

Stern, P.C., 2000. Toward a Coherent Theory of Environmentally Significant Behavior. *Journal of Social Issues*, 56(3), pp.407–424.

Story, P.R., Galipeau, D.W. & Mileham, R.D., 1995. A study of low-cost sensors for measuring low relative humidity. *Sensors and Actuators: B. Chemical*, 25(1-3), pp.681–685. DOI: 10.1016/0925-4005(95)85150-X.

Van Strien, R., Verhoeff, A.P., Brunekreef, B. & Van Wijnen, J.H., 1994. Mite Antigen in-House Dust - Relationship With Different Housing Characteristics in the Netherlands. *Clinical and Experimental Allergy*, 24(9), pp.843–853. DOI: 10.1111/j.1365-2222.1994.tb01807.

Su, J.G., Jerrett, M., Meng, Y.Y., Pickett, M. & Ritz, B., 2015. Integrating smart-phone based momentary location tracking with fixed site air quality monitoring for personal exposure assessment. *Science of the Total Environment*, 506–507, pp.518–526. DOI: 10.1016/j.scitotenv.2014.11.022.

Sullivan, L., Smith, N., Adams, D., Andrews, I., Aston, W., Bromley, K. & Butler, K., 2013. *Mechanical Ventilation With Heat Recovery in New Homes*, London.

Sullivan, L., Andrews, I., Christie, A. & Houghton, C., 2012. *Mechanical Ventilation With Heat Recovery in New Homes*, London.

Sundell, J., 2004. On the history of indoor air quality and health. *Indoor Air*, 14(Suppl. 7), pp.51–58. DOI: 10.1111/j.1600-0668.2004.00273.x.

Sundell, J., 2007. The indoor environment in homes and health - What we have learnt, if any? In *IAQVEC 2007 Proceedings - 6th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings: Sustainable Built Environment*, 2(January 2007).

Sundell, J., Levin, H., Nazaroff, W.W., Cain, W.S., Fisk, W.J., Grimsrud, D.T., Gyntelberg, F., Li, Y., Persily, K., Pickering, C., Samet, J.M., Spengler, J.D., Taylor, S.T. & Weschler, C.J., 2011. Ventilation rates and health: Multidisciplinary review of the scientific literature. *Indoor Air*, 21(3), pp.191–204. DOI: 10.1111/j.1600-0668.2010.00703.x.

Sunikka-Blank, M. & Galvin, R., 2012. Introducing the prebound effect: the gap between performance and actual energy consumption. *Building Research & Information*, 40(3), pp.260–273. DOI: 10.1080/09613218.2012.690952.

Sunwoo, Y., Chou, C., Takeshita, J., Murakami, M. & Tochihara, Y., 2006. Physiological and subjective responses to low relative humidity in young and elderly men. *Journal of physiological anthropology*, 25(3), pp.229–238. DOI: 10.2114/jpa2.25.229.

Szirtesi, K., Angyal, A., Szoboszlai, Z., Furu, E.E., Török, Z., Igaz, T. & Kertész, Z., 2018. Airborne particulate matter investigation in buildings with passive house technology in Hungary. *Aerosol and Air Quality Research*, 18(5), pp.1282–1293. DOI: 10.4209/aaqr.2017.05.0158.

Tabatabaei Sameni, S.M., Gaterell, M., Montazami, A. & Ahmed, A., 2015. Overheating investigation in UK social housing flats built to the Passivhaus standard. *Building and Environment*, 92, pp.222–235. DOI: 10.1016/j.buildenv.2015.03.030.

Tarran, J., Torpy, F. & Burchett, M., 2007. Use of living pot-plants to cleanse indoor air - research review. In *Proceedings of Sixth International Conference on Indoor Air Quality, Ventilation & Energy Conservation in Buildings – Sustainable Built Environment, Oct 28-31, 2007, Volume III*, pp.249–256.

Taylor, M.D. & Nourbakhsh, I.R., 2015. A low-cost particle counter and signal processing method for indoor air pollution. *Air Pollution XXIII*, 198, pp.337–348. DOI: 10.2495/AIR150291.

Teichman, K. & Howard-reed, C., 2016. *NIST Technical Note 1868 Characterizing Indoor Air Quality Performance Using a Graphical Approach*, Washington, DC. DOI: 10.6028/NIST.TN.1868.

Thunshelle, K. & Hauge, Å.L., 2016. User evaluation of the indoor climate of the first passive house school in Norway. *Energy Efficiency*, 9(5), pp.965–980. DOI: 10.1007/s12053-015-9399-2.

Tigchelaar, C. & Daniëls, B., 2011. Obligations in the existing housing stock : Who pays the bill? In *ECEEE 2011 Summer Study*, pp.353–363.

Tommerup, H. & Svendsen, S., 2006. Energy savings in Danish residential building stock. *Energy and Buildings*, 38(6), pp.618–626. DOI: 10.1016/j.enbuild.2005.08.017.

Tong, Z., Xiong, X. & Patra, P., 2015. Miniaturized $PM_{2.5}$ Particulate Sensor Based on Optical Sensing. In *2015 ASEE-NE Conference*. Boston, US: ASEE, p. 6604.

Treut, L., Somerville, R., Cubasch, U., Ding, Y., Mauritzen, C., Mokssit, A., Peterson, T., Prather, M., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B. & Tignor, M., 2007. Chapteer 1 - Historical Overview of Climate Change Science. In *IPCC WG1 Fourth Assessment Report*, pp.93–127. DOI: 10.1016/j.soilbio.2010.04.001.

Truong, H. & Garvie, A.M., 2017. Chifley Passive House: A Case Study in Energy Efficiency and Comfort. In *Energy Procedia*. Elsevier B.V., pp. 214–221. DOI: 10.1016/j.egypro.2017.08.020.

Tuohy, P., Murphy, G. & Deveci, G., 2012. Lessons from Post Occupancy Evaluation and Monitoring of the 1st Certified Passive House in Scotland. Available from OpenAIR@RGU. [Online].

Turpin, B., Weisel, C.P., Morandi, M., Colome, S., Stock, T., Eisenreich, S. &

Buckley, B., 2007. *Relationships of Indoor, Outdoor, and Personal Air (RIOPA): part II. Analyses of concentrations of particulate matter species.* Health Effects Institute.

U.S. Green Building Council, 2015. LEED. Available at: http://www.usgbc.org/leed [Accessed November 1, 2015].

Ucci, M., Biddulph, P., Oreszczyn, T., Crowther, D. & Wilkinson, T., 2011. Aplication of a transient hygrothermal population model for house dust mites in beds: assesment of control strategies in UK buildings. *Journal of Building Performance Simulation*, 4(3), pp.285–300. DOI: 10.1080/19401493.2010.532235.

Uhde, E. & Salthammer, T., 2007. Impact of reaction products from building materials and furnishings on indoor air quality-A review of recent advances in indoor chemistry. *Atmospheric Environment*, 41(15), pp.3111–3128. DOI: 10.1016/j.atmosenv.2006.05.082.

Ulmer, H. & Herberger, S., 2012. New Developments in VOC Sensing for DCV. In *33rd AIVC and 2nd TightVent Conference - Optimising Ventilative Cooling and Airtightness for [Nearly] Zero-Energy Buildings, IAQ and Comfort*. Copenhagen, Denmark: AIVC.

United Nations, 1998. *Kyoto Protocol To the United Nations Framework Kyoto Protocol To the United Nations Framework*, Available at: http://unfccc.int/resource/docs/convkp/kpeng.pdf.

United Nations, 2016. *Paris Agreement*, Available at: http://ec.europa.eu/clima/policies/international/negotiations/paris/index_en.htm.

Vaisala Oyj, 2013. Humidity conversiuon formulas - Calculation formulas for humidity.

De Vito, S., Fattoruso, G., Liguoro, R., Oliviero, A., Massera, E., Sansone, C., Casola, V. & Di Francia, G., 2011. Cooperative 3D Air Quality assessment with wireless chemical sensing networks. *Procedia Engineering*, 25, pp.84–87. DOI:

10.1016/j.proeng.2011.12.021.

Vlk, A. & Novák, J., 2017. Impact of Airtightness on the Heat Demand of Passive Houses in the Central European Climate. In *38th AIVC Conference "Ventilating healthy low-energy buildings."* Nottingham, UK: Society of Environmental Engineering, pp. 360–365.

Wallace, L., Wang, F., Howard-Reed, C. & Persily, A., 2008. Contribution of Gas and Electric Stoves to Residential Ultrafine Particle Concentrations between 2 nm and 64 nm: Size Distributions and Emission and Coagulation Rates. *Environmental science & technology*, 42(23), pp.8641–8647. DOI: 10.1021/es801402v.

Wallner, P., Tappler, P., Munoz, U., Damberger, B., Wanka, A., Kundi, M. & Hutter, H.P., 2017. Health and wellbeing of occupants in highly energy efficient buildings: A field study. *International Journal of Environmental Research and Public Health*, 14(3). DOI: 10.3390/ijerph14030314.

Wallner, P., Munoz, U., Tappler, P., Wanka, A., Kundi, M., Shelton, J.F. & Hutter, H.P., 2015. Indoor environmental quality in mechanically ventilated, energy-efficient buildings vs. Conventional buildings. *International Journal of Environmental Research and Public Health*, 12(11), pp.14132–14147. DOI: 10.3390/ijerph121114132.

Waltjen, T., Georgii, W., Torghele, K., Mötzl, H. & Zelger, T., 2009. *Passivhaus-Bauteilkatalog/Details for Passive Houses: Okologisch Bewertete Konstruktionen / A Catalogue of Ecologically Rated Constructions* 3rd ed. IBO OEsterreichisches Institut fur Baubiologie und -oekologie, 4th ed., Basel, Switzerland, Switzerland: Birkhauser.

Wan, M.P., Wu, C.L., Sze To, G.N., Chan, T.C. & Chao, C.Y.H., 2011. Ultrafine particles, and PM2.5generated from cooking in homes. *Atmospheric Environment*, 45(34), pp.6141–6148. DOI: 10.1016/j.atmosenv.2011.08.036.

Wang, C.H., Huang, Y.K., Zheng, X.Y., Lin, T.S., Chuang, C.L. & Jiang, J.A., 2012. A self sustainable air quality monitoring system using WSN. *Proceedings - 2012 5th IEEE International Conference on Service-Oriented Computing and*

Applications, SOCA 2012. DOI: 10.1109/SOCA.2012.6449427.

Wang, R., Henderson, S.B., Sbihi, H., Allen, R.W. & Brauer, M., 2013. Temporal stability of land use regression models for traffic-related air pollution. *Atmospheric Environment*, 64, pp.312–319. DOI: 10.1016/j.atmosenv.2012.09.056.

Wang, Y., Kuckelkorn, J., Zhao, F.Y., Spliethoff, H. & Lang, W., 2017. A state of art of review on interactions between energy performance and indoor environment quality in Passive House buildings. *Renewable and Sustainable Energy Reviews*, 72(November 2016), pp.1303–1319. DOI: 10.1016/j.rser.2016.10.039.

Wang, Y., Li, J., Jing, H., Zhang, Q., Jiang, J. & Biswas, P., 2015. Laboratory Evaluation and Calibration of Three Low-Cost Particle Sensors for Particulate Matter Measurement. *Aerosol Science and Technology*, 49(11), pp.1063–1077. DOI: 10.1080/02786826.2015.1100710.

Wang, Z., Xue, Q., Ji, Y. & Yu, Z., 2018. Indoor environment quality in a low-energy residential building in winter in Harbin. *Building and Environment*, 135(March), pp.194–201. DOI: 10.1016/j.buildenv.2018.03.012.

Wang, Z. & Yu, Z., 2017. $PM_{2.5}$ and Ventilation in a Passive Residential Building. *Procedia Engineering*, 205, pp.3646–3653. DOI: 10.1016/j.proeng.2017.10.226.

Wargocki, P., 2013. The Effects of Ventilation in Homes on Health. *International Journal of Ventilation*, 12(2), pp.101–118. DOI: 10.1080/14733315.2013.11684005.

Wargocki, P., Lan, L., Lian, Z. & Wyon, D.P., 2018. Thermal environment, IAQ and sleep. *ASHRAE Journal*, 60(4), pp.60–63.

Wargocki, P., Sundell, J., Bischof, W., Brundrett, G., Fanger, P.O., Gyntelberg, F., Hanssen, S.O., Harrison, P., Pickering, A., Seppänen, O. & Wouters, P., 2002. Ventilation and health in non-industrial indoor environments: report from a European multidisciplinary scientific consensus meeting (EUROVEN).

Indoor air, 12, pp.113–128. DOI: 10.1034/j.1600-0668.2002.01145.x.

Wargocki, P., Wyon, D. & Fanger, P.O., 2000. Pollution source control and ventilation improve health, comfort and productivity. In *German air condition and refrigeration meeting 2000*. Bremen, Germany: Deutscher Kaelte- und Klimatechnischer Verein e.V. (DKV), pp. 47–54.

Wassouf, M., 2014. *De la casa pasiva al estándar Passivhaus, la arquitectura pasiva en climas cálidos.* First., Barcelona, Spain: Gustavo Gili.

Watson, J., 1984. The tin oxide gas sensor and its applications. *Sensors and Actuators*, 5(1), pp.29–42. DOI: 10.1016/0250-6874(84)87004-3.

Weichenthal, S., Mallach, G., Kulka, R., Black, A., Wheeler, A., You, H., St-Jean, M., Kwiatkowski, R. & Sharp, D., 2013. A randomized double-blind crossover study of indoor air filtration and acute changes in cardiorespiratory health in a First Nations community. *Indoor Air*, 23(3), pp.175–184. DOI: 10.1111/ina.12019.

Weichenthal, S., Hoppin, J.A. & Reeves, F., 2014. Obesity and the Cardiovascular Health Effects of Fine Particulate Air Pollution. *Obesity*, 22(7), pp.1580–1589. DOI: 10.1002/oby.20748.

Wharton, G., 1970. Mites and commercial extracts of house dust. *Science (Washington)*, 167(3923), pp.1382–1383.

White, W.H., 2009. Considerations in the use of ozone and PM2.5 data for exposure assessment. *Air Quality, Atmosphere and Health*, 2, pp.223–230. DOI: 10.1007/s11869-009-0056-9.

WHO, 2000. *Air quality guidelines for Europe* Sencond Ed. F. Theakston, ed., Copenhagen: WHO Regional Publications.

WHO, 1997. Assessment of exposure to indoor air pollutants. *WHO regional publications. European series no. 78*.

WHO, 1989. Indoor air quality: Organic pollutants. *Environmental Technology*

Letters, 10(9), pp.855–858.

WHO, 1991. Indoor Environment: Health Aspects of Air Quality, thermal environment, light and noise. pp.17–21.

WHO, 2010. *WHO guidelines for indoor air quality: selected pollutants* First Edit. F. Theakston, ed., Copenhagen: World Health Organization Regional Office for Europe.

WHO Regional Office for Europe, 2000. *The right to healthy indoor air*, Netherlands.

Williams, R., Rea, A., Vette, A., Croghan, C., Whitaker, D., Stevens, C., McDow, S., Fortmann, R., Sheldon, L., Wilson, H., Thornburg, J., Phillips, M., Lawless, P., Rodes, C. & Daughtrey, H., 2009. The design and field implementation of the detroit exposure and aerosol research study. *Journal of Exposure Science and Environmental Epidemiology*, 19(7), pp.643–659. DOI: 10.1038/jes.2008.61.

Wilson, J., Dixon, S.L., Jacobs, D.E., Breysse, J., Akoto, J., Tohn, E., Isaacson, M., Evens, A. & Hernandez, Y., 2014. Watts-to-Wellbeing: Does residential energy conservation improve health? *Energy Efficiency*, 7(1), pp.151–160. DOI: 10.1007/s12053-013-9216-8.

Wolcott, H.F., 2005. *The art of fieldwork* 2nd ed., Plymouth, UK: AltaMira Press.

Wolkoff, P. & Kjærgaard, S.K., 2007. The dichotomy of relative humidity on indoor air quality. *Environment International*, 33(6), pp.850–857. DOI: 10.1016/j.envint.2007.04.004.

Wolverton, B. & Wolverton, J., 1993. Plants and soil microorganisms: removal of formaldehyde, xylene, and ammonia from the indoor environment. *Journal of the mississippi academy of sciences*, 38(2), pp.11–15. Available at: http://www.wolvertonenvironmental.com/MsAcad-93.pdf.

Woodside, A., 2010. *Case Study Research:Theory, Methods and Practice: Theory, Methods, Practice* 1st ed., Emerald Group Publishing Limited.

Woolley, T., 2017. *Building materials, health and indoor air quality: No breathing space?* 1st ed., Abingdon: Routledge.

World Health Organization Europe, 2009. Dampness and mould. *WHO guidelines for indoor air quality:dampness and mould*.

Worldwatch Institute, 2014. Energy Agency Predicts High Prices in Future. Available at: http://www.worldwatch.org/node/5936 [Accessed March 21, 2018].

Wu, Z., Hu, M., Lin, P., Liu, S., Wehner, B. & Wiedensohler, A., 2008. Particle number size distribution in the urban atmosphere of Beijing, China. *Atmospheric Environment*, 42(34), pp.7967–7980. DOI: 10.1016/j.atmosenv.2008.06.022.

Yik, F.W.H. & Lun, Y.F., 2010. Energy saving by utilizing natural ventilation in public housing in Hong Kong. *Indoor and Built Environment*, 19(1), pp.73–87. DOI: 10.1177/1420326X09358021.

Yin, R.K., 1994. *Case study research: design and methods* 2nd ed., London: SAGE.

Yin, R.K., 2013. *Case study research: design and methods* 5th ed., Los Angeles, CA: SAGE.

Yip, M. & Madl, P., 2000. Air pollution in Mexico City: smog, health effects, fossil fuels. Available at: http://biophysics.sbg.ac.at/mexico/air.htm#Pollution [Accessed May 1, 2015].

Yoneyama, T., Kim, H.Y., Morikawa, H. & Srivastava, H.S., 2002. Metabolism and Detoxification of Nitrogen Dioxide and Ammonia in Plants. In *Air Pollution and Plant Biotechnology*. Tokyo: Springer

Yu, C. & Crump, D., 2010. Indoor Environmental Quality - Standards for Protection of Occupants' Safety, Health and Environment. *Indoor and Built Environment*, 19(5), pp.499–502. DOI: 10.1177/1420326x10381106.

Yu, C.W.F. & Kim, J.T., 2012. Low-carbon housings and indoor air quality. *Indoor* *and Built Environment*, 21(1), pp.5–15. DOI: 10.1177/1420326X11431907.

Yu, T.-C., Lin, C.-C., Chen, C.-C., Lee, W.-L., Lee, R.-G., Tseng, C.-H. & Liu, S.-P., 2013. Wireless sensor networks for indoor air quality monitoring. *Medical Engineering & Physics*, 35(2), pp.231–235. DOI: 10.1016/j.medengphy.2011.10.011.

Zagreus, L., Huizenga, C., Arens, E. & Lehrer, D., 2004. Listening to the occupants: a Web-based indoor environmental quality survey. *Indoor Air*, 14(Suppl 8), pp. 65–74. DOI: 10.1111/j.1600-0668.2004.00301.x

Zampolli, S., Elmi, I., Ahmed, F., Passini, M., Cardinali, G.C., Nicoletti, S. & Dori, L., 2004. An electronic nose based on solid state sensor arrays for low-cost indoor air quality monitoring applications. *Sensors and Actuators, B: Chemical*, 101(1–2), pp.39–46. DOI: 10.1016/j.snb.2004.02.024.

Zangheri, P., Pagliano, L. & Carlucci, S., 2009. Passive house optimization for Southern Italy based on the "New Passivhaus Standard." In C. Broussous, ed. *Act! Innovate! Deliver! : reducing energy demand sustainably, ECEEE 2009 summer study*. Stockholm: European Council for an Energy Efficient Economy.

Zero Carbon Hub, 2015. *Overheating in Homes: the big picture*.

Zero Carbon Hub, 2012. *Understanding overheating - where to start: An introduction for house builders and designers.*

Zhang, J. & Smith, K.R., 2003. Indoor air pollution: A global health concern. *British Medical Bulletin*, 68, pp.209–225. DOI: 10.1093/bmb/ldg029.

Zhao, J. & Carter, K., 2015. Perceived Comfort and Adaptive Process of Passivhaus "Participants." *Energy Procedia*, 83, pp.121–129. DOI: 10.1016/j.egypro.2015.12.202.

Zhou, C., Li, S. & Wang, S., 2018. Examining the Impacts of Urban Form on Air Pollution in Developing Countries: A Case Study of China's Megacities. *Environmental Research and Public Health*, 15(8), p.1565. DOI: 10.3390/ijerph15081565.

Zikova, N., Hopke, P.K. & Ferro, A.R., 2017. Evaluation of new low-cost particle monitors for PM2.5 concentrations measurements. *Journal of Aerosol Science*, 105(November 2016), pp.24–34. DOI: 10.1016/j.jaerosci.2016.11.010.

Zimmerman, A. & Martin, M., 2001. Post-occupancy evaluation: benefits and barriers. *Building Research & Information*, 29(2), pp.168–174. DOI: 10.1080/09613210010016857.