Department of Mechanical and Aerospace Engineering

Detailed simulation of the indoor environment to aid ventilation system design in low energy houses

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Copyright Declaration

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Signed: Maria del Carmen Bocanegra-Yanez Date: 11^{th} June 2018

“All models are wrong but some are useful”

- George Box (1976)

Abstract

According to the International Energy Agency, buildings represent over one-third of total final energy consumption. Thus, a more sustainable future begins with low energy buildings which must combine comfort and function using passive systems and new evolving technologies. Policies to reduce building energy consumption and carbon emissions have been developed worldwide during the last decades. As a consequence, Building Regulations and Standards require more insulated and air tight buildings which may lead to indoor environment issues when the ventilation system is not designed appropriately or it is not used as designed. Poor Indoor Air Quality (IAQ) in low energy buildings is a concern, not only as a result of reduced ventilation rates, but also due to the increased number of materials used in modern building construction. These materials, together with cleaning products and occupants' activities, emit pollutants to the indoor environment and can lead to health problems.

Detailed building modelling and simulation can provide an indication of building performance and furthermore, it can be used to assess indoor environment issues. This research is focused on the variability of overheating risk and poor IAQ at different locations in the building at different times. The impact that different pollutant sources and ventilation strategies has on the distribution of thermal comfort levels and IAQ in low-energy houses has been assessed through a modelling study using the detailed thermal simulation program, ESP-r. CO_2 is commonly used as a proxy for IAQ, but a novelty of this research is the integrated analysis of distribution for other pollutants, specifically formaldehyde, $PM_{2.5}$, PM_{10} and nitrogen dioxide. A model was created based on monitored data from a Passivhaus development in Scotland. Acceptance criteria for calibrating the model were defined, addressing the current absence of specific guidelines for model calibration based on the monitored indoor environment. Then, a review of current literature of indoor pollutants was undertaken and source emission models were implemented in ESP-r making use of the available published literature, with release rates as a function of the prevailing temperature and humidity. Different scenarios were defined to investigate specific design questions and common ventilation issues regarding the indoor environmental quality (IEQ). Ventilation regimes included natural ventilation, mechanical ventilation and mechanical ventilation with heat recovery options. These scenarios were compared in terms of energy demand, plus temporal and spatial variation of indoor environment metrics (thermal comfort and IAQ).

The general conclusion arising from the analysis is that, contrary to the usual assumption of even distribution of the indoor environmental conditions, there can be significant variations in the internal distribution. Important factors are number and location of occupants and the movement of air within the building. The results demonstrate that detailed modelling and simulation can predict IEQ issues and help to design ventilation strategies in low energy houses. Although this study was focused on climate representative of conditions in Scotland, similar variations would be expected in other climates.

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Chapter 1. Introduction

This chapter sets the context and background of the research presented in this thesis. The aim of the research and the specific objectives are defined, followed by the methodology and the general structure of this thesis.

1.1. Background

To reduce building energy consumption and carbon emissions, Building Standards require more insulated and airtight buildings, which may lead to a poor quality indoor environment if the ventilation provision is not designed appropriately. Indoor Environmental Quality (IEQ) refers to all the environmental conditions inside a building that affect its occupant's comfort, health and productivity. The metrics that define the IEQ can be summarised in five groups as shown in Figure 1.1.

Figure 1.1: Basic metrics of the Indoor Environmental Quality (IEQ) (Angelova, 2016)

Many energy performance standards have arisen to promote energy consumption reduction in buildings through different measures. Passivhaus (PH) is probably the most worldwide known low energy building standard since its foundation in Germany in the early 1990s (Building Research Establishment, 2011). The PH standard is based on reducing the energy demand needed for heating and cooling by the use of passive measures such as high levels of insulation, air tightness and control of solar gains. Apart from its obvious benefits reducing energy consumption and the environmental impact of buildings, the PH standard can lead to health risks due to noise from installations, poor Indoor Air Quality (IAQ) or overheating according to Hasselaar (2008).

Houses built to the PH standard are not the only ones with rising concern regarding IEQ. There have been studies reporting that IEQ in PH is comparable or better than conventionally new-built houses in Sweden due to the high air changes per hour (ach) achieved by the mechanical ventilation (MV) system (Langer et al., 2015). Furthermore, recent studies have monitored the indoor conditions in new-built dwellings to investigate possible health impacts from energy efficiency improvements in homes and found poor IEQ as a result of poor design, construction and operation of ventilation systems (Cartwright Pickard Architects and MEARU, 2015; McGill et al., 2017, 2015; Sharpe and Charles, 2015).

Phillips and Levin (2015) did a review of IEQ studies in low-energy residential buildings in order to highlight the current research needs. The study concluded that the main research gaps are: pollutant sources, human behaviour and integrated whole-building design. Problems in the design process were also highlighted, by Tuohy and Murphy (2014) after reviewing several study cases, as the main reason for discomfort and increased energy demand in new and renovated buildings.

1.1.1. Ventilation

Ventilation is the change of air in buildings by introducing fresh air and/or extracting the polluted one. The fresh air can either enter the building intentionally through openings (windows, doors and vents) and fans; or unintentionally through cracks or gaps in the construction. The former one is called ventilation, while the latter one is called infiltration. In order to reduce the heat losses, infiltration needs to be minimised. Thus, low-energy buildings are becoming very airtight and the adequate design of the ventilation system is becoming increasingly important. Good ventilation is essential to reach comfort inside buildings since excessive heat, moisture and contaminants may be removed. Moreover, the ventilation system needs to be controlled properly to avoid preventable heat losses.

1.1.2. Indoor Air Quality

IAQ can be defined as the characteristics of the air inside buildings which impact occupants' health and comfort (EPA, 2017). According to the EnVIE project report "Co-ordination Action on Indoor Air Quality and Health Effects", UK is the European country with worst IAQ-related health effects, like asthma (Birket, 2012).

Poor IAQ in low energy buildings is a concern since these buildings are very airtight and therefore, infiltration rates are significantly reduced. An example of low-energy houses where IAQ problems were found is the three PH dwellings monitored by McGill et al. (2014) in England, which had operation and maintenance issues of the Mechanical Ventilation Heat Recovery (MVHR) system. Conversely, new built houses with good IAQ may also be found, like the houses investigated by Langer et al. (2015), where the MV ensured high ventilation rates. Concern about these issues is increasing nowadays but it is still not fully addressed by Building Standards, which require minimum background ventilation rates but do not include compulsory concentration limits for different pollutants.

1.1.3. Overheating

Nowadays, overheating is a concern even in places with a temperate climate, like the UK. Some examples can be found in the Dormont Park Passivhaus Development in Scotland, where significant overheating was recorded, even during winter periods (MEARU, 2015; Morgan et al., 2017), and in Coventry where 18 out of 25 flats built to the PH standard failed the overheating criteria of the standard (Sameni et al., 2015).

High indoor temperatures do not cause only thermal discomfort, but they can also diminish night rest and even cause death in high-risk individuals, like the elderly. Heat-related mortality in the UK is currently around 2,000 deaths per year and it is expected to increase 70 % by 2020 and 540 % by 2080 (AECOM, 2012; Vardoulakis and Heaviside, 2012). This increase will be due to climate change and ageing in the population (Vardoulakis et al., 2014).

1.1.4. Building modelling and simulation

Building modelling and simulation can predict the performance of buildings and therefore, it can be used for early design purposes. Traditionally, predictions focused on the energy demand with the intention of minimising it. However, building modelling and simulation could also be used to design appropriate ventilation systems reducing the risk of overheating and poor IAQ.

Detailed studies that address both thermal comfort and IAQ distribution within the building are still scarce. Some examples of recent simulation studies that looked at IEQ are the studies carried by the University College London (Mavrogianni et al., 2014; Symonds et al., 2016; Taylor et al., 2015), where only one pollutant was investigated. This limitation emphasises the lack of integrated tools that could simulate the thermal behaviour and the emission and transportation of several pollutants simultaneously. Therefore, further research in this area is needed.

1.2. Research question

This research examines the question of how important is the use of detailed modelling in predicting IEQ issues in low energy houses and whether this approach is recommended to help decision-making and the design of appropiate ventilation strategies, which focus not only on reducing energy consumption and costs, but also on occupants’ comfort and health.

1.3. Aim and Objectives

The aim of this project is to assess the impact that different ventilation strategies, occupant's behaviour and pollutant sources have on thermal comfort levels and IAQ in low energy houses using dynamic thermal simulation. The program ESP-r was selected for its capability to simulate dynamic variations of indoor environmental conditions, in particular, temperature, relative humidity (RH) and concentrations of different pollutants, in different zones within a building. Moreover, it has been extensively validated (Strachan et al., 2008).

To accomplish this aim, the following project objectives have been defined:

- Development of a detailed model of a low energy house and its calibration using monitored data to confirm that the modelling results are in good agreement with the measured data in terms of the indoor environment (temperature, humidity and pollutant distribution) within various rooms of the buildings.
- Upgrading of ESP-r simulation tool by implementing emission, deposition and resuspension models for different pollutants.
- Identification of scenarios to investigate typical design questions and the impact that common ventilation issues have on the indoor environment.
- Analysis of the simulation results comparing the different options in terms of thermal comfort, IAQ and energy demand levels.
- Recommendations to tackle the IEQ issues investigated.

1.4. Methodology

A well-defined methodology is essential to meet the objectives of the project in an efficient way. The work needs to be divided into small tasks forming a project plan. The methodology defined in this project and the tasks identified are shown in Figure 1.2.

A review of previous studies addressing overheating and IAQ problems in low-energy buildings was carried out first in order to identify limitations and possible solutions needed for further research. This review helped in the definition of scenarios to investigate typical design questions and the impact that common ventilation issues have on the indoor environment. Secondly, a review of common indoor pollutants and the models developed to estimate their concentration was undertaken, concluding with a review of available simulation tools used to model the built environment.

Following this review, three time-dependent models and a detailed model which estimates the emission rate based on physical parameters of building materials, were implemented in ESP-r. In addition, a deposition and resuspension model was also included in the tool. These changes enhanced ESP-r allowing it to accurately model the thermal behaviour of buildings and the concentration of pollutants in different parts of the building at different times taking into account the impact of the indoor environment (temperature, relative humidity, air velocity etc.) on emission rates.

A model was created based on the available constructional information, monitored data of the external and internal conditions over a 2-year period, and detailed occupant diaries. Although calibration is not the main focus of this work, it was necessary in order to get acceptable agreement with measured data, helping to define realistic pollutant scenarios. To calibrate the model, a ranking of the sources of uncertainty according to their influence on the indoor environment was done. In this way, the categories that had a greater impact on the results were prioritised, and their related input variables were the focus of the sensitivity analysis. Thus, these parameters were modified within feasible limits to improve the fit between measurements and predictions. The indoor parameters used for the calibration are temperature and CO_2 concentration in the living room and bedrooms. Calibration acceptance criteria were defined, addressing the current absence of specific guidelines for model calibration based on the indoor environment. After the calibration, RH results were checked and other pollutants (formaldehyde, $PM_{2.5}$, PM_{10} and NO_2) were included in the model, adjusting their sources so the concentrations obtained were in good agreement with those measured in the actual building. As a result of this phase of the research, it was concluded that the low-energy house model developed could be used as a basis for making acceptable predictions of the temporal and spatial variations in indoor environmental quality.

The calibrated model was then modified using a realistic occupancy profile with allocation of occupants and IHG to different spaces at different times of the day. Different scenarios including mechanical ventilation with heat recovery (MVHR) with and without summer bypass, natural and MEV ventilation, with different control strategies were defined. The results gathered from the simulations were the operative temperature, RH and pollutant concentrations (CO_2, formaldehyde, $PM_{2.5}$, PM_{10} and NO_2) in the living room, kitchen and bedrooms. In addition, the heating demand in the whole building was also retrieved for some cases. The simulation results were assessed using the IEQ criteria previously defined, comparing different ventilation strategies under different circumstances.

Finally, a summary of findings and recommendations for further research are presented. Although this study was focused on one specific building, similar conclusions would be expected in other houses. The temperature, RH and pollutants concentration levels will differ from one building to another, but the comparison between different ventilation strategies and controls will still be valid, as this depends greatly on how the building is operated rather than the particular characteristic of the building. Furthermore, the PH standard is getting spread rapidly in the UK with more than 250 certified buildings in 2013 (Passivhaus Trust, 2016). Thus, the Dormont Passivhaus investigated represents well the type of houses that will be built in the future.

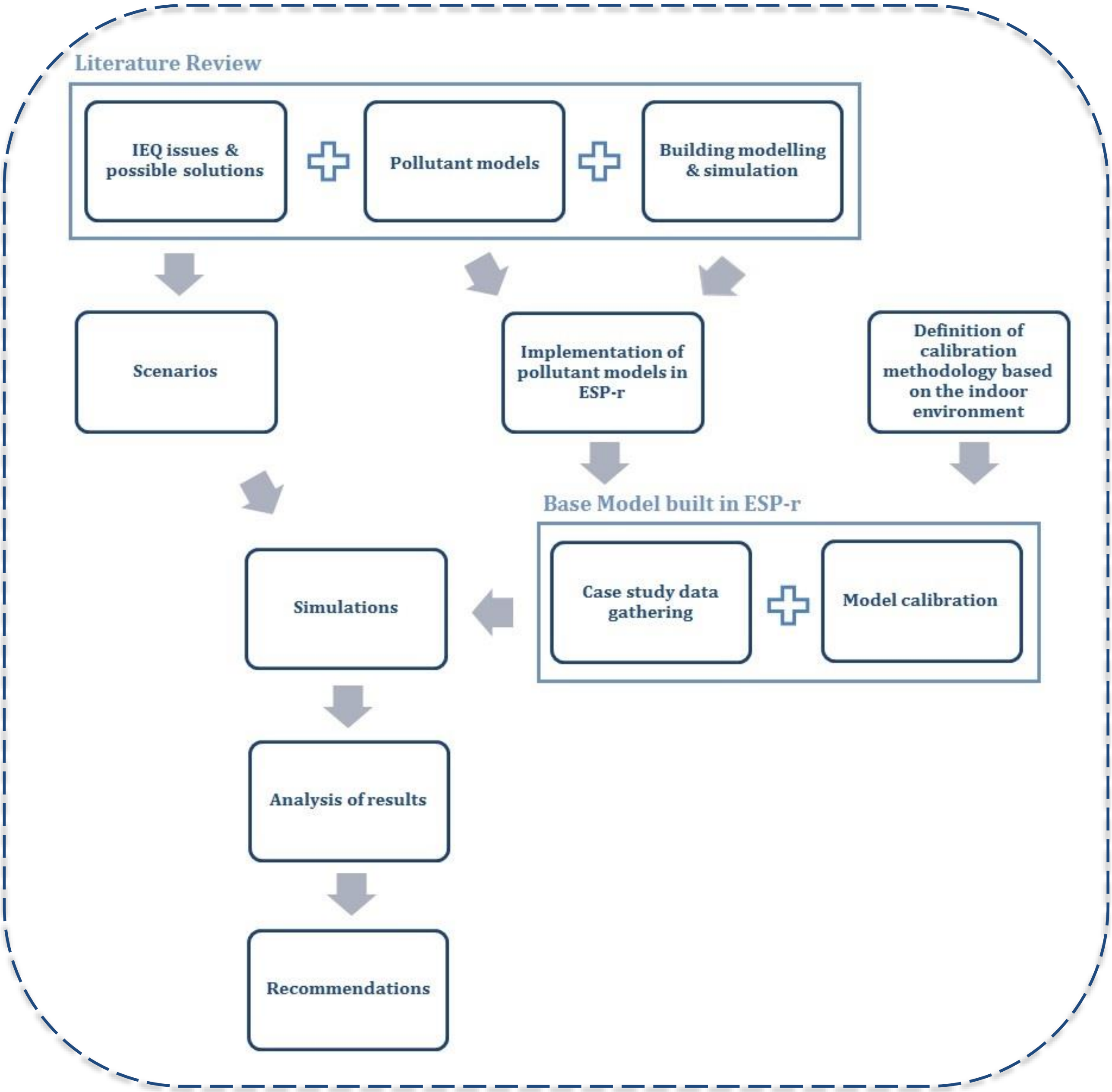

Figure 1.2: Methodology

1.5. Thesis structure

Chapter 2 includes a review of overheating, discomfort and IAQ issues in low-energy buildings and ventilation strategies to mitigate them; pollutant models, including sources, sinks, filtration and chemical reactions; and available building modelling and simulation tools for early building design.

Chapter 3 defines the calibration methodology used to verify that the modelling results are in good agreement with the measured data in terms of the indoor environment (temperature, humidity and pollutant distribution) within various rooms of the buildings.

Chapter 4 describes the main characteristics of the model built using the ESP-r simulation tool determined by the property documentation and assumptions, finishing with the application of the calibration methodology defined in Chapter 3.

Chapter 5 explains the implementation of different emission, deposition and resuspension models in ESP-r, the assumptions made to simplify their implementation and the checks made to identify the impact of these assumptions on the simulation results. Finally, the limitations of these models are highlighted.

Chapter 6 describes the scenarios that have been defined to investigate typical design questions and the impact that common ventilation issues have on the indoor environment. Common assumptions for all scenarios regarding occupancy and internal heat gains (IHG) are described and so are the IEQ criteria used to assess the simulation results.

Chapter 7 analyses the simulation results obtained for the different scenarios described in the previous chapter. The results gathered are the operative temperature, RH and pollutant concentrations (CO_2, formaldehyde, $PM_{2.5}$, PM_{10} and nitrogen dioxide) in the living room, kitchen and bedrooms. In addition, the heating demand in the whole building was also retrieved for some cases.

Finally, Chapter 8 highlights the conclusions regarding the ventilation systems and their control, that arise from the analysis of results presented in the previous chapter. Finally, some recommendations for further work are provided.

Chapter 2. Literature Review

This chapter includes a review of ventilation and indoor environment issues in low-energy buildings. A review of target pollutants and mechanisms involved (sources, sinks, filtration and chemical reactions) is also included. Finally, commonly used building modelling and simulation tools for building design are analysed, focusing on their ability to model IEQ.

2.1. Ventilation

Ventilation is the change of air in buildings by introducing fresh air and/or extracting the polluted one. Ventilation systems have a major role in achieving good IEQ in low-energy buildings since they impact both IAQ and thermal comfort. For that reason, they should be carefully designed, commissioned, operated and maintained.

2.1.1. Ventilation, IAQ and health

The relationship between ventilation rates and Indoor Air Quality (IAQ) and health is clear and has been investigated in many studies. For instance, Wargocki et al. (2002) and Sundell et al. (2011) reviewed 105 and 27 published papers respectively, concluding that increasing ventilation rates reduce the risk of Sick Building Syndrom (SBS) symptoms, house dust mites and allergic symptoms in Northern countries. This was also observed by Fisk et al. (2009), who developed a correlation relating ventilation rates and incidence of SBS syndrome using linear regression. Additionally, Aganovic et al. (2017) did a review of monitored studies in mechanical ventilated residential buildings in Europe, finding that CO_2 and TVOC levels were above the recommended limits of the European Standard EN 15251:2007 (BSI, 2007) if the ventilation rate of the whole building was below 0.5 ach.

However, IAQ is not fully addressed by Building Standards, which require minimum background ventilation rates based mainly on body odour and not on concentration of health-related pollutants, not preventing occupants from suffering health issues (Bluyssen, 2009). Recommended limits for many indoor contaminants that can affect health in the short- and long-term have been defined by the World Health Organisation (WHO) and are highlighted for each of the target pollutants of this study in Section 2.2.1.

2.1.2. Ventilation overview

Building construction types have changed over time making the ventilation regimes to evolve accordingly. Howieson (2005) reviewed historical changes in domestic ventilation by developing models of the five most representative building types in Glasgow. The five construction types, shown in Figure 2.1, were: 19th-century tenement, 1930s semi-detached, 1950s tenement, 1960s multi-storey and 2000s timber frame. Simulations were run for a winter period using ESP-r and the air change rate in the living room was calculated (see Table 2.1). Results show that air change rates have decreased dramatically in the past century. These results agree with the measurements obtained using blower door test in typical dwellings identified in the project. In addition, this trend has been found in other countries, like Norway (Oie et al., 1998). Therefore, an effective ventilation strategy becomes essential in new or retrofitted buildings.

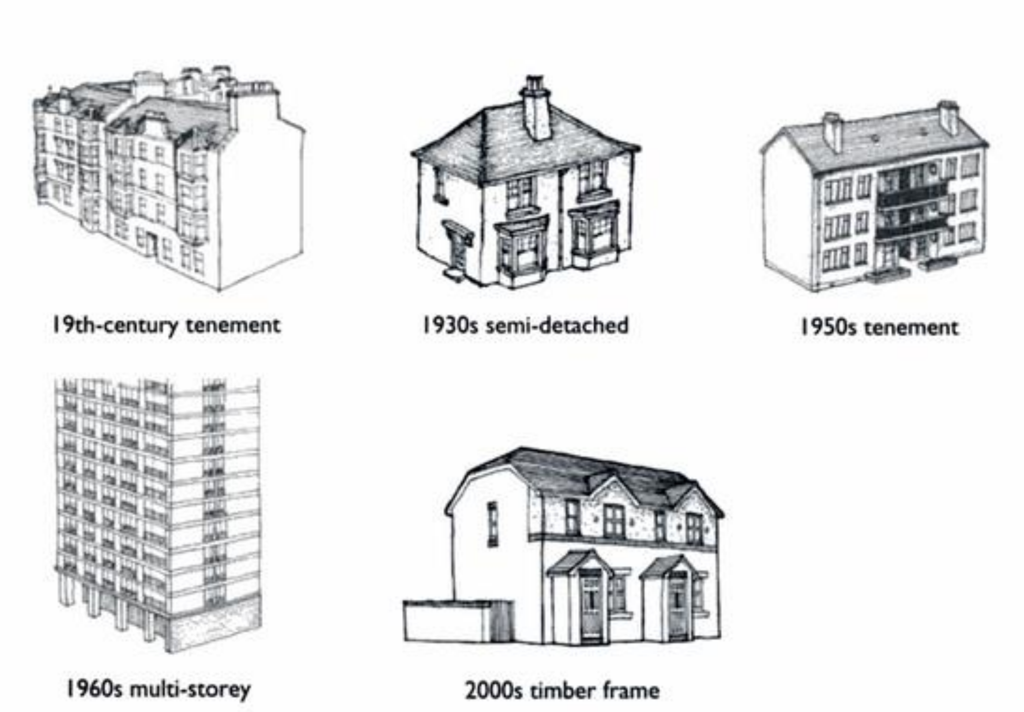

Figure 2.1: Representative Scottish house types (Howieson, 2005)

Table 2.1: Air change rate for the living room models of five representative Scottish house types (Howieson, 2005)

Model	**Average air change rate (h^{-1})**
19^{th}-century tenement	1.66
1930s semi-detached	1.63
1950s tenement	0.83
1960s multi-storey	0.74
2000s timber frame	0.45

Ventilation can be natural, hybrid or mechanical. Natural ventilation occurs due to pressure and temperature differences between two rooms in the building, and between a room and the ambient air. A good building design, placing windows on opposite walls, will help the air to move naturally due to cross-ventilation. In addition, door undercuts are used to enable cross-ventilation in the building even when internal doors remain shut. The ventilation rate will depend on the wind speed and direction, and the magnitude of the openings. In high buildings, the stack effect may be used. This is based on the density difference between hot and cold air. Thus, the ventilation rate will vary mainly depending on temperature differences. Some disadvantages of natural ventilation are the lack of control of the airflow rate, the undesirable heat loss or gain depending on ambient air temperature, the introduction of pollutants in the building from the outside, noise and insecurity.

Natural ventilation is allowed by Building Standards in most countries if the minimum background ventilation rate is “guaranteed”. The ventilation rate required is country specific and can be expressed as ach, m^3/h per person, l/s m^2 floor area or m^3/h depending on number of rooms (Bocanegra-Yanez et al., 2017). For instance, in England and Wales, the minimum ventilation rate is 0.3 l/s per m^2 internal floor area, or depending on the number of rooms, 13 l/s, 17 l/s, 21 l/s, 25 l/s and 29 l/s for 1, 2, 3, 4 and 5 rooms respectively (HM Government, 2010). On the other hand, in Scotland, the minimum opening area is specified as $1/30^{th}$ of the floor area it serves, with a minimum trickle vent area of 12,000 mm^2 (The Scottish Government, 2015).

In the UK, MEV with trickle vents is by far the most common ventilation strategy (Adam-Smith, 2014). Trickle vents are small openings located in the top part of the windows to provide background ventilation. Therefore, they should be always open. However, some studies have found that occupants do not usually know the purpose of these openings and keep them closed. In addition, curtains or blinds can prevent this ventilation system from providing enough ventilation (Dimitroulopoulou, 2012; T. Sharpe et al., 2015; Sharpe et al., 2014). T. Sharpe et al. (2015) estimated the ventilation rates in the main bedroom of 40 naturally ventilated new-built dwellings in Scotland using measured CO_2 concentrations and occupants’ surveys. The average ventilation rate obtained was 0.7 ach. However, the ventilation rate of 42 % of the dwellings was lower than 0.5 ach.

Mechanical ventilation is induced by the use of supply and/or extraction fans. This type of ventilation, when functioning as designed, has the advantage of supplying the correct ventilation rate independently of weather conditions. Moreover, this system allows for the inclusion of filters limiting the pollution that enters the building from the outside, and the inclusion of a heat exchanger to recover heat from the polluted air, leading to significant energy savings. For this reason, MVHR is required by low-energy standards like PH. Despite its benefits, MVHR is not fully accepted in many countries like China, France or the UK (Bocanegra-Yanez et al., 2017), because the technology is not completely mature and presents several shortcomings. Some shortcomings are excessive noise, lack of summer bypass, dirt in ducting, high capital cost, spatial requirements, inadequate commissioning and poor maintenance (Balvers et al., 2012; Bocanegra-Yanez et al., 2017; Sharpe et al., 2016).

There have been a number of studies reporting measured ventilation rates in dwellings. Dimitroulopoulou (2012) and Aganovic et al. (2017) did a review of previous ventilation studies in Europe, concluding that ventilation rates in European dwellings are generally poor, with ventilation rates usually under 0.5 ach.

Sharpe and Charles (2015) monitored twenty dwellings in London which are representative of new-built dwellings in the UK. The ventilation rates measured are shown in Table 2.2 and they ranged from 0.07 to 0.40 l/s m^2 floor area for extract and 0.13 to 0.34 l/s m^2 for supply, with 65 % of the dwellings not complying with the minimum ventilation rate of 0.3 l/s m^2 required by the Building Standards. It can be seen that low extract flow rates are higher for MVHR compared to MEV. However, boost extract flow rates are similar in both ventilation systems, being slightly higher for MEV.

Table 2.2: Ventilation flow rates of typical new-built dwellings in the UK (Sharpe and Charles, 2015)

			Extract flow rate (l/s m^2)		**Supply flow rate (l/s m^2)**	
			Low	**Boost**	**Low**	**Boost**
Ventilation	**MVHR**	**MIN**	0.11	0.15	0.13	0.17
		MAX	0.35	0.37	0.31	0.34
	MEV	**MIN**	0.07	0.18	-	-
		MAX	0.24	0.40	-	-

2.1.3. Ventilative cooling

The use of ventilation to reduce overheating risk inside buildings is called ventilative cooling (Heiselberg and Kolokotroni, 2017). There have been many studies that have investigated and/or quantified the impact of ventilative cooling on the indoor environment and energy reduction associated with it through modelling and monitoring studies (e.g. Barbosa et al., 2015; Givoni, 2011, 1992; Justo Alonso et al., 2015; Mavrogianni et al., 2011; Santamouris et al., 2007). However, ventilative cooling is not fully addressed by building standards and its application in domestic buildings is still limited.

As part of the recent IEA EBC Annex 62 project entitled "Ventilative Cooling" (International Energy Agency, 2017), a review of the state of the art of ventilative cooling practice was carried out (Kolokotroni and Heiselberg, 2015). This review included potentials and limitations of ventilative cooling, its inclusion in regulations, tools available for its calculation and case studies where it has been applied. These case studies consisted of 26 buildings, out of which only six were residential buildings. The review concluded that an appropriate control strategy and occupant's behaviour were crucial to ensure comfort and good IAQ inside buildings.

Night cooling is generally claimed as the main strategy to reduce indoor temperatures by cooling the thermal mass of the building (AECOM, 2012; Foldbjerg et al., 2015; Heiselberg and Kolokotroni, 2017; Santamouris et al., 2007; Seppänen and Fisk, 2004). However, in buildings with light thermal mass, this effect decreases and in some cases it may not have any positive impact (Justo Alonso et al., 2015). In addition, the effectiveness of this measure is determined by the ambient temperature, being more beneficial in climates with large variations of the ambient temperature during the day (Givoni, 2011).

Ventilation can also enhance thermal comfort by increasing the air velocity (Seppänen and Fisk, 2004). Figure 2.2 shows the increase in operative temperature that would be accepted as comfortable depending on the air velocity. This is particularly beneficial in hot humid climates, since the evaporation from the skin is increased and the wet skin effect reduced (Givoni, 2011; Santamouris et al., 2007). On the other hand, increased air speeds can create discomfort due to draughts. HVAC designers are generally advised to keep the air velocity below 0.2 to 0.25 m/s although higher velocities may be acceptable in some circumstances (John, 2011). Nonetheless, other authors stated different ranges for recommended air velocities. Therefore, the optimum air velocity for thermal comfort is still disputable (Santamouris et al., 2007).

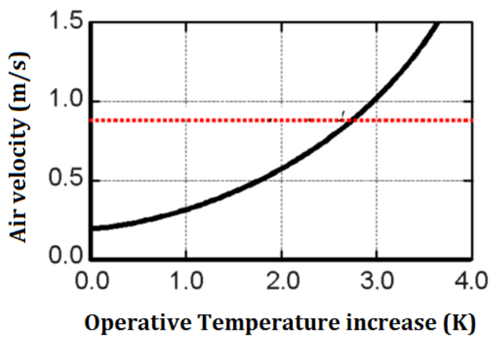

Figure 2.2: Air speed required to increase the operative temperature (BSI, 2005)

2.2. Indoor Air Quality

IAQ can be defined as the characteristics of the air inside buildings which impact occupants' health and comfort (EPA, 2017). Building Standards require more airtight buildings to reduce their energy consumption and carbon emissions but they may also have undesirable consequences, like poor IAQ, if the ventilation provision is not designed appropriately.

In addition to the reduced ventilation rates, the increased number of materials used in modern building construction and furniture (Raw, 1992; Woolley, 2017) together with cleaning products and occupants' activities, emit pollutants to the indoor environment and can lead to health problems. An example of a daily activity that can impact the indoor environment is passive indoor drying, which increases the indoor humidity, intensifying the growth of mould and dust mites (Porteous et al., 2014).

The most common proxy used to assess IAQ is carbon dioxide (CO_2) which is easy and inexpensive to measure. Typical CO_2 concentrations in the environment are around 400 parts per million volume based concentration (ppmv) (IAQ UK, 2015). An indoor concentration of CO_2 should be lower than 1000 ppmv to ensure a comfortable and healthy environment. This limit was first set by Pettenkofer in 1858 and many authors have supported this as an indication for good IAQ afterwards (Sundell, 2004). However, there are concerns about considering CO_2 as a good proxy for good IAQ. According to the Scientific Committee on Health and Environmental Risks (SCHER), indoor air may contain over 900 chemicals, particles, and biological substances that could harm health (Awbi, 2015). Therefore, although positive correlations between CO_2 and other pollutants have been found (Ramalho et al., 2015), evaluating IAQ based only on one parameter could lead to a misleading indication of good IAQ.

There have been several attempts to define a unique IAQ index based on several pollutants. However, an agreed index that compiles information of all the most important pollutants is still missing. One attempt was the Indoor Air Pollution Index (IAPI) proposed by Sofuoglu and Moschandreas (2003). This index is based on eight pollutants: bacteria, carbon monoxide (CO), CO_2, formaldehyde, fungi, $PM_{2.5}$, PM_{10}, radon, and total volatile organic compounds (TVOC). A benefit of the IAPI is that it relates well to occupants' symptoms but it has the drawback of being sensitive to the number of pollutants used in its definition. A more recent study by Salis et al. (2017), as part of the Subtask 1 of the IEA-EBC Annex 68 research project, also tried to define a single IAQ index. However, the authors finally proposed three different indices to assess the risk of short and long-term exposures, highlighting the complexity of defining a sole metric. The IEA-EBC Annex 68 project entitled “Indoor Air Quality Design and Control in Low Energy Residential Buildings” started in 2015 and its duration is five years. The main objectives of this project, which are very relevant to the research in this thesis, are:

- To deliver a scientific foundation for the optimal design and operation of low-energy buildings which guarantee minimum energy consumption and very high standards regarding indoor environmental quality

- To gather pollutant emission data from materials under different temperature and humidity conditions

The project is divided in five different subtasks:

1. Defining the metrics
2. Pollutant loads in residential buildings
3. Modelling - review, gap analysis and categorization
4. Strategies for design and control of buildings
5. Field measurements and case studies

Subtask 1 has been completed and the other subtasks are still ongoing, finishing at the end of 2018, when the reporting stage of the project begins.

There are mainly three approaches to reduce indoor pollutant concentrations: source control, increased ventilation rates and air purification (Al horr et al., 2016; BSI, 2017; Kolarik and Rusaounen, 2015). The first one focuses on reducing the emissions inside buildings using, for example, low-emission certified materials. The second approach is based on eliminating the pollutants using ventilation, supplying fresh air to the living room and bedrooms, and extracting the polluted air from the wet rooms (kitchens, bathrooms and utility rooms). The third approach, air purification, includes the use of filters and other cleaning devices. For instance, formaldehyde can be absorbed by certain indoor plants (Kim et al., 2008) or can react with metal oxides (Sekine, 2002). In addition, UV lights and negative air ionization can be used to remove airborne bacteria like tuberculosis (TB) (Escombe et al., 2009).

2.2.1. Target pollutants

There are a huge number of pollutants that can be found in the indoor environment. These contaminants include CO_2, CO, sulphur dioxide (SO_2), nitrogen oxides (NOx), volatile organic compounds (VOCs), particulate matter (PM), radon, etc. A review of commonly found pollutants and their impact on health is needed in order to prioritise the most relevant pollutants for the residential buildings. This is the idea behind Method 2 of the recently published British Standard ISO 17772-1:2017 (BSI, 2017), which includes three methods to define the design parameters to ensure good IAQ. Thus, Method 2 provides the required ventilation rate to dilute the "most critical or relevant pollutant" identified.

Crump (2013) did a general review of pollutants based on previous literature (see Table 2.3). However, a list of specific pollutants of concern in domestic buildings was not provided.

Table 2.3: Sources and types of indoor air pollution

Source	Main pollutants
Combustion of fuel	Carbon monoxide, NOx (i.e. nitrogen oxides, including nitrogen dioxide), VOCs, particulates
Tobacco smoke	Carbon monoxide, VOCs, particulates
People	Carbon dioxide, organic compounds
Building materials	VOCs, formaldehyde, radon, fibres, other particulates
Consumer products	VOCs, formaldehyde, pesticides
Furnishings	VOCs, formaldehyde
Office equipment	VOCs, ozone
Outdoor air	Sulphur dioxide, NOx, ozone, particulates, biological particulates, benzene
Contaminated land	Methane, VOCs
Washing and cleaning	Water, VOCs
Animals	Allergens

Djouad et al. (2015) produced a list of pollutants in offices and hospitals according to their acute and chronic risk. These risks were calculated as the ratio of the maximum concentration measured, according to literature data, divided by the exposure limit value (ELV). Similarly, Salis et al. (2017) selected the relevant pollutants for IAQ in residential buildings based on measurements of these pollutants in low-energy buildings and their ELVs for the short- and long-term. According to this, the relevant pollutants for the long-term exposure were: acetaldehyde, alpha-pinene, benzene, formaldehyde, naphthalene, NO_2, PM_{10}, $PM_{2.5}$, radon, styrene, toluene and trichloroethylene. Regarding short-term exposure, the relevant pollutants were: CO_2, formaldehyde, NO_2, PM_{10}, $PM_{2.5}$, radon and total volatile organic compound (TVOC). Finally, the authors included also mould for its proven effects on health.

Looking at the previous lists, it can be seen that the relevant pollutants for both, short- and long-term exposure were: formaldehyde, NO_2, PM_{10}, $PM_{2.5}$, radon and mould. Therefore, these are, in principle, the target pollutants for the present study. In addition, CO_2 was included for its extended use as IAQ proxy. TVOC is also widely used in IAQ studies. However, as formaldehyde is already included within the target pollutants, as it is relevant for both short- and long-term exposure, it is considered a good proxy for VOCs and TVOC is not considered in this study.

Carbon dioxide (CO_2)

Despite the current discussions about CO_2 being considered an indoor pollutant or not, there have been studies that found that, at certain levels, it may impact health causing drowsiness, dizziness, headaches, nauseas or breathlessness (Vural, 2011). Therefore, in this study, CO_2 is considered an indoor pollutant. In addition to these health effects, high levels of CO_2 can have an economic consequence as stated by Satish et al. (2012), who found that *"the direct impacts of CO_2 on performance […] may be economically important"*. Typical CO_2 concentrations in the environment are around 400 ppmv (IAQ UK, 2015) and its main source inside buildings come from their occupants. The emission rate is directly proportional with the activity level or metabolic rate. Maximum CO_2 concentrations of 5000 ppmv (8-hour reference period) and 15000 (15-minute reference period) are recommended by the Health and Safety Executive (HSE, 2011). However, a maximum CO_2 concentration of 1000 ppmv is generally accepted as indicative of good ventilation level.

Formaldehyde

Formaldehyde is a recognised carcinogen (NTP, 2016; WHO Regional Office for Europe, 2010) and it can be found in common products such as adhesives, cleaning fluids, wood furniture, carpets, plastics and cosmetics. In addition, it may be released from burning candles or incense. One of the main sources is attributed to wood products due to their content of urea-formaldehyde resin (Raw et al., 2004). Formaldehyde emission rate decreases with time as the concentration in the material decreases, and it increases with increasing temperature and RH (Corbey and Loxton, 2017). The ambient concentration of formaldehyde is usually from 1 to 4 $\mu g/m^3$ and its recommended limit to avoid short-term health problems is 0.1 mg/m^3 (30-minute average concentration), which will prevent *"sensory irritation in the general population [and] will also prevent long-term health effects, including cancer"* (WHO Regional Office for Europe, 2010).

Mould

Mould grows on internal surfaces or the structure of a building if there is enough moisture. According to CIBSE Guide A (2015) if the RH is above 80 % for less than two hours a day, and it does not stay above 70 % for long periods, there is no risk of mould growth. Mould is associated with respiratory problems such as asthma and allergies (WHO, 2009) and it is incentivised by fuel poverty practices like inadequate heating to avoid costs (R. A. Sharpe et al., 2015). The economic impact of this issue in the USA was estimated by Mudarri and Fisk (2007), who found that *"of the 21.8 million people reported to have asthma in the USA, approximately 4.6 million cases are estimated to be attributable to dampness and mould exposure in the home"*, leading to an annual cost of approximately $3.5 billion.

Nitrogen dioxide (NO_2)

NO_2 is a combustion product and it can enter the building from outside due to car engine combustion, for example, or it can be generated indoors by activities such as cooking, smoking or heating with gas stoves (Mawditt, 2007). Studies have shown pulmonary problems in asthmatic individuals for short-term exposure. However, difficulties exist in identifying the long-term health effects related to NO_2 since this is usually found together with other combustion products. Despite this, the WHO Guidelines (World Health Organization, 2006) recommends the following concentration limits to protect occupants against short- and long-term adverse health effects:

- 40 µg/m^3 annual mean
- 200 µg/m^3 1-hour mean

Particulate Matter (PM)

PM is usually divided in categories according to particle size. PM_{10} is defined as the particles with diameter less or equal to 10 µm. Similarly, $PM_{2.5}$ refers to the particles with diameter less or equal to 2.5 µm, and so on (Sykes, 2016). PM is released by mechanical and combustion processes (World Health Organization, 2006). PM, especially those of small diameter like $PM_{2.5}$, have demonstrated to impact the health in the short- and long-term, as they can penetrate into the lungs creating respiratory and cardiovascular issues (WHO, 2014). The Committee on the Medical Effects of Air Pollutants (COMEAP) estimated that *"a pollution reduction of 1 µg/m^3 of $PM_{2.5}$ would lead to an increased UK total survival of approximately 4 million life years, or 20 days increased life expectancy from birth"* (Committee on the Medical Effects of Air Pollutants, 2010), which highlights the huge health impact of this pollutant. WHO Guidelines (World Health Organization, 2006) were defined for PM_{10} and $PM_{2.5}$ concentrations in order to avoid their associated health effects.

$PM_{2.5}$:

- 10 µg/m^3 annual mean
- 25 µg/m^3 24-hour mean

PM_{10}:

- 20 µg/m^3 annual mean
- 50 µg/m^3 24-hour mean

Radon

Radon is a radioactive gas associated with lung cancer, leukaemia and genetic damage (Al-Zoughool and Krewski, 2009). It is estimated that *"9 % of all lung cancer cases in Europe are attributable to Radon (8 % of IAQ DALYs)"* according to Jantunen et al. (2011). The definition of DALY (Disability-Adjusted Life Year) is *"one lost year of healthy life"* and it is the *"sum of the Years of Life Lost (YLL) due to premature mortality in the population and the Years Lost due to Disability (YLD) of people living with the health condition or its consequences"* (WHO, 2018).

The main sources of radon in residential buildings are soil gas, building materials, and tap water (Bruno, 1983). Chung et al. (2016) reviewed the current guidelines for radon, highlighting that in EU countries the threshold is set up to 400 Bq/m^3 for existing dwellings and 200 Bq/m^3 for new dwellings. Public Health England (PHE) defines as "radon affected areas" as those with 1% chance or more of having a radon concentration of 200 Bq/m^3 or above (Miles et al., 2007). These areas are shown in an interactive map for the entire UK territory and have been published in three indicative atlases of radon: Scotland, England and Wales, and Northern Ireland.

2.2.2. Sources

Emission models

Pollutants may be emitted from indoor materials, cleaning products, combustion processes, etc. To estimate these emission rates, many models have been developed and they can be classified into three main categories:

1) Steady-state emission models

2) Time-dependent models

3) Detailed models

The models in the first two categories are simple and easy to implement. They are usually developed using regression analysis of chamber test data (Liu and Little, 2012). Their main advantage is that they require less specific parameters than more detailed models, and these parameters are easily found in the literature, for example, in the PANDORA (a comPilAtioN of inDOor aiR pollutAnt emissions) database (Abadie and Blondeau, 2011). This database was created in 2011 and it has been updated with new available data since then. It compiles emission data of gases (96.5 %) and particles (3.5 %), containing and extending previous databases, which mainly focussed on emission of VOCs from building materials. Example of these previous databases are SOPHIE (SOurces of Pollution for a Healthy and comfortable Indoor Environment) (Bluyssen et al., 2000), MEDB-IAQ (Material Emission DataBase and Single-Zone IAQ Simulation Program) (Zhang et al., 1999), and the U.S. Environmental Protection Agency (EPA) database (U.S. EPA, 2016). The SOPHIE database is used in the IA-QUEST tool (2011), while the latter two databases are used in CONTAM (Dols and Polidoro, 2015).

Regarding the third category, detailed models which estimate the emission rate based on physical parameters of building materials, their main advantage is that they are able to take into account the impact of the indoor environment (temperature, RH, air velocity etc.) on the emission rate. Previous studies have found that indoor environment conditions have a significant impact on formaldehyde and other VOCs emissions (Haghighat and De Bellis, 1998; Liang et al., 2014; Liu and Little, 2012). Consequently, these models may obtain a better level of accuracy when indoor conditions differ from the fixed chamber test conditions used in more simple models.

Resuspension

Resuspension of particles due to occupants' activities such as walking or cleaning is of great importance to account for the actual PM exposure indoors. According to Ferro et al. (2004), activities like blanket folding are responsible for higher personal exposure due to the proximity to the source. This phenomenon is called 'personal cloud', where air around occupants' presents a higher concentration of particles than the air in the rest of the house due to resuspension (Samuel, 2006). A dynamic model that takes into account the resuspension mechanism is the one used in CONTAM. This model was implemented in the version 3.0 of the tool in 2010. As inputs, it requires the resuspension area and resuspension rate. However, resuspension rates as a function of different activity levels, particle size, air velocity, etc. are still missing. More detail on this model is given in Chapter 5.

Desorption

Pollutants can be emitted to the indoor environment from material surfaces where they were previously adsorbed. The adsorption/desorption behaviour will depend on different factors such as chemical properties of the pollutants, physical properties of the materials, temperature, humidity and air velocity (Zhang et al., 2002).

2.2.3. Sinks

Deposition

Deposition of particles and gases on indoor surfaces is very important in the estimation of pollutant concentrations indoor. The deposition rates of gases will depend on the material surfaces and the environmental conditions (temperature and humidity) (Grøntoft and Raychaudhuri, 2004). The deposition of particles may be governed by several mechanisms. Depending on particle size, one mechanism may impact the deposition rate more than others. Deposition of ultrafine particles (particles with diameter less or equal to 0.1 µm) is mainly influenced by Brownian diffusion, while the deposition of larger particles is determined by interception, impaction and gravitational settling (Hodas et al., 2016; Nazaroff, 2004). A regression model to estimate the deposition rate in relation to particle size was developed by Riley et al. (2002) (see Figure 2.3). For this model, least-square regression was used to fit experimental data from previous studies. In addition to particle size, ventilation conditions, room turbulence, surface-to-volume ratios, and room surface orientations will also vary the deposition rate. El Orch et al. (2014) investigated the influence of airflow on the deposition rates, estimating that size-dependent deposition rate should be multiplied by 1.7 for windows open "a large amount" and by 1.23 for "a small amount".

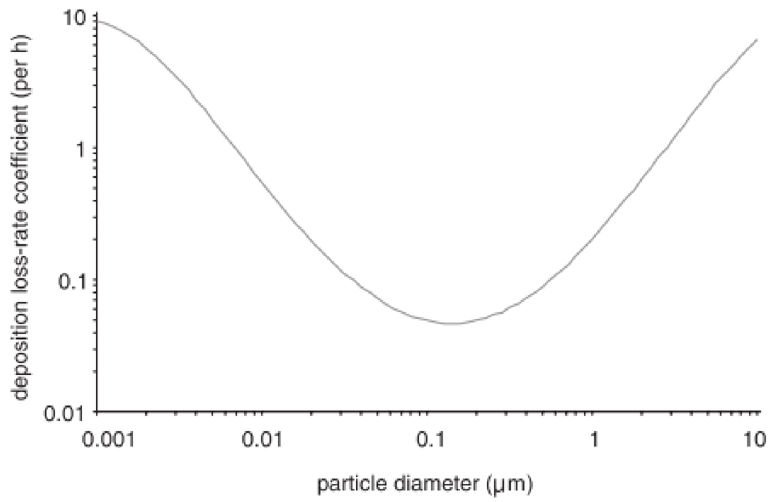

Figure 2.3: Deposition rate coefficient as a function of particle size (Nazaroff, 2004)

Adsorption

Studies have found that adsorption and desorption phenomena can have a significant impact on IAQ in some circumstances and therefore, should be taken into account (Huang et al., 2006). As mentioned before, the adsorption/desorption behaviour will depend on different factors such as chemical properties of the pollutants, physical properties of the materials, temperature, humidity and air velocity (Zhang et al., 2002).

2.2.4. Filtration

Increasing the ventilation rate is not always beneficial for IAQ and occupants' health. In areas near busy roads, for example, outside air may be more polluted than indoors. Therefore, filters constitute a crucial part of ventilation systems. Sublett et al. (2010) did a review of previous studies, finding evidence of air filtration reducing the concentration of particles in the indoor air. However, filters have to be designed and maintained properly in order to be effective (Zhang et al., 2011). A reason for this is that dirty filters can lead to chemical reactions in the presence of ozone (Buchanan et al., 2008; Clausen, 2004).

There are two types of filters depending on the target pollutant: air filters and gas-phase filters. The latter one is not frequently used in residential buildings (EPA, 2008). Zhang et al. (2011) did a review of the impact of air cleaning devices on IAQ. This extensive review included fifteen articles on laboratory or field studies of filters. The conclusion about this technology was that filtration is one of the most effective technologies removing particles. However, it is less effective for organic and inorganic pollutants.

According to Paul Heat Recovery Scotland (2017a), filters should be cleaned every three to six months and replaced once a year. Typical filter grades used are G4 grade for extract, and G4 or M5/F5 grades for intake, although F7 grade is recommended for the latter. Finally, for the kitchen extract, G3 grade is usually used (Paul Heat Recovery Scotland, 2017a). The efficiency of the different filters is given by Equation (2.1) and Table 2.4 shows the corresponding efficiencies for the different filter grades depending on particle size.

$$E(\%) = \left(1 - \frac{n_i}{N_i}\right) \times 100 \tag{2.1}$$

Where n_i and N_i are the number of particles in the size range "i" downstream and upstream of the filter respectively.

Table 2.4: Initial efficiencies of air filters based on EN 779 (Paul Heat Recovery Scotland, 2017b)

Filter grade	**Particle size**						
	10 µm	**5 µm**	**3 µm**	**1 µm**	**0.5 µm**	**0.3 µm**	**0.1 µm**
G1	40-50%	5-15%	0-5%	–	–	–	–
G2	50-70%	15-35%	5-15%	0-5%	–	–	–
G3	70-85%	35-70%	15-35%	5-15%	0-5%	–	–
G4	85-98%	60-90%	30-55%	15-35%	5-15%	0-5%	–
F5/M5	>98%	90-99%	70-90%	30-50%	15-30%	5-15%	0-10%
F6/M6	>99%	95-99%	85-95%	50-65%	20-40%	10-25%	5-15%
F7	>99%	>99%	>98%	85-95%	60-75%	45-60%	25-35%
F8	>99%	>99%	>99%	95-98%	80-90%	65-75%	35-45%
F9	>99%	>99%	>99%	>98%	90-95%	75-85%	45-60%

The efficiencies shown in Table 2.4 give an idea of filter performance but cannot be assumed as the real-life operation. Filter efficiency may increase as particle load in the filter increases, for example, or it can decrease due to charge loss in electrostatic filters (The British Standards Institution, 2012).

2.2.5. Chemical reactions

Chemical reactions vary the concentration of indoor pollutants by decreasing the concentration of the reactants and increasing the concentration of the products. This may have a significant impact on IAQ under certain circumstances. For instance, high concentrations of ozone will boost oxidation reactions (Weschler, 2004). However, understanding of these processes is still needed due to their complexity (Liu et al., 2004; Uhde and Salthammer, 2007).

2.3. Thermal Comfort

There are six key parameters that influence thermal comfort: mean radiant temperature, air temperature, relative humidity, air velocity, clothing and activity level (or metabolic rate) (Al horr et al., 2016). However, there is not a unique definition of thermal comfort. In 1970, Fanger (1970) developed a method to calculate thermal comfort based on the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD). This method has been widely used and it is the basis of the standard BS EN ISO 7730:2005 (BSI, 2005).

Another method which has gained increasing interest in the past years is the adaptive comfort method (Humphreys and Nicol, 1998), which takes into account the ability of occupants to adapt their behaviour to their environment given sufficient time. This method is applied in the British Standard BS EN 15251:2007 (BSI, 2007) and ASHRAE Standard 55-2013 (ASHRAE, 2013) for buildings with no mechanical cooling. According to these standards, buildings with mechanical cooling should follow the PMV-PPD criteria. However, for buildings in free-running mode, a broader temperature range is allowed as the expectations differ and the occupants can open or close windows and adapt their clothing. According to the British Standard BS EN 15251:2007, the temperature of a room is considered acceptable if it is above or below the comfort temperature (T_{comf}) two degrees for Category I, three degrees for Category II and four degrees for Category III. These categories are shown in Figure 2.4 where dark green corresponds to Category I, medium green to Category II and light green to Category III. T_{comf} is given by Equation (2.2) and the explanation of the different categories is given in Table 2.5.

$$T_{comf} = 0.33\, T_{rm} + 18.8 \tag{2.2}$$

where T_{rm} is the running mean temperature and it is given by Equation ((2.3).

$$T_{rm} = (1-\alpha)\{T_{ed-1} + \alpha T_{ed-2} + \alpha^2 T_{ed-3} \ldots\} \tag{2.3}$$

where, α is the response factor, which is a constant value between 0 and 1, but it is usually assumed as 0.8. T_{ed-1} is the daily mean temperature for the previous day; T_{ed-2} is the mean external temperature for the day before and so on.

Table 2.5: Description of the applicability of the categories used (BSI, 2007)

Category	Explanation
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons
II	Normal level of expectation and should be used for new buildings and renovations
III	An acceptable, moderate level of expectation and may be used for existing buildings
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year

A graphical representation of the comfort zones using the ASHRAE Standard 55-2013 is also shown in Figure 2.4, where the colour bands represent the 80 % (dark blue) and 90 % (light blue) acceptability limits. The 80 % acceptability limit is used for typical applications while the 90 % acceptability limit is recommended when higher levels of comfort need to be achieved, i.e. for health centres where occupants are more vulnerable.

Finally, looking at the horizontal axis in Figure 2.4, it can be derived that the ASHRAE Standard 55-2013 allows the use of the adaptive comfort method if the prevailing mean outdoor temperature is greater than 10 °C and less than 33.5 °C; while the British Standard BS EN 15251:2007 requires the outdoor running mean temperature to be between 10 and 30 °C.

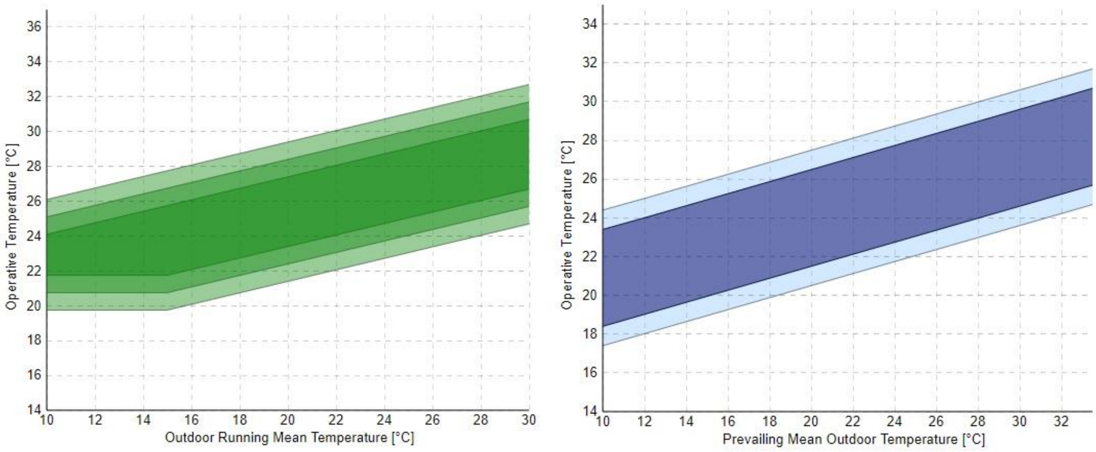

Figure 2.4: Comfort zones using the British Standard BS EN 15251:2007 (left) and ASHRAE Standard 55-2013 (right) (Hoyt Tyler et al., 2013)

The Chartered Institution for Building Services Engineer's (CIBSE) Guide A – Environmental Design (Chartered Institution of Building Services Engineers, 2015) also uses static criteria recommending fixed temperature thresholds for air conditioned buildings (see Table 2.6). However, CIBSE recommends the use of the adaptive comfort temperature defined in Equation (2.2) for natural ventilated free-running homes or homes with MVHR and possibilities for natural ventilation (CIBSE, 2017). The adaptive comfort in residential buildings is assessed by the following criteria:

- CIBSE TM52 Criterion 1 should be met for living rooms, kitchens and bedrooms. This criterion limits the number of hours that the operative temperature can exceed the adaptive comfort temperature by 1 °C or more to 3 % of the occupied time (Nicol and Spires, 2013).

- The operative temperature in the bedrooms should not exceed 26 °C for more than 1 % of the occupied time, assuming the occupied time from 10 pm to 7 am.

Table 2.6: Recommended comfort criteria for air conditioned dwellings (Chartered Institution of Building Services Engineers, 2015)

Room type	Winter operative temperature (°C)	Summer operative temperature (°C)
Bathrooms	20-22	23-25
Bedrooms	17-19	23-25
Halls	19-24	21-25
Kitchen	17-19	21-25
Living rooms	22-23	23-25
Toilets	19-21	21-25

Discussion about the advantages and disadvantages of Fanger's and the adaptive comfort method is an on-going topic which needs further research (Halawa and Van Hoof, 2012; Nicol and Humphreys, 2002; Tsinghua University, 2016).

Another way of calculating discomfort due to high air temperature or overheating is provided by the Appendix P of the Government's Standard Assessment Procedure (SAP) (DECC, 2014), which calculates the expected indoor temperature of the dwelling from June to August and if its average is above 23.5 °C, there is overheating risk. The PH standard defines overheating as the period when indoor temperature rises above 25 °C, and it is calculated by the PHPP (Passive House Institute, 2012).

In places with cold winters, the focus has been placed on reducing the heating needs and discomfort due to cold temperatures. This is the situation in the UK, where deaths due to cold temperatures are higher than deaths due to hot temperatures (Lomas and Porritt, 2017). To avoid this, standards require more insulated and airtight buildings, which reduce the heat losses but can have undesired consequences, like overheating.

It is common to explain overheating issues focusing on this greater level of insulation in new buildings. However, the problem is more complex as there are many factors involved (Bateson, 2015). Some of the reasons why a building may overheat are:

- Light thermal mass
- Uncontrolled heat gains (internal and external)
- Inefficient ventilation

Thermal mass in buildings helps to buffer the indoor temperature as the heat is absorbed into the internal surfaces and released when the indoor temperature drops. The beneficial effect of thermal mass reducing high indoor temperatures during summer has been demonstrated by several studies (Hacker et al., 2008; Lomas and Kane, 2013; Tuohy et al., 2005). However, modern buildings are usually built with light materials which have low thermal mass, like timber-frame, in order to reduce construction and transportation costs (Hoes et al., 2011; Lomas and Porritt, 2017). In addition, new buildings have high levels of insulation to reduce the heating losses through the envelope and to comply with the standards. If the thermal mass is not located between the indoor air and this insulation layer, its efficiency decreases (Hoes et al., 2011; Mavrogianni et al., 2012; Richards Partington Architects, 2012), eliminating the buffering effect and leading to greater temperature peaks.

Heat gains are very important when assessing overheating risks. Internal heat gains (IHG) may come from occupants, appliances, lighting, heat losses from the hot water system, etc. (Zero Carbon Hub, 2012). In the Glasgow House, for example, faults in the insulation of the heating system led to undesirable heat gains (Carr, 2012; Tuohy and Murphy, 2014). These gains can be quite high and their impact increases as buildings get more insulated and air-tight since it becomes more difficult to release the excess heat into the ambient (Bone et al., 2010). Furthermore, heat gains may also come from the exterior due to high ambient temperatures and solar gains if proper shading devices are not in place. This problem gets worse in cities where the ambient temperature is greater due the urban heat island effect (Mavrogianni, 2014).

Finally, inefficient ventilation systems, i.e. MVHR systems with no summer bypass or switched off to prevent noise or running costs, exacerbate the overheating issue. Several studies have found that lack of summer bypass is a common shortcoming of MVHR systems in new buildings (Balvers et al., 2012; Sharpe et al., 2016). In addition, impossibility of cross-ventilation or absence of night ventilation due to noise or security concerns can also worsen the overheating issue (Lomas and Porritt, 2017; Mavrogianni et al., 2013).

In addition to indoor air temperature, discomfort may be caused by low or high RH levels. It is generally accepted that RH should stay between 40 and 60 %. RH levels below 40 % may lead to eye or skin dryness, while levels above 60 % can increase the risk to mould growth and proliferation of dust mites. The upper limit is related to respiratory comfort rather than humid skin comfort, which may allow RH levels near 100 % (Toftum et al., 1998; Toftum and Fanger, 1999).

There are some concerns that MVHR can lead to dry air, where RH levels are generally below 30 %. One example can be found in the Dormont Passivhaus Development, where the air was found to be dry in all monitored rooms during winter periods (MEARU, 2015). In addition, there are several studies that have found that the air is perceived drier when MVHR is used compared to natural or mechanical extract ventilation (MEV) (Balvers et al., 2012; Mlecnik et al., 2012).

2.4. Building Modelling and Simulation

Currently, there are different tools available to model buildings and assess IEQ. They differ in their capabilities and complexity, all of them having advantages and disadvantages.

PHPP, for example, is the official tool that is used for certifying that a house complies with the PH standard, and it has been validated against measured data (Passivhaus Institut, 2014). However, it has limitations. PHPP, as well as other simplified tools, models the entire house as one single zone, where the air is well mixed and the internal heat gains are constant and evenly distributed within the building. This simplification decreases the accuracy of the model when the heat gains are highly localised in certain areas, such as cooking appliances in the kitchen or a number of electronic devices in the living room. Therefore, dynamic simulations are recommended when designing large and complex buildings (Siddall and Grant, 2016). In addition, PHPP follows the quasi-steady monthly method included in the European Standard EN ISO 13790:2008 for the calculation of energy use for space heating and cooling in buildings (Passive House Institute, 2012). Therefore, PHPP is focused on estimating annual energy performance, but it does not account for variation in the indoor environmental conditions in different parts of the house at different times.

There are detailed simulation tools, like EnergyPlus and ESP-r, that include both thermal and contaminant calculations. These tools have the capability to simulate thermal flows in multi-zone models, being potentially more accurate than simplified tools. However, care must be taken when using these tools. Peacock et al. (2010), for instance, conducted a modelling study to predict overheating risks in the UK under future climate assumptions, concluding that overheating will not be an issue in Scotland. The tool used was ESP-r but no airflow network was defined. Therefore, fixed ventilation rates for infiltration, trickle vents and window opening were assumed which is unlikely to happen in reality. In addition, the contaminant modelling in these tools is limited. EnergyPlus Generic Contaminant Model, for instance, can only model one pollutant and therefore, IAQ assessment is restricted to that pollutant. ESP-r, on the other hand, is able to simulate several pollutants at the same time, but the source and sink models are limited, not being able to take into account deposition and resuspension mechanisms, for example.

CONTAM (Dols & Polidoro 2015) is widely used for IAQ and ventilation analysis. However, this program is not a thermal simulation tool and it does not have the capability of calculating the spatial and temporal distribution of temperature within the building, which makes impossible the assessment of overheating risks under different conditions. In addition, temperature can also vary the pollutant emission rates, and therefore, IAQ. A recent modelling study (Liang et al., 2017) introduced a tool, PACT-IAQ, to assess IAQ taking into account the impact of temperature and humidity on emission rates. However, no spatial and time variation of temperature and humidity was reported and constant emission parameters were assumed for the different materials. In addition, another study (Liang and Qin, 2016) used CONTAM to analyse the impact of window/door opening behaviour on IAQ. One of the conclusions was that airflows through openings were unidirectional when there was no temperature difference between rooms, but they were bi-directional when the temperature of the rooms was different. Therefore, taking into account the indoor temperature within the building may have a significant impact on airflows and pollutant transportation.

An attempt to unify the thermal and IAQ capabilities was done by Taylor et al. (2014), who developed PolyPol, a post-processing tool for contaminant transport and decay to use in conjunction to EnergyPlus. This tool presents significant advantages; for instance, it enables the simulation of multiple pollutants at the same time and takes into account temperature and RH on reaction and decay mechanisms. However, the fact that it is a post-processing tool is a main drawback since it is not able to provide feedback to EnergyPlus in order to simulate different control strategies based on IAQ. Another approach is the use of co-simulation, which consists on running two separate programs simultaneously with data exchange between them in each time step. This approach has the benefit of unifying the capabilities of existing programs, like CONTAM and EnergyPlus, Trnsys or CHAMPS-Multizone (Chen et al., 2015; Dols et al., 2016a, 2016b). However, the data exchange procedure between the programs can lead to instabilities and convergence issues and its use might be limited to researchers rather than designers (Dols et al., 2016b; Ng and Persily, 2011).

The previous tools follow the multi-zone approach, assuming the air is mixed within a zone, presenting uniform temperature, RH and pollutant concentrations. This assumption can lead to reasonably accurate results in some cases but it may not be appropriate in others. For instance, CONTAM and ESP-r were validated using measured data from two single-family houses in Ottawa, showing good agreement between predictions and measurements (Haghighat and Li, 2004). However, large zones like open offices, for instance, may lead to different indoor conditions within the same room (Foucquier et al., 2013). In those cases, Computational Fluid Dynamics (CFD) can provide more accurate results since the zone is divided in a number of control volumes. The mesh does not need to be homogeneous and therefore can be reduced in parts where more accuracy is needed, for example, near supply and extract fans, and enlarged somewhere else. An example of the use of CFD to assess ventilation strategies was done by Ekren et al. (2017). In that study, three MVHR configurations were compared changing the location of the supply and extract grills in one classroom for 8 hours. This highlights the main drawback of this approach. It requires great computational capacities and it is time consuming. Therefore, it is unpractical for complex whole-building analysis for long simulation periods (Wang and Zhai, 2016). In addition, CFD modelling requires a great expertise of the modeller since the accuracy of the results will depend on the definition of boundary conditions, selection of the mesh, turbulence model used, etc. Finally, regardless the correct use of CFD modelling, many uncertainties will still influence the accuracy of the results, like furniture layout, movement of occupants within the room, etc.

After this review, ESP-r was selected as the modelling tool for this study for its capability to simulate dynamic variations of indoor environmental conditions in different zones within a building. A multi-zone approach, assuming the air is mixed within a zone, presenting uniform temperature, RH and pollutant concentrations was assumed as it can provide reasonably accurate results when zones are not very large, like in standard dwellings (Wang and Zhai, 2016). In addition, CFD was not considered practical as simulating a whole house during long periods would require excessive time and computational capacity.

2.5. Summary

The main indoor environment issues, specifically overheating and poor IAQ have been discussed, highlighting their importance and common causes. The ventilation strategy used in buildings has a great impact on the indoor environment and can therefore mitigate these issues. Thus, the use of ventilative cooling and the relation between ventilation and IAQ has been reviewed. Furthermore, a review of target pollutants usually found in domestic buildings, including their health effects, sources and guidelines has been conducted. The main source and sink mechanisms that affect indoor pollution have been summarised. Finally, commonly used building modelling and simulation tools for early building design were analysed, emphasising the advantages and disadvantages of each of them. After this review, ESP-r was selected for this study as it provided much of the necessary functionality.

Chapter 3. Calibration methodology based on the indoor environment

This chapter defines the calibration methodology that will be used to verify the modelling results are in acceptable agreement with the measured data in terms of the indoor environment (temperature, humidity and pollutant distribution) within various rooms of the building. The calibration acceptance criteria are defined, addressing the current absence of specific guidelines for model calibration based on the indoor environment.

3.1. Calibration methodology

Once the model is built, it is crucial to investigate the results obtained to make sure the model is reasonable and results are in acceptable agreement with measured data. This is done by model calibration. Many calibration methods have been developed to date, and there are many possible solutions (Kaplan et al., 1990). These can be divided in the following categories (Clarke et al., 1993):

- Calibration based on manual, iterative and pragmatic intervention.
- Calibration based on a suite of informative graphical comparative displays.
- Calibration based on special tests and analytical procedures.
- Calibration based on a technique for automatically adjusting user selected input parameters.

Coakley et al. (2014) did an extensive review of calibration approaches concluding that calibration methods are, at best, based on optimisation techniques such as Bayesian calibration methods and at worst, based on manual change of inputs until an acceptable solution is obtained. In addition, they highlighted that very detailed calibration can provide accurate predictions of building performance. However, these methods usually require a lot of time, effort and expertise.

As mentioned in Chapter 1, model calibration is not the main focus of the present study but a tool to ensure the model is acceptable to investigate IEQ issues in low-energy houses. Therefore, efforts were made to define a pragmatic calibration process. The methodology proposed in the current study is shown in Figure 3.1 and is based on previous methodologies from the literature (Coakley et al., 2014; Raftery et al., 2011; Westphal and Lamberts, 2005) and adapted to fit the current case study. Raftery's methodology, for instance, is based only on measurements and therefore needs to be modified for the cases where measured data is missing. On the other hand, Westphal's methodology is specific for electric end-uses of a building but can also be adapted to be applied to the indoor environment.

3.1.1. Initial model built

The initial model is built following an evidence-based approach (Raftery et al., 2011). It is important to clearly define priorities or "hierarchy of sources" for model inputs as defined in Table 3.1 (Coakley et al., 2012; Yang and Becerik-Gerber, 2015).

Table 3.1: Hierarchy of sources (Coakley et al., 2012; Yang and Becerik-Gerber, 2015)

Hierarchy of sources
1) Continuous measurement (BMS data/sensor data)
2) Spot-measured data, physically verified data, surveys and interviews
3) As-built documents and O&M manuals or derived from measured data
4) Design documents
5) Guides & Standards
6) Default values for a similar type of buildings
7) No available information.

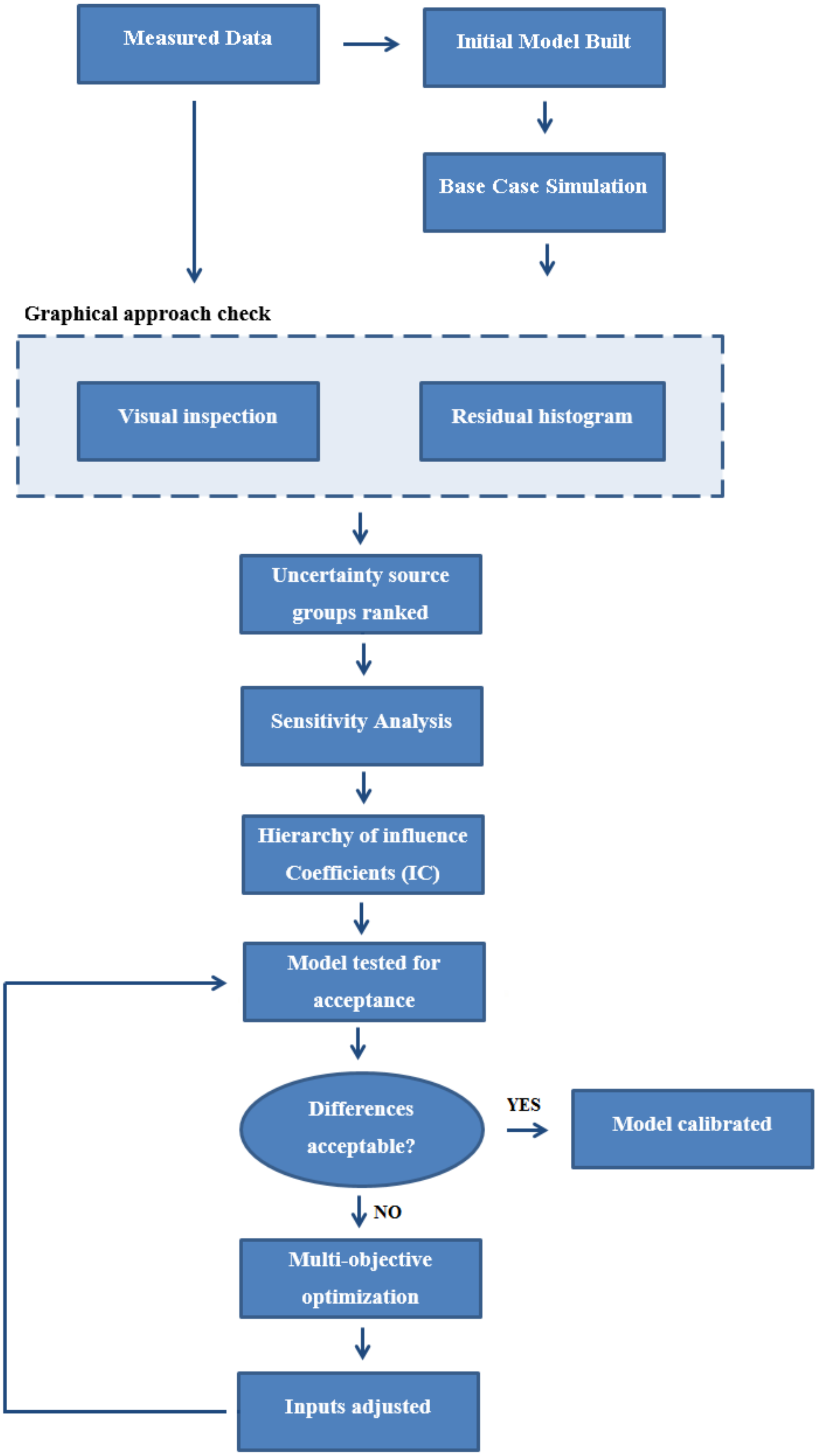

Figure 3.1. Calibration Methodology

3.1.2. Graphical approach check

The graphical checks considered are visual inspection and residual histograms. The visual inspection helps to identify where the greatest discrepancies between the simulated and measured data are. Sometimes there might be an offset between the simulated and measured data or there might be a specific period where the match is worse. The visual inspection could also help to obtain more information about the input parameters of the model. For instance, the minimum CO_2 concentration measured during unoccupied periods (no contaminant sources from occupants' activities) could be assumed to be approximately the ambient CO_2 concentration. Finally, there might be errors in the data measurements. To avoid using those data points in the calibration, short periods when measured data show a very different behaviour from the general trend, with no different conditions to justify it, can be identified and taken out from the calibration study. Regarding the residual histogram, it helps to identify the magnitude and spread of model errors (Royapoor and Roskilly, 2015). The residuals (r_i) are defined as:

$$r_i = m_i - s_i \tag{3.1}$$

where m_i is the measured data and s_i is the simulated data for the instance 'i'.

3.1.3. Uncertainty source group ranked

In this stage, sources of uncertainty are listed and ranked according to their impact on the indoor environment (Westphal and Lamberts, 2005). Thus, the categories that lead to, for example, greater heat gain/losses will require more attention for the temperature calibration, and their related input variables will be the focus of the sensitivity analysis (SA) in the next stage of the calibration process. To simplify the process, only categories with high level of hierarchy (i.e. 5 or more) according to Table 3.1 will be considered for the ranking, as these categories have a greater level of uncertainty.

3.1.4. Sensitivity Analysis (SA)

Next, SA of input parameters related to significant heat and pollutant gains/losses is carried out. There are many SA techniques that could be used. Tian (2013) did a review of different SA methods highlighting their advantages and disadvantages. According to this review, there are two main types of SA: local and global. The local or differential SA focusses on one input at the time and it is very straightforward. The main benefit of this approach is its simplicity. However, the interactions between the different parameters are not considered and only a small portion of the possible range of input values is explored. On the other hand, global SA can consider several parameters simultaneously (Pianosi et al., 2016) but it is more difficult to implement and it usually requires a greater number of simulations (Tian, 2013).

In this case, the local SA approach is used because, as explained previously, the aim of this calibration methodology is not to obtain a highly accurate model but one that can give reasonable results to investigate the indoor environment in low-energy houses. Therefore, the SA is developed changing the input values for each variable under study, following Westphal and Lamberts' methodology (Westphal and Lamberts, 2005). The influence of each parameter is calculated using the Influence Coefficient (IC) defined by Lam & Hui (1996) as shown in Equation (3.2).

$$IC = \frac{\Delta OP \div OP_{BC}}{\Delta IP \div IP_{BC}} \tag{3.2}$$

where ΔOP and ΔIP are changes in output and input, respectively; and OP_{BC} and IP_{BC} are the output and the input base case values.

3.1.5. Hierarchy of Influence Coefficients

Parameters are then sorted from the highest IC to the lowest. This gives the order in which the parameters will be adjusted in order to meet the calibration criteria.

3.1.6. Model tested for acceptance

In order to assess the model, the calibration criteria need to be defined. According to Coakley et al. (2014), there are three main calibration criteria: ASHRAE Guideline14 (ANSI/ASHRAE, 2002), IPMVP (EVO, 2002) and FEMP (U.S. Department of Energy, 2008). However, these guidelines are meant only for energy consumption and not the indoor environment.

Despite the absence of a specific guideline there have been previous studies that have calibrated models based on indoor environment parameters (Foldvary, 2016; Paliouras et al., 2015). These studies used the Coefficient of Variation of Root Mean Square Error (CV RMSE) (see Table 3.2) to assess the model. The criteria they used to consider the model is acceptably calibrated are a CV RMSE less than 5 % for temperature and 20 % for CO_2 concentration and RH.

The calibration criteria to address the current absence of specific guidelines for model calibration based on the indoor environment were defined for the current study. First, a review of common metrics was undertaken in order to find the most suitable metrics.

Metric review and selection

To find the most suitable metrics for this study, a review of some common metrics has been undertaken. According to Yu et al. (2006), quantitative metrics can be divided in three categories: correlation, absolute difference and relative difference. Correlation metrics describe the dependence between two variables, in this case, the simulation and the measured data sets. Absolute difference metrics describe the magnitude and direction of the error between two variables. However, according to Savage et al. (2013), comparing errors using absolute differences for different pollutants can give misleading results since the pollutants' concentrations may be very different and so will be the magnitude of the error. It is useful, therefore, to use relative difference metrics that are normalised and can provide comparable results independently of the pollutants modelled (Savage et al., 2013; Yu et al., 2006). Finally, in addition to the previous metrics, there is also the possibility of combining several metrics creating a new one, which is more complete and can, therefore, provide more information than a single metric. Table 3.2 summarises the metrics reviewed including their definition and brief description of their meaning and key characteristics.

Table 3.2: Metric review

Metric	Definition	Description	Reference
Correlation			
Pearson correlation coefficient (r)	$r = \frac{\sum_{i=1}^{n}(m_i - \bar{m}) \cdot (s_i - \bar{s})}{\sqrt{\sum_{i=1}^{n}(m_i - \bar{m})^2 \cdot \sum_{i=1}^{n}(s_i - \bar{s})^2}}$	It indicates whether there is a linear dependence between two variables, m and s. The correlation is +1 in the case of a perfect positive linear relationship, zero for no relationship and -1 in case of a negative linear relationship.	(Benesty et al., 2009).
Nash-Sutcliffe coefficient (E)	$E = 1 - \frac{\sum_{i=1}^{n}(m_i - s_i)^2}{\sum_{i=1}^{n}(m_i - \bar{m})^2}$	It can be used to quantitatively assess the accuracy of model outputs and it can range from -∞ to 1. The closer E is to 1, the more accurate the model is.	(McCuen et al., 2006)
FAC2	This is the fraction of model predictions where the predicted value is within a factor of 2 of the measured value.	This is a simple metric that can give a rough idea on how good the match between simulated and measured data is.	(Savage et al., 2013).
Absolute difference			
Mean Bias Error (MBE)	$MBE = \frac{\sum_{i=1}^{n}(m_i - s_i)}{n}$	It gives information on the overestimation or underestimation of the model. Positive errors may cancel the negative ones, giving an overall value of MBE, which suggests a good match between the simulated and measured data, contrary to the actual situation.	(Royapoor and Roskilly, 2015)
Mean Absolute Error (MAE)	$MAE = \frac{\sum_{i=1}^{n}\lvert m_i - s_i \rvert}{n}$	The MAE solves the problem of the cancellation effect of the MBE.	(Royapoor and Roskilly, 2015)
Root Mean Square Error (RMSE)	$RMSE = \sqrt{(\sum_{i=1}^{n}(m_i - s_i)^2/n)}$	It is better than the MAE representing the model performance if the error distribution is Gaussian.	Chai and Draxler (2014)
Percentile comparison	The 50 % percentile is the limiting value for 50 % of the population, therefore 50 % of the population will not exceed this value; the 75 % percentile is the limiting value for 75 % of the population, and so on.	The percentiles indicate the magnitude and distribution of a variable. The percentile comparison will give information on the distribution match between two variables.	(Berthouex and Brown, 2002)

Relative difference			
Modified normalised mean bias (MNMB)	$\text{MNMB} = \frac{2}{n}\sum_{i}\left(\frac{s_i - m_i}{s_i + m_i}\right)$	This is a normalised metric which is symmetric regarding over- and underestimation errors. It ranges from -2 to +2.	(Savage et al., 2013)
Normalised Mean Bias Error (NMBE)	$NMBE\ (\%) = \frac{\sum_{i=1}^{n}(m_i - s_i)}{n \times \bar{m}} \times 100$	As for the MBE, the NMBE suffers from the cancellation effect.	(Sun et al., 2014)
Coefficient of Variation of Root Mean Square Error (CV RMSE)	$CVRMSE\ (\%) = 100 \times \frac{\sqrt{(\sum_{i=1}^{n}(m_i - s_i)^2/n)}}{\bar{m}}$	The CV RMSE solves the cancellation effect and the problem of absolute differences when comparing several pollutants.	(ANSI/ASHRAE, 2002)
Normalized mean bias factor (BNMBF)	$B_{NMBF} = s\left[\exp\left(\left\|ln\frac{\sum_i s_i}{\sum_i m_i}\right\|\right) - 1\right]$	This metric has the advantage of being robust while solving the asymmetry of the previous normalised metrics, where increasing overestimation errors tend to infinity while underestimation errors tend to a limited value.	(Yu et al., 2006)
Normalized mean absolute error factor (ENMAEF)	$E_{NMAEF} = \frac{\sum_i \|s_i - m_i\|}{(\sum_i m_i)^{[1+S]/2}(\sum_i s_i)^{[1-S]/2}}$	This metric presents the same advantages as the BNMBF.	(Yu et al., 2006)
Metric combinations			
Inequality coefficient (U)	$U = \frac{\sqrt{\frac{1}{n}\sum(m_i - s_i)^2}}{\sqrt{\frac{1}{n}\sum m_i^2} + \sqrt{\frac{1}{n}\sum s_i^2}}$	This coefficient describes the discrepancies between two variables based on three values: mean, variance and covariance. The use of combined metrics like the inequality coefficient has the advantage of considering different aspects but it also implies information loss as it does not clarify where the error is coming from.	(Theil and Goldberger, 1961; Williamson, 1995)

In the Table equations m_i and s_i are the respective measured and simulated data for each model at the instance ‘i’; $\bar{m}$ and $\bar{s}$ are the average of the measured and simulated data respectively; n is the number of data points; and s = $\frac{(\bar{s}-\bar{m})}{|\bar{s}-\bar{m}|}$

As stated by Chai and Draxler (2014), one single metric provides only one view of the model performance and, therefore, more than one metric is usually needed. For the current case study, important aspects to consider the model is in acceptable agreement against the measured data are: the mean, the overall distribution and the variance of the results.

The CV RMSE is widely used and recommended by previous studies due to its ability to inform the overall prediction accuracy of the model. In addition, this metric is recommended when trying to compare several variables because the error is normalised with respect to the measured data. Thus, this metric will be used as the output for the calculation of the IC previously explained in Equation (3.2), defining a modified influence coefficient (IC') as Equation (3.3).

$$IC' = \frac{\Delta CVRMSE \div CVRMSE_{BC}}{\Delta IP \div IP_{BC}} \tag{3.3}$$

Where IC' is the modified influence coefficient; ΔCV RMSE and ΔIP are changes in the CV RMSE and input, respectively; and CV $RMSE_{BC}$ and IP_{BC} are the CV RMSE and the input base case values respectively. IC' will help to identify the parameters that have a greater influence on the results and at the same time, it gives information on which values minimise the CV RMSE, providing a better match between the simulated and measured data. Finally, the CV RMSE metric will be also used in the multi-objective calibration that will be explained later.

The model acceptance will be assessed using the percentile comparison (50 %, 75 % and 90 %) as it is a simple quantitative way of comparing the distribution of the simulation and measured data. This is especially useful in this study as one of the objectives is the assessment of temporal and spatial distribution of overheating and poor IAQ within the house. In addition, 50 % percentile (median) will give similar information to the mean, giving an easy indication of whether the simulation results overestimate or underestimate the monitored results. The main drawback of this metric is that it does not consider time discrepancy between the simulated and measured values. This is solved by using the CV RMSE metric in the optimisation function. In addition, predicting the exact time of pollutant concentrations, for instance, is not critical in this study as the aim is to identify whether periods of overheating and poor IAQ exist within the building.

3.1.7. Multi-objective calibration

To calibrate the model based on several parameters, a multi-objective function needs to be defined and minimised. As previously mentioned, the CV RMSE metric has been chosen as it is widely used and recommended to predict the overall accuracy of the model. The multi-objective function has been defined using three terms regarding the indoor environment: temperature, RH and IAQ. This last term, IAQ, has been defined as the average CV RMSE of the target pollutants. Therefore, a reasonable match for the concentrations of all the relevant pollutants involved in the study is desired to avoid great discrepancies for any of them. The multi-objective function is defined in Equation (3.4).

$$f = \sum_{zones} \Big(w_t CVRMSE(T) + w_{rh} CVRMSE(RH) + w_{iaq} Average\big(CVRMSE(p_i)\big) \Big) \quad (3.4)$$

In the previous equation, p_i is each of the pollutants used to calibrate the model; w_t, w_{rh} and w_{iaq} are the weighting factors for the temperature, RH and IAQ respectively. These weighting factors should be defined by the person responsible for the calibration and will depend on the focus of the study. The sum of the weighting factors must be equal to 1.

3.1.8. Inputs adjusted

If the calibration criteria are not met, the inputs of the model need to be adjusted. This is done following the order established in the ranking of IC'. These inputs are adjusted and so Equation (3.4) is minimised as explained before. Once the calibration criteria are met, the differences between the simulation results and measured data can be considered acceptable and the model calibrated.

3.2. Summary

A calibration methodology based on previous methodologies has been defined and explained (see Figure 3.1). A review of common metrics has been carried out, selecting the most appropriate metrics for the SA and calibration criteria in this study. This calibration methodology will be applied to a case study in the next chapter.

Chapter 4. Calibration Case Study – Dormont

This chapter describes the main characteristics of the detailed model built and the calibration carried to ensure results are in acceptable agreement with measured data. The model characteristics have been determined by the property documentation, measured data and occupants' diary, and the calibration methodology applied was the one explained in the previous chapter.

To simplify the calibration process, a step-by-step calibration was undertaken. First, the indoor parameters used for the calibration were temperature and CO_2 concentration in the living room and bedrooms. RH is not included in the calibration as humidity absorption and desorption, and the hygrothermal properties of the different materials have not been considered in the model, and therefore, very accurate humidity levels are not expected. Thus, RH results are checked after the calibration. Finally, other pollutants (formaldehyde, $PM_{2.5}$, PM_{10} and NO_2) are included in the model, adjusting their sources so the concentrations obtained are in acceptable agreement with those measured in the actual building. This is explained in more detailed in Chapter 6.

4.1. Initial model built

The house selected for the case study is a PH built in Scotland in 2011. This house has been selected for the extensive information available and it is believed to represent well the future type of low-energy houses. The construction plans were provided. Additionally, the house has been extensively monitored since 2013, gathering the following data:

- Ambient temperature and RH
- Opening of windows in the living room and bedrooms

- Energy consumption and power: stove, towel rail, sockets, cooker, lighting and MVHR post-heater
- Temperature, RH and CO_2 concentration in the living room and bedrooms

In addition, detailed occupant's diaries were gathered for one winter week and other pollutant concentrations (formaldehyde, $PM_{2.5}$, PM_{10} and NO_2) were measured for a week in the living room and three days in the main bedroom. According to the review of commonly found pollutants and their impact on health undertaken in Chapter 2, the target pollutants selected were: CO_2, formaldehyde, NO_2, PM_{10}, $PM_{2.5}$, radon and mould. However, measurements of radon and mould were not included in the monitoring. The probability of a house located in the Dormont Estate of having a concentration of radon above 200 Bq/m^3 is less than 1 % according to the indicative atlas of radon in Scotland (Miles et al., 2011). Therefore, risk of poor IAQ due to this pollutant can be neglected. Regarding mould, its risk of growth can be determined from RH levels in the house (Chartered Institution of Building Services Engineers, 2015).

All this information reduces the uncertainties and makes possible the creation of a detailed model which will be able to provide accurate results for the purpose of this study. Moreover, as mentioned in Chapter 1, the PH standard is getting spread rapidly in the UK with more than 250 certified buildings in 2013 (Passivhaus Trust, 2016). Thus, the Dormont PH selected represents a good case study to investigate the indoor environment in low-energy houses. Figure 4.1 shows a front view of the 2-bedroom PH in Dormont and Figure 4.2 shows a sketch of the model built in ESP-r.

Figure 4.1: Front view of the 2-bedroom PH in Dormont

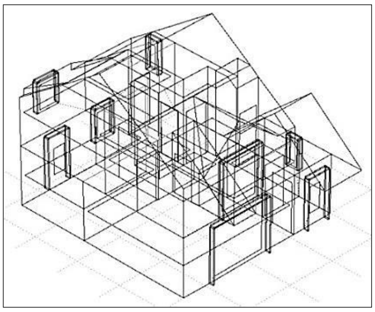

Figure 4.2: ESP-r model of the case study

4.1.1. Location and climate

The house modelled is a semi-detached house situated in the Dormont Park Passivhaus Development in Lockerbie, Scotland (see Figure 4.3). The climate is typically mild, with a yearly average minimum temperature of 5.8 °C, maximum of 12.8 °C and 1335.5 sunshine hours (Met Office, n.d.).

Figure 4.3: Location of the Dormont Park Passivhaus Development (Google, n.d.)

4.1.2. Geometry

The dwelling comprises two floors and nine habitable rooms. The ground floor includes a hall, cloak-room, living room, kitchen and utility room, while the first floor consists of a hall, two bedrooms and a bathroom. Each room has been modelled as an independent zone to quantify its indoor conditions separately. A plan of the zone distribution can be seen in Figure 4.4 and the floor area of each zone is indicated in Table 4.1.

Figure 4.4: Zone distribution of the case study

Table 4.1: Zone floor area of the case study

Zones	**Area (m^2)**
Living room	21.5
Kitchen	10.6
Utility room	5.2
Hall	2.6
Cloak room	3.0
Main bedroom	15.6
Rear bedroom	11.7
Bathroom	4.6
Upper hall	6.1
Total	80.8

4.1.3. Materials and constructions

The constructions used are summarised in Table 4.2. These U-values are measured values for the external wall and the roof, and calculated values for the floor and window. The U-values were measured by MEARU using in-situ testing procedures according to the ISO 9869:1994. Hukseflux equipment (dataloggers, sensors and flux plates) was installed in a typical section of the roof and the wall in the North-facing area of the house to minimise the influence of sunlight (MEARU, 2015).

Table 4.2: Main construction details

	U-value (W/m^2K)	**Insulation**		
		Thickness (mm)	**Conductivity (W/mK)**	**Type**
External Wall	0.12	150	0.032	Mineral wool
		70	0.022	PUR
Ground Floor	0.11	200	0.022	XPS
Roof	0.12	170	0.032	Mineral wool
		55	0.022	PUR
Window	0.74	-		

The in-situ U-value testing was undertaken as far as possible from the timber structure to avoid the impact of thermal bridges. Therefore, the thermal bridges of the construction need to be calculated in order to take into consideration the consequent heat losses. The linear thermal transmittance of the thermal bridges have been calculated using the tool THERM (Lawrence Berkeley National Laboratory, 2013) and are shown in Table 4.3.

Table 4.3: Thermal bridges for the Dormont house

Thermal bridge	**Linear thermal transmittance (W/mK)**
Wall-ground floor	0.033
Wall-wall	0.028
Jamb at window	0.040
Roof-wall	0.033

Windows are triple glazed gas filled and are modelled as a transparent multilayer construction (TMC). For this, the direct transmission and the absorption in each layer of the glazing system needs to be specified for 5 angles of incidence (0,40,55,70, and 80 degrees). These properties are modified when internal curtains are used as shown in Table 4.4. Internal curtains are the only solar protection applied in this case as the building was built without external shading.

Table 4.4: Glazing properties with and without internal curtains

		Without curtains					With curtains				
Angle (°)		**0**	**40**	**55**	**70**	**80**	**0**	**40**	**55**	**70**	**80**
Trans. (-)		0.382	0.361	0.313	0.193	0.077	0.038	0.028	0.019	0.010	0.003
Absorption (-)	**Layer 1**	0.260	0.264	0.264	0.255	0.195	0.893	0.892	0.890	0.803	0.600
	Layer 2	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	Layer 3	0.103	0.111	0.115	0.107	0.083	0.004	0.003	0.002	0.002	0.001
	Layer 4	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	Layer 5	0.098	0.095	0.086	0.061	0.028	0.003	0.002	0.001	0.001	0.001

4.1.4. Internal Heat Gains

The IHG can be divided in three categories: occupants, lighting and appliances. The occupants' heat gains have been estimated using Table 4 of ASHRAE Handbook, *Typical Metabolic Heat Generation for Various Activities* (ASHRAE, 2009) and the occupancy schedule in the building, gathered by the occupants' diary. This diary includes information on whether occupants are in the building and specifies times for sleeping, cooking or bathing. Therefore, the number of occupants and their location in the different rooms can be determined.

The lighting and appliances' heat gains have been estimated using the energy consumption and power data measured. The lighting data is given by floors and therefore, the exact location of the IHG is unknown and needs to be assumed. For this, it is assumed that the maximum lighting power of a certain floor occurs when all the lights in that floor are switched ON. Then, that maximum power is divided by floor area. The lights of a zone are assumed to be ON when the zone is occupied except for the bedrooms during sleeping hours. The maximum lighting power of each zone is shown in Table 4.5. It can be seen that the maximum lighting power used in the living room and kitchen is very low. This could be due to the use of natural light in these rooms.

Table 4.5: Zone lighting power of the case study

Zones	Maximum lighting power (W)
Living room	32
Kitchen	16
Main bedroom	138
Rear bedroom	104
Bathroom	41

Regarding appliances, data was provided for the kitchen, the ground floor and the first floor. The kitchen sensible heat gains are directly obtained from measurements and the latent heat gains due to cooking activities have been defined as 200 g/h according to Markopoulos et al. (2013). This gain can be converted to Watts using the heat of vaporisation of water which is 2257 J/g (Osborne et al., 1939). It has been assumed that all the appliances of the ground floor are placed in the living room except for the washing-machine, which is located in the utility-room. The latent load due to clothes drying has been assumed as 3.1 kWh/use as established in PHPP (Passive House Institute, 2012). For the first floor, the power has been divided between the main bedroom and the bathroom. The IHG due to appliances in the rear bedroom has been assumed to be zero since the room is occupied by a two years-old child. The latent load due to bathing has been calculated according to the household moisture sources in Christian (1994), which is 0.06 L for a standard size bath.

4.1.5. Infiltration and Ventilation

To include infiltration and ventilation information in ESP-r, an airflow network needs to be defined (see Figure 4.5). This network is formed by nodes, components and connections. The nodes can be internal, to represent the air in each zone, or boundary nodes, to represent the ambient air outside the building. Four different types of components have been defined: openings, doors, cracks and fans.

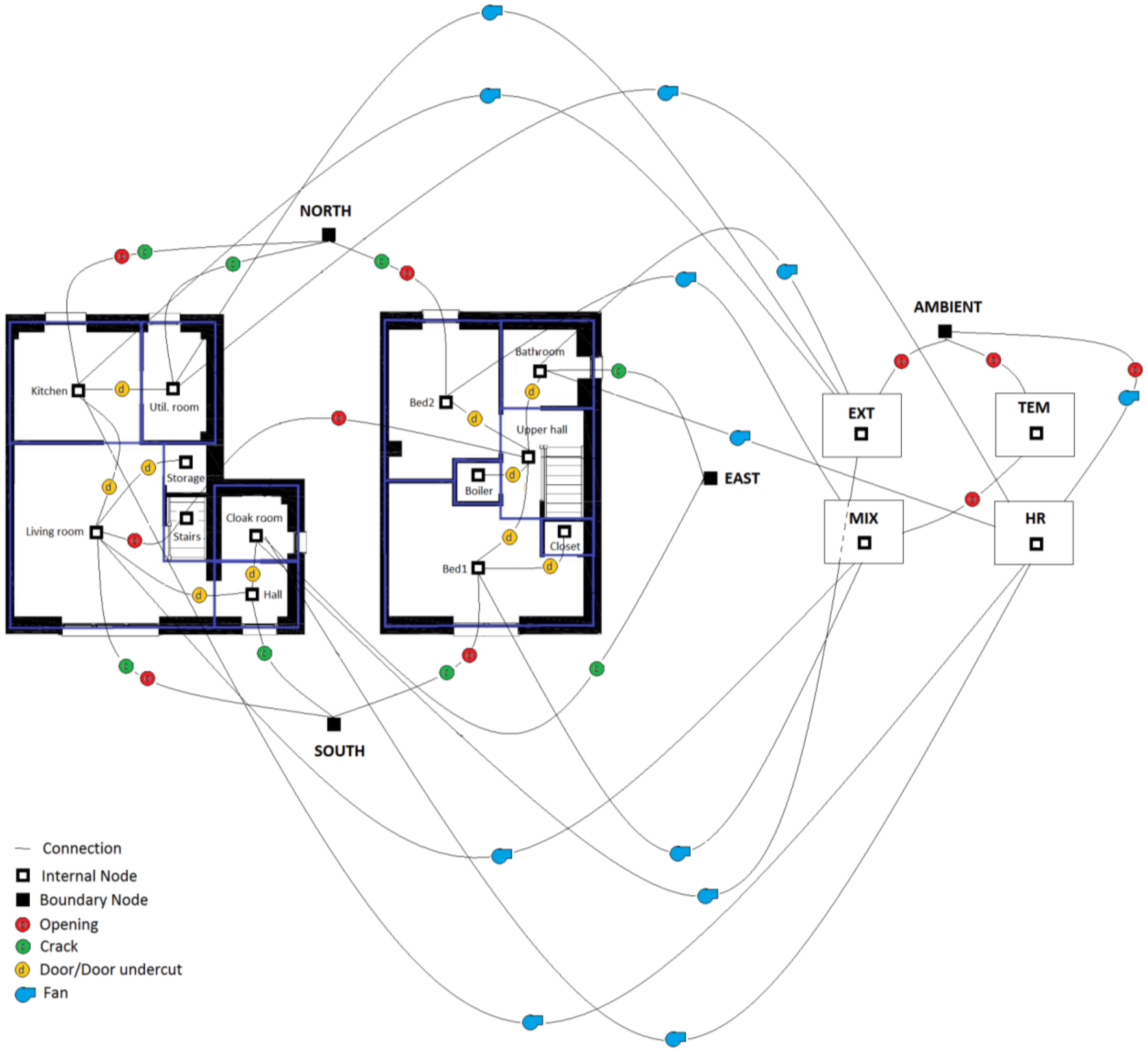

Figure 4.5: Airflow network of the case study

The openings are used to define windows, where the flow can be modelled as unidirectional. The doors are represented by bi-directional components since their height is large enough to allow density differences due to different temperatures at different heights along the door, which could induce flow in both directions (see Figure 4.6).

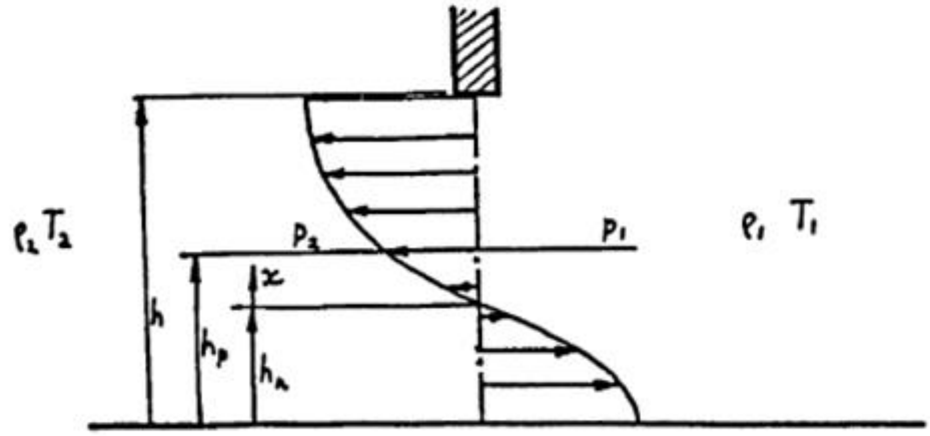

Figure 4.6: Bi-directional airflow across a doorway (Cockroft, 1979)

Cracks are defined to take into account undesirable infiltration into the building. The dimension of the cracks is calculated using the result from the blower door test carried out by MEARU (2015), which was 1.78 ach at 50 Pascal. However, location of these cracks is uncertain. It is, therefore, assumed that crack dimensions are proportional to the window width in each room, assuming the main source of infiltration is due to the cracks between the window frame and the wall. The crack width is 3 mm. The crack component is also used to define door undercuts, which are 15 mm x 0.8 m.

Finally, extract and supply fans are defined as part of the MVHR system. Ventilation flows were measured by MEARU (2015), and are listed in Table 4.6. The efficiency of the heat exchanger in the MVHR system is 91 % according to the manufacturer specifications (PAUL Wärmerückgewinnung GmbH, 2017). To model this efficiency in ESP-r, four virtual zones were defined: TEM, MIX, EXT and HR. The air is supplied to the living room and bedrooms from the MIX zone and extract from the wet rooms to the EXT and HR zones. 91 % of the ventilation rate is supplied to the HR zone, where is mixed with 9 % of the ventilation rate of ambient air. Then, the temperature of the TEM zone is forced to match the temperature of the HR zone. Thus, 91 % of the heat from the ventilation air is recovered. Figure 4.7 shows a schematic of this modelling approach.

Table 4.6: Extract and supply ventilation rates

Extract rates (l/s)		Supply rates (l/s)	
Kitchen	14.06	Living room	12.25
Utility room	5.07	Main bedroom	15.06
Cloak room	5.68	Rear bedroom	12.58
Bathroom	11.91	Total	39.89
Total	36.72		

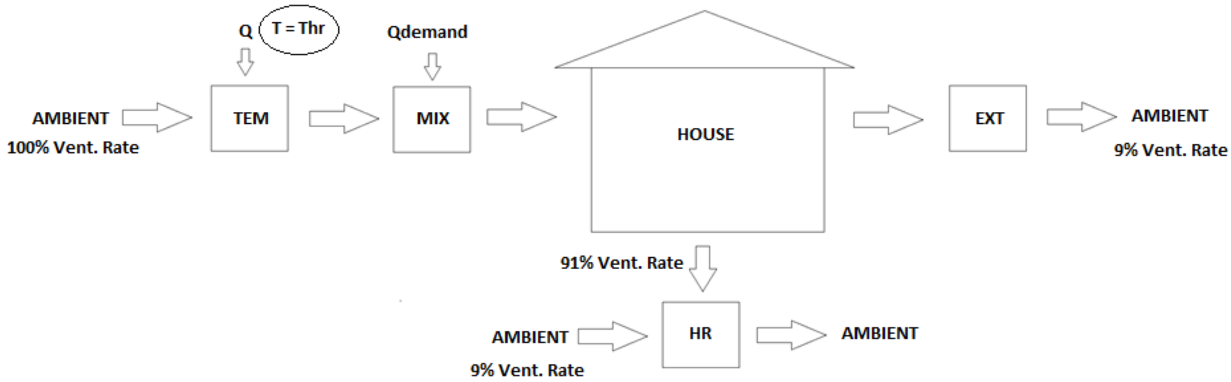

Figure 4.7: Modelling of heating recovery efficiency

4.1.6. Heating system

Heating is supplied by a post-air heating unit as part of the MVHR system. This unit senses the temperature in the kitchen and supplies warm air when the temperature drops below the set-point. There is also a towel rail in the bathroom and wood stove in the living room to provide extra heating. The heat released by the towel rail and the stove have been added to the bathroom and living room respectively as part of the appliances' IHG.

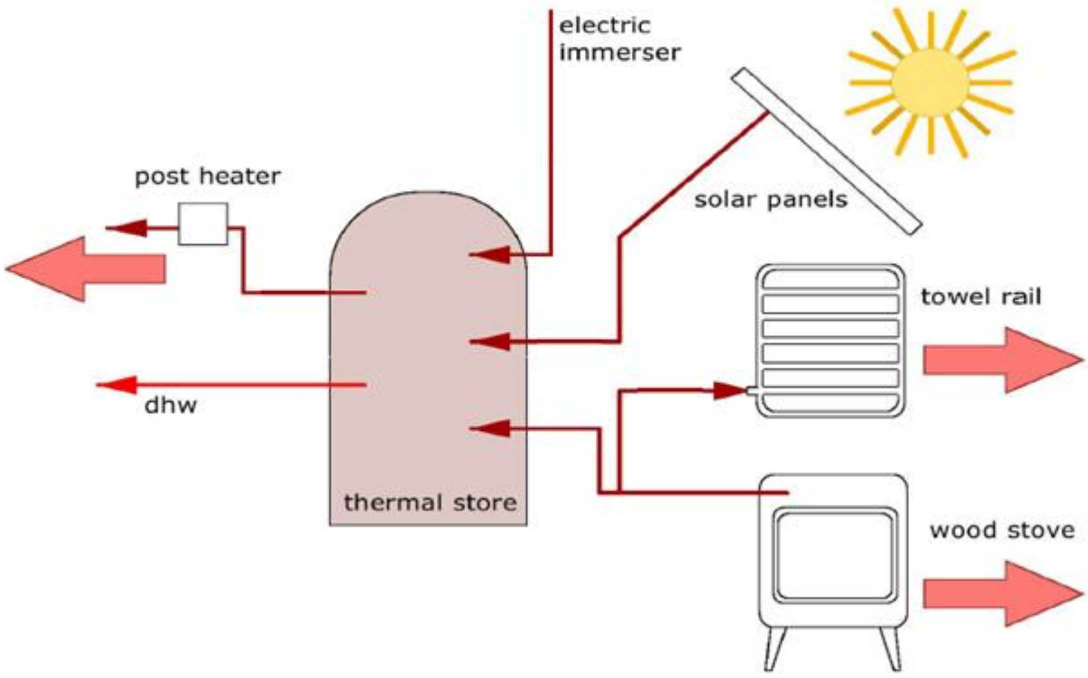

Figure 4.8: Simplified diagram of Dormont Heating Systems (MEARU, 2015)

4.1.7. Solar protection

All external windows and glass doors in the house are provided with curtains. For the base model, the use of curtains was assumed when the indoor temperature rises over the comfort levels defined in Chapter 6 (Table 6.4).

4.1.8. Hierarchy of sources

The initial model described was constructed following the evidence-based approach (Raftery et al., 2011). Table 4.7 lists the model input variables and their level of hierarchy according to the recommended categories of Raftery et al. (2011).

Table 4.7. Base model inputs and hierarchy of sources

Category	Input variables	Hierarchy level	Source
Climate	Temperature	1	Monitored data
	Relative Humidity	1	Monitored data
	Wind speed and direction	2	Weather Observation Website (Met Office, 2015)
	Global solar radiation	2	Met Office
	Direct and diffuse solar	3	Calculated using Muneer Model (Muneer, 1997)
	CO_2 concentration	5	ProOxygen (2016)
Envelope	Geometry	4	Design Plans
	Shading	4	Design Plans
	Constructions	2	Design Plans and In-situ U Value Testing
	Thermal bridges	4	Calculated using THERM
Internal thermal mass	Internal geometry and constructions	4	Design Plans
Ventilation and Infiltration	% Opening area: Windows Internal doors	 1 7	 Monitored data for windows No available information for doors
	Schedule: Windows Internal doors	 1 7	 Monitored data for windows No available information doors
	Blower door test	2	Monitored data
	Distribution of cracks	7	No available information
	Supply and extract rates: Magnitude Schedule	 2 7	Monitored data for standard and boost rates Not available information
Solar gains	Internal solar protection	7	No available information
Appliances heat gains	Power	1	Monitored data
	Schedule	1	Monitored data
	Spatial distribution	7	No available information.
Lighting heat gains	Power	1	Monitored data
	Schedule	1	Monitored data
	Spatial distribution	7	No available information.
Occupancy	Quantity	2	Occupant diary
	Metabolic rate	5	CIBSE Guide values
	Schedule	2	Occupant diary
	Spatial distribution	2	Occupant diary
Heating system	Maximum power	4	Information by Paul Heat Recovery Scotland
	Temperature set-point	5	CIBSE Guide
	Control type	4	Information by Paul Heat Recovery Scotland
	Maximum supply temperature	4	Information by Paul Heat Recovery Scotland
	Schedule	3	Passivhaus Standard confirmed by measured data
Pipe losses	Magnitude	4	PHPP
	Location	4	Design Plans
	Schedule	4	PHPP

As mentioned in Chapter 3, hierarchy of source levels 5 to 7 have a greater level of uncertainty and therefore they will be included in the uncertainty ranking later. Only these high uncertainty levels have been considered to simplify the calibration process.

4.2. Graphical approach check

4.2.1. Visual inspection

As explained in Chapter 3, the visual inspection can help to identify where the greatest discrepancies between the simulated and measured data are.

CO_2 concentration inspection

Figure 4.9 to Figure 4.11 show the comparison between the hourly simulated and measured CO_2 concentrations for a winter week (11th to 17th of November) for the living room, main bedroom and rear bedroom.

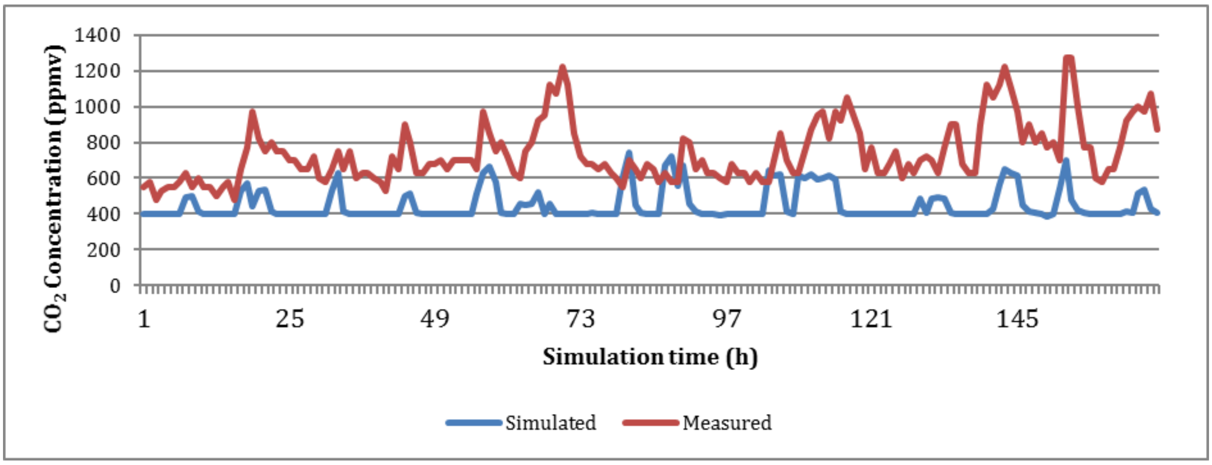

Figure 4.9. Simulated and measured CO_2 results for the base model in the living room

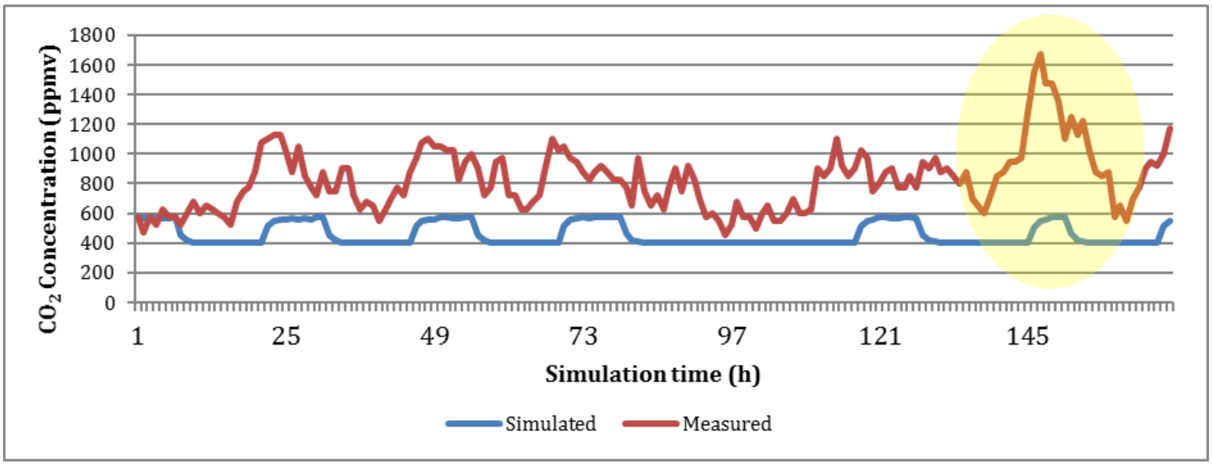

Figure 4.10. Simulated and measured CO_2 results for the base model in the main bedroom

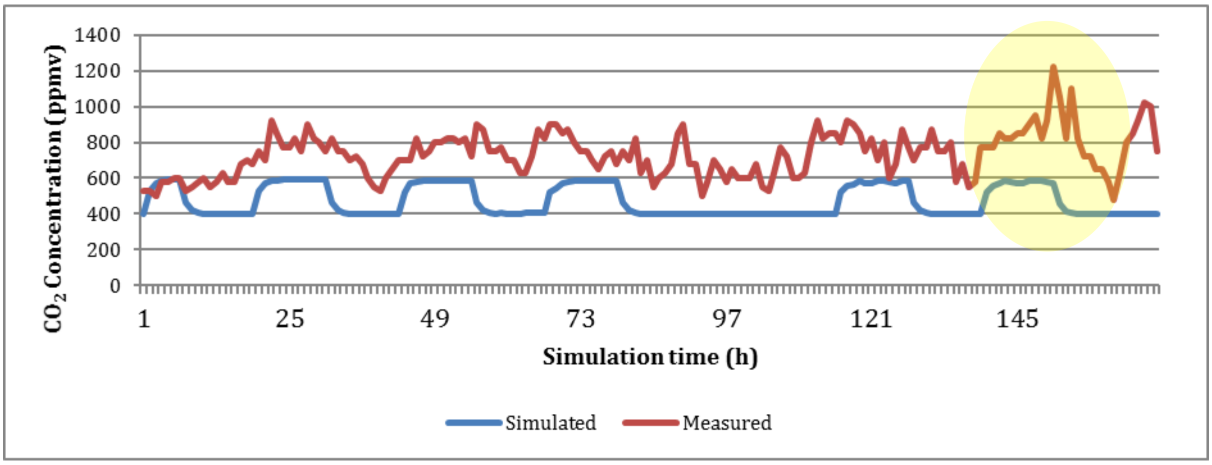

Figure 4.11. Simulated and measured CO_2 results for the base model in the rear bedroom

In the graphs above, it can be seen that predicted CO_2 concentrations remain below the monitored concentrations most of the time. This may be due to an error in the current assumptions (ambient CO_2 concentration, ventilation rates, etc.), measurements (due to a poor accuracy of the sensor at low CO_2 levels) or occupants' diary (higher activity levels or number of occupants than stated). In these situations, gaining knowledge about the dwelling to be modelled can make easier the calibration process, as the level of evidence of the inputs increases and the reason for the above discrepancies can be identified. For this, zones and times with less uncertainty are identified; for example, unoccupied periods when there are no CO_2 sources in the dwelling (see Figure 4.12).

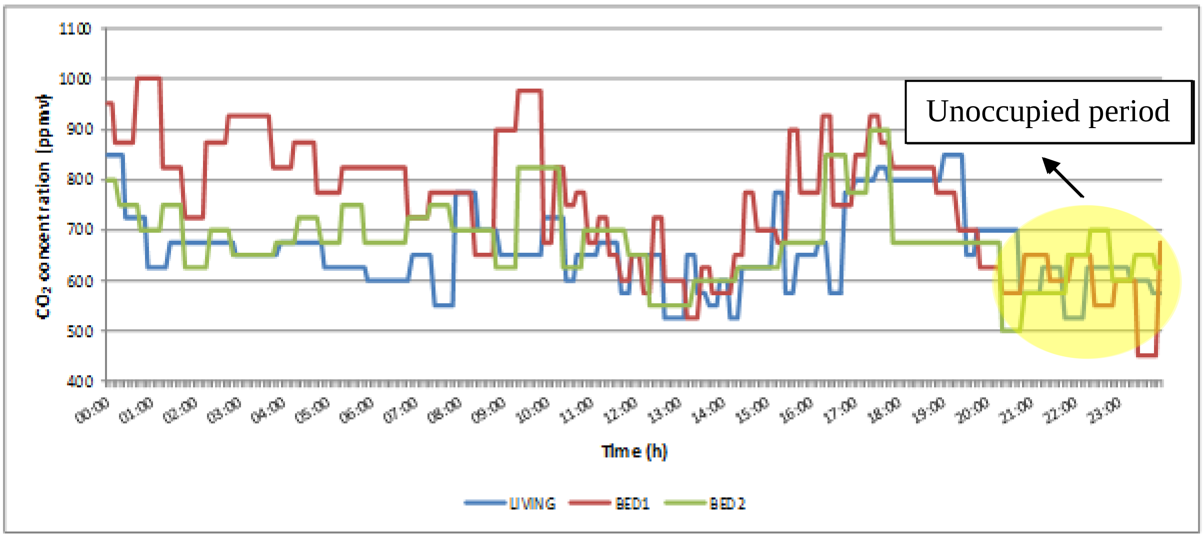

Figure 4.12. CO_2 concentrations for the 14th November

The CO_2 concentration during unoccupied periods tends to the ambient CO_2 concentration which, according to Figure 4.12, is around 600 ppmv. This value is much higher than the ambient CO_2 concentration measured by ProOxygen (2016), which is slightly above 400 ppmv. One possible reason is poor sensor accuracy. According to the manufacturer specifications, the sensors have an accuracy of ±0.5 ppmv at 25 °C and 50 % RH although Figure 4.12 shows steps of ±25 ppmv. However, these fluctuations do not explain the high "ambient concentration". In addition, MEARU and T-Mac Ltd, who were responsible for the monitored data, reviewed the installation of the equipment, stating that there were some data collection and connectivity problems at the beginning of the monitoring in 2012. However, in 2013 the measured data was "largely accurate" (MEARU, 2015).

Another reason for this offset is the location of intake and exhaust vents. If these vents are poorly located, polluted air from the exhaust could penetrate the building through the intake and, therefore, the CO_2 concentration of the supply air would be above the ambient concentration. To avoid this, intake and exhaust vents were separated by two metres according to the plans of the as-built MVHR of the Dormont houses and this distance was checked during a site visit (see Figure 4.13).

Figure 4.13: Intake and exhaust vents of the Dormont PH

Finally, the most probable reason for the ambient concentration offset is the automatic base calibration of the sensors (Foster, 2017). This calibration method assumes that a typical room is unoccupied during a period every day and therefore, the minimum CO_2 concentration measured would be the ambient concentration. The advantage of this method is that sensors self-calibrate themselves during their lifespan. The main disadvantage is that if CO_2 concentrations are consistently high, the new "zero" value of the sensor could be higher than it should be (CO2Meter.com, 2013). To take this into account, the new ambient concentration in the model is set to 600 ppmv for the comparison with measurements.

In addition to the ambient concentration offset, in the period investigated there is an excessive peak in the CO_2 concentration for the night of the 16th of November in both bedrooms (see yellow areas in Figure 4.10 and Figure 4.11). However, there are no records of any changes in the occupants' diary that could lead to it. Therefore, this anomaly will be taken out of the analysis to be conservative and avoid including an error in the calibration. Thus, the calibration will focus only on the period from the 11th to the 16th of November.

Temperature inspection

Figure 4.14 to Figure 4.16 show the comparison between the simulated and measured dry air temperatures for a winter week (11th to 17th of November). Looking at these graphs, it can be seen that predicted temperature in the living room is in acceptable agreement with measured data. However, simulated temperatures in the bedrooms are higher than the monitored ones.

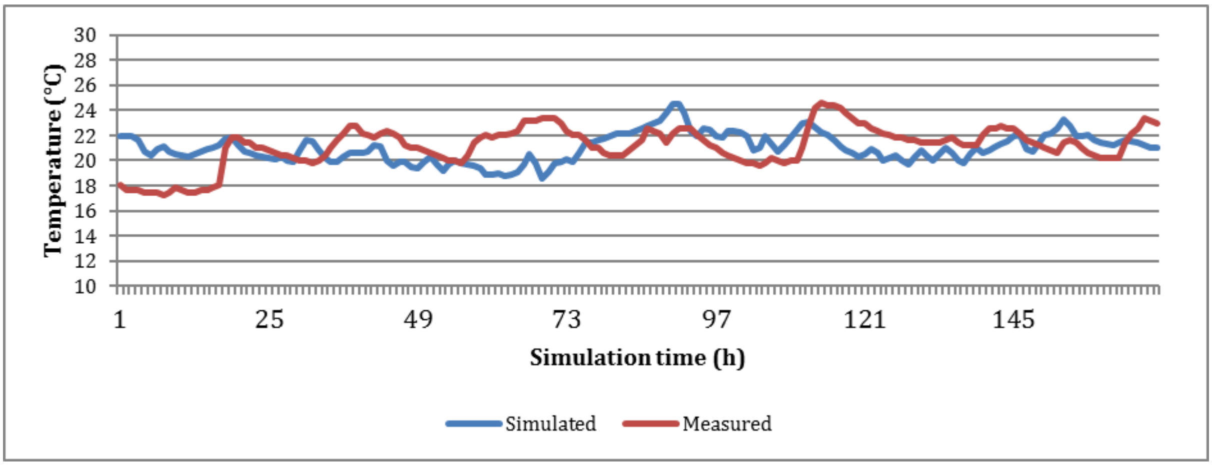

Figure 4.14. Simulated and measured temperature results for base model in the living room

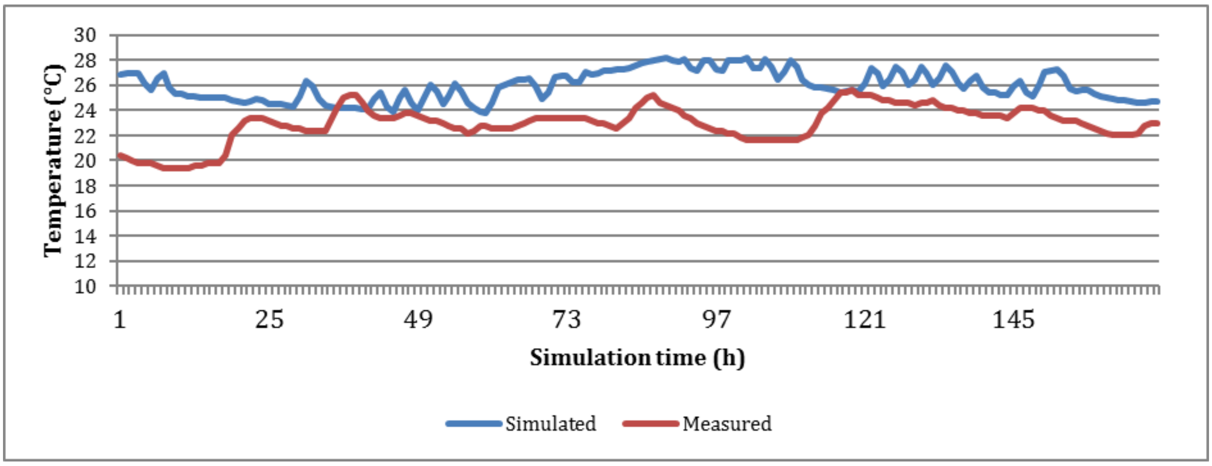

Figure 4.15. Simulated and measured temperature results for base model in the main bedroom

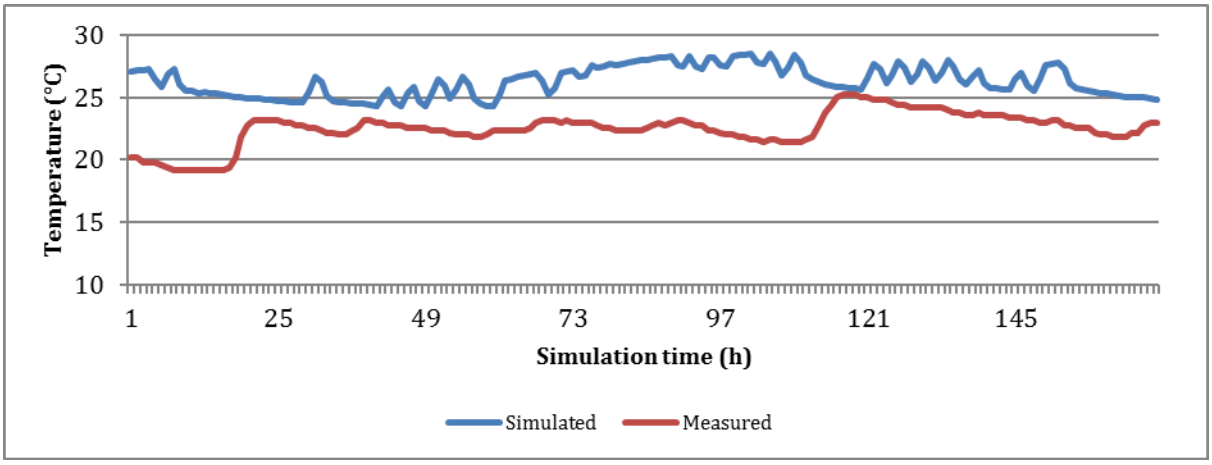

Figure 4.16. Simulated and measured temperature results for base model in the rear bedroom

A common observation for all the rooms is that simulated temperatures show more oscillations than the measured temperatures. A possible reason could be that the simulated control of the heating system is ON/OFF, which is an ideal control. In reality, the response of the system will not be instantaneous. Thus, using a proportional control instead of an ON/OFF one could give more reasonable results. Figure 4.17 to Figure 4.19 show the comparison between the simulated and indoor temperatures for a winter week (11^{th} to 17^{th} of November) using a proportional control. Looking at these results it can be seen that the simulated temperatures are smoother when using a proportional control, and therefore the oscillation issue shown previously can be explained.

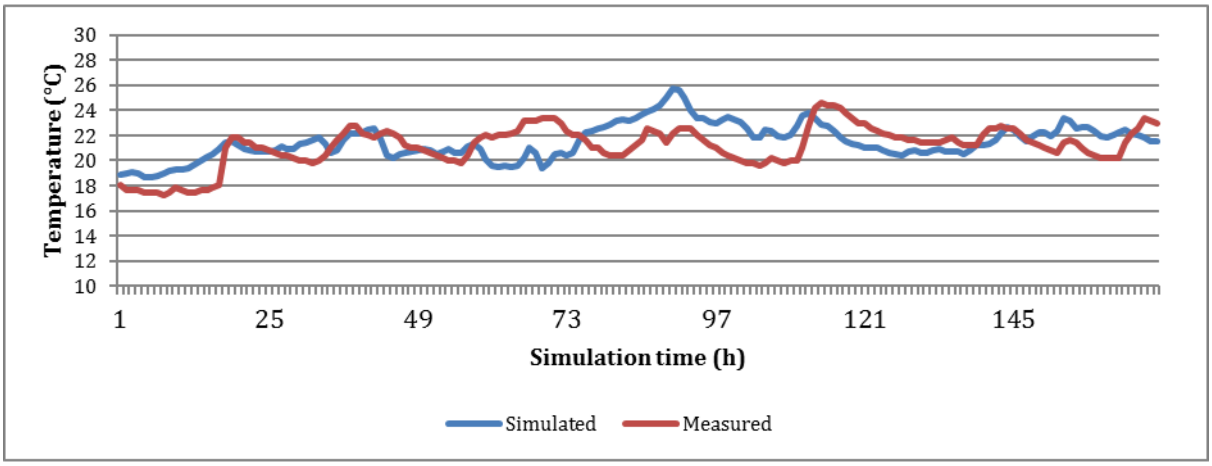

Figure 4.17: Simulated and measured temperature results in the living room using a proportional control

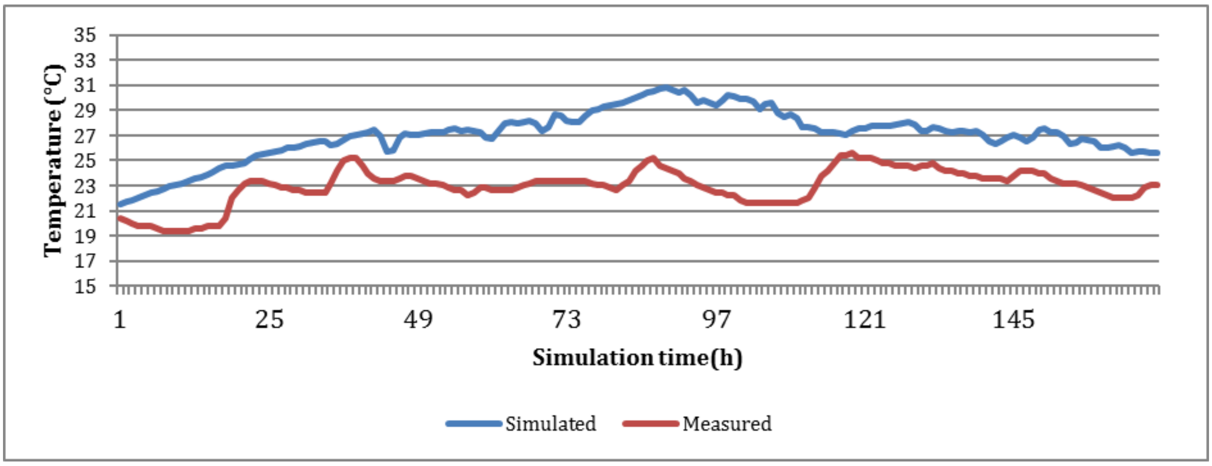

Figure 4.18: Simulated and measured temperature results in the main bedroom using a proportional control

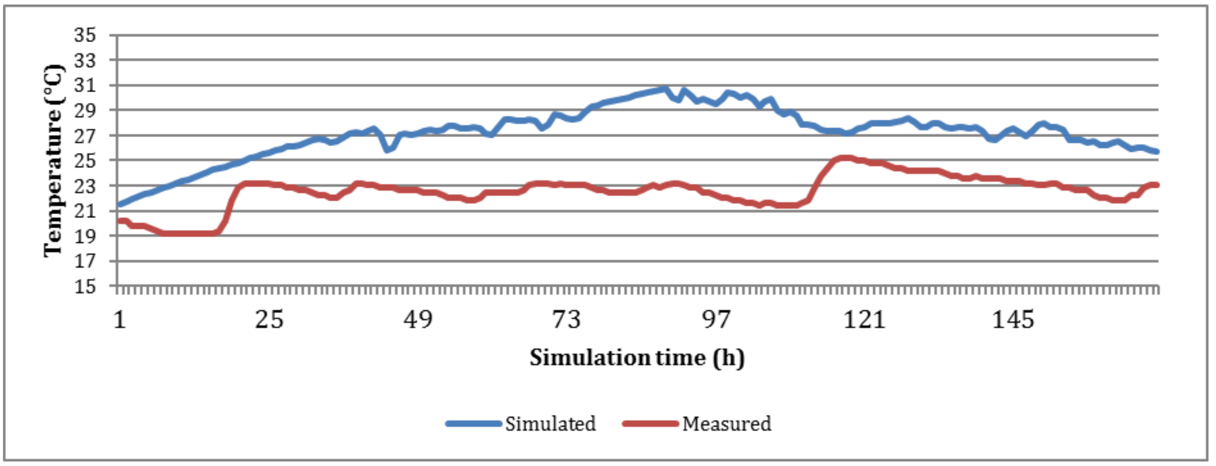

Figure 4.19: Simulated and measured temperature results in the rear bedroom using a proportional control

4.2.2. Residual histogram

The graphical representation of the model errors or residuals in a histogram form can help to identify the magnitude and spread of model errors (Royapoor and Roskilly, 2015).

CO_2 concentration residual histogram

Figure 4.20 to Figure 4.22 show the residual histograms for hourly CO_2 concentrations in the living room and the bedrooms previous to the ambient concentration assumption of 600 ppmv. These graphs confirm that simulated results are consistently below measured data due to the ambient concentration offset, with practically all the residuals in the positive region. It can also be seen that most errors are around 250 ppmv in the living room and rear bedroom. However, for the main bedroom, differences are greater, resulting in errors around 500 ppmv.

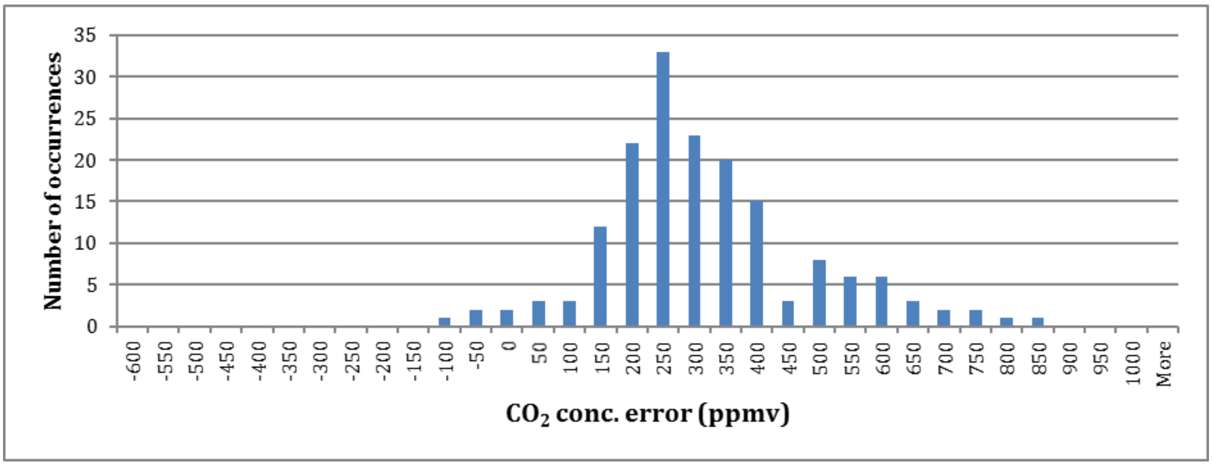

Figure 4.20: Residual histogram of the CO_2 concentrations in the living room

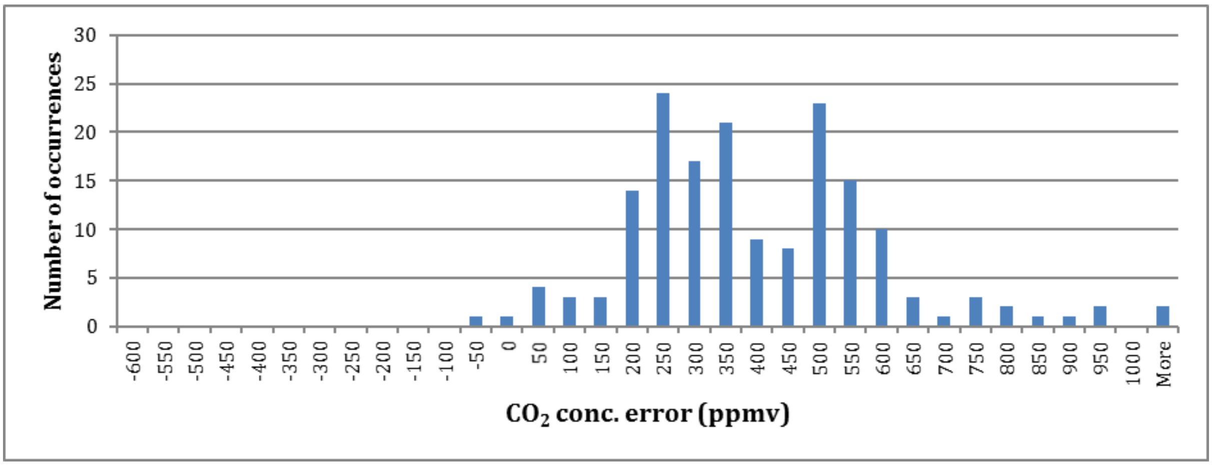

Figure 4.21: Residual histogram of the CO_2 concentrations in the main bedroom

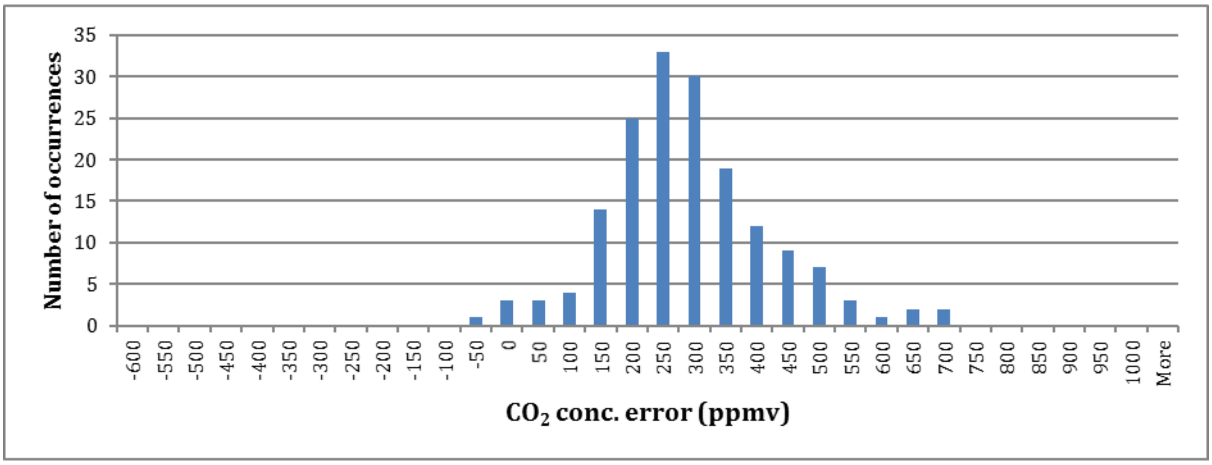

Figure 4.22: Residual histogram of the CO_2 concentrations in the rear bedroom

Temperature residual histogram

Figure 4.23 to Figure 4.25 show the residual histograms for the hourly temperature in the living room and the bedrooms. Figure 4.23 confirms that simulated results agree well with measured data in the living room, where residuals are evenly distributed around zero, being most located at -1 or 1 °C. Figure 4.24 and Figure 4.25 confirm that simulated temperature is consistently below measured data for both bedrooms, with practically all the residuals in the negative region. It can also be seen that most errors are around 2.5 °C.

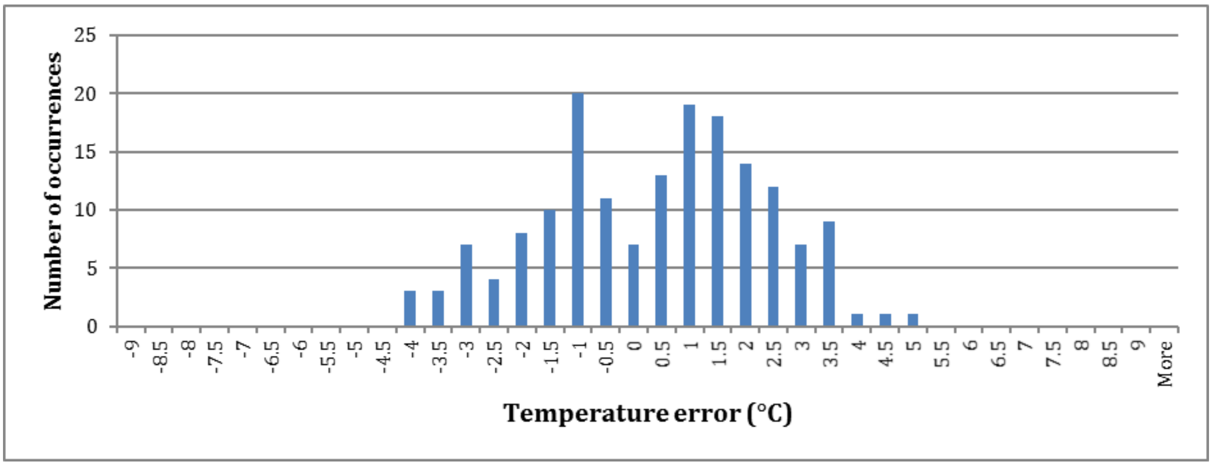

Figure 4.23: Residual histogram of the temperature in the living room

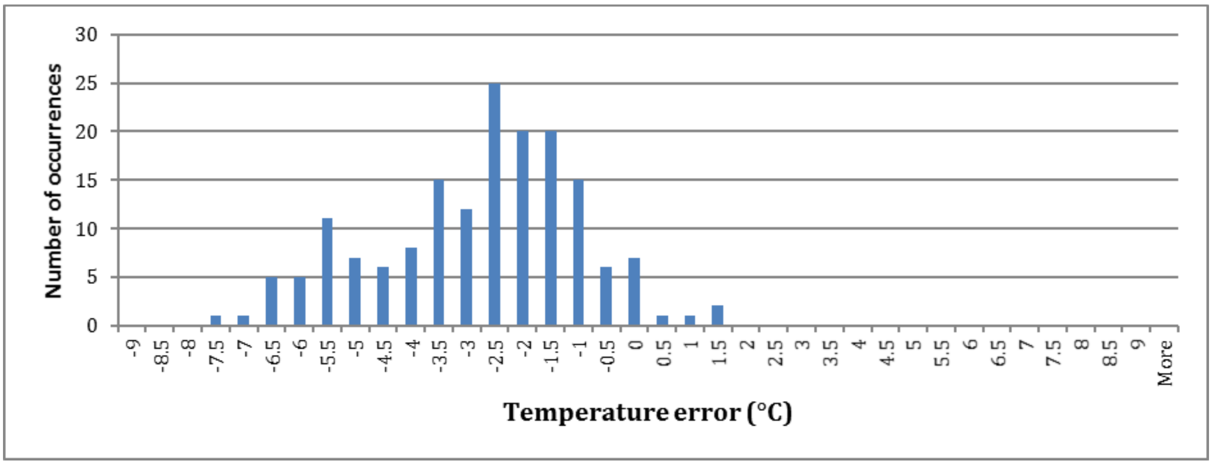

Figure 4.24: Residual histogram of the temperature in the main bedroom

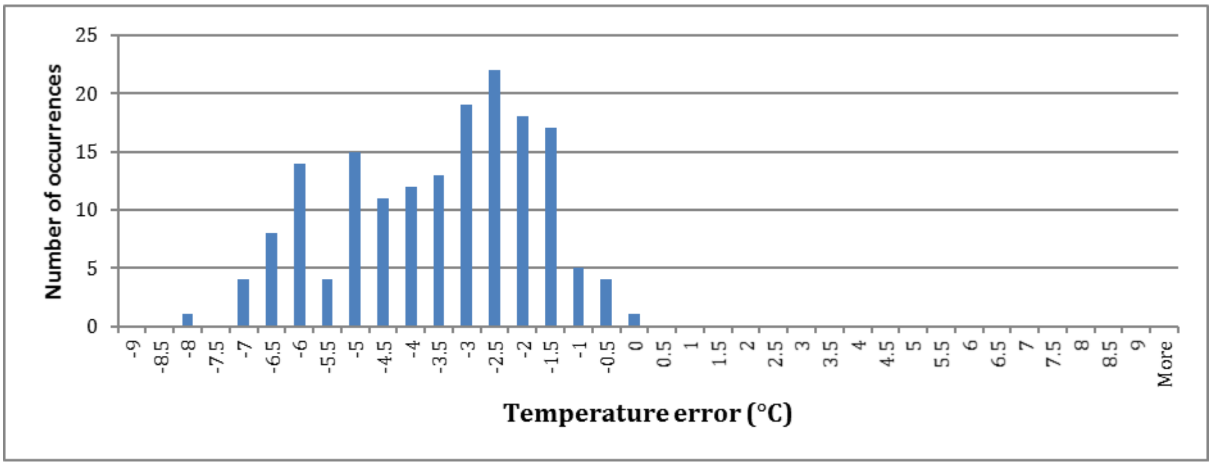

Figure 4.25: Residual histogram of the temperature in the rear bedroom

4.3. Uncertainty source group ranked

To calibrate the model, a ranking of the sources of uncertainty according to their participation in the indoor environment has to be done. In this way, the categories that have a greater impact on the results are prioritised, and their related input variables will be the focus of the SA.

The lists of uncertain variables that influence the CO_2 concentration are shown in Table 4.8, and the ones that influence the temperature in the building are shown in Table 4.9 and Table 4.10. These variables are the ones with greater level of uncertainty (levels 5 to 7) in Table 4.7.

Table 4.8. Uncertain variables that affect CO_2 concentration

CATEGORY	VARIABLES
Occupancy	Metabolic rate
Ventilation and Infiltration	Internal door opening (schedule and percentage of opening area), supply/extract rates (schedule), envelope cracks (distribution)

For the CO_2, there is no need of doing a ranking since there is only one category as a source (occupancy) and one category as a sink (infiltration/ventilation). Therefore, both of them will be considered in the SA.

Table 4.9. Uncertain thermal gains

CATEGORY	VARIABLES
Solar gains	Internal solar protection
Appliances heat gains	Spatial distribution
Lighting heat gains	Spatial distribution
Occupancy	Metabolic rate
Heating system	Temperature set-point

Table 4.10. Uncertain thermal losses

CATEGORY	INPUT VARIABLES
Ventilation and Infiltration	Internal door opening (schedule, percentage of opening area), supply and extract rates (schedule), envelope cracks (distribution)

As mentioned in the case of CO_2, for the heat losses there is no need for ranking since there is only one category, ventilation/infiltration. The ranking of heat sources that impact on the indoor temperature is shown in Table 4.11. For this, average heat gains during the simulated period (11^{th} to the 16^{th} of November) were retrieved from ESP-r results. Peak values were also calculated, and the same conclusions were drawn.

Table 4.11: Participation of heat sources over the total heat flux in the building

	Average Heat Gain (W)			Contribution (%)		
	Living	**Bed1**	**Bed2**	**Living**	**Bed1**	**Bed2**
Solar gains	35.7	22.8	2.8	7.3%	6.5%	1.1%
Appliances heat gains	169.9	10.3	0.0	34.9%	2.9%	0.0%
Lighting heat gains	12.2	7.8	0.0	2.5%	2.2%	0.0%
Occupancy	24.2	12.3	7.4	5.0%	3.5%	2.9%
Heating system	245.4	297.8	245.3	50.3%	84.8%	96.0%

According to **¡Error! No se encuentra el origen de la referencia.**, the most significant heat sources for the living-room are the appliances heat gains and the heating system. In the case of the bedrooms, the most important heat source is the heating system. Therefore, the focus will be on the heating system.

4.4. Sensitivity Analysis

The SA is conducted by modifying the inputs variables within feasible limits to improve the fit between measurements and predictions. The influence of each parameter is calculated using the IC' defined in Equation (3.3). To calculate the IC', feasible limits for the input parameters must be identified. These limits are shown in Table 4.12 and have been derived from previous studies in the literature, guidelines and measured data from the Dormont PH.

Table 4.12: Feasible limits for the input parameters used in this study

Input parameter	**Feasible limits**	
Metabolic rate (male/female/child)	59/50/44 W	1.8 * Metabolic rate defined in the ASHRAE Handbook - Fundamentals
Door opening area inside the house	0.12 m^2	1.68 m^2
Supply/extract flow rates	Standard ventilation rate with 50 % of filter occlusion	Boost ventilation rate with no occlusion
Crack distribution	Based on window width	Based on wall area
Temperature set-point	17 °C	25 °C

4.4.1. CO_2 sensitivity analysis

In the case of CO_2, the occupancy and ventilation/infiltration were chosen to be investigated in the SA. The metabolic rate, percentage of door opening area inside the house, the supply/extract flow rates and the crack distribution have a low level of evidence. In addition, the schedule of indoor door opening is unknown. However, this latter variable has not been taken into account, assuming the percentage of door opening area do not vary during the simulation, not to add complexity to the process. Thus, ICs' have been calculated for the metabolic rate, percentage of door opening area inside the house, the supply/extract flow rates and the crack distribution.

Metabolic rate

The metabolic rate was retrieved from the ASHRAE Handbook - Fundamentals (ASHRAE, 2009). According to the international standard ISO 8996 (ISO 8996, 1989), estimation of metabolic rates by Screening (Level I) using tables according to kind of activity will have a very great risk of error. Previous studies used different levels of uncertainty for occupant heat loads (Brohus et al., 2009; Calleja Rodriguez et al., 2013; Havenith et al., 2002; MacDonald and Strachan, 2001; Malchaire, 2004). A range of uncertainty of ± 80 % would be conservative. However, this range gives an unrealistic minimum metabolic rate of 12.6 W. Thus, the literature has been reviewed for a more realistic minimum value. There have been several studies on variations of metabolic rates between individuals (Ganpule et al., 2007; Jung et al., 2011; Katayose et al., 2009). The study by Ganpule et al. (2007) investigated the variability in sleeping metabolic rate in Japanese subjects, giving a sleeping metabolic rate (8 hour-period) of 4.929 ± 0.607 MJ for female individuals. This gives a minimum value of 50 W for a female adult. Considering ASHRAE ratios between a male adult, female adult and a child metabolic rate (ASHRAE, 2009), the minimum metabolic rate for a child would be 44 W.

Door opening area inside the house

In this case, the range goes from 0.12 m^2 (15 mm of door undercut when the door is closed) to 1.68 m^2 when the door is fully opened.

Supply/extract flow rates

Ventilation fans can operate at different velocities which will vary the airflow rate they supply or extract. Information on airflow rates at standard and boost rates with clean and 50 % filter occlusion were gathered by MEARU (2015) (see Table 4.13). The maximum airflow rate is assumed as the boost ventilation rate with no occlusion, and minimum ventilation rate will be the standard ventilation rate with 50 % of filter occlusion. In this case, filter occlusion does not have a significant impact on the airflow rate since fans are variable speed, and they compensate for changes in pressure to deliver the required air volume. This leads to an energy penalty as the energy consumed by the fans would increase.

Table 4.13: MVHR ventilation rates for the Dormont house

Room	Extract rates (l/s)		Room	Supply rates (l/s)	
	Standard, 50 % occlusion	Boost, no occlusion		Standard, 50 % occlusion	Boost, no occlusion
Kitchen	15.16	17.27	Living room	15.70	20.49
Utility room	4.79	5.93	Main bedroom	16.35	20.07
Cloak room	6.36	7.62	Rear bedroom	13.53	16.41
Bathroom	12.32	14.12			

Crack distribution

Total envelope crack dimension was calculated using the result from the blower door test carried out by MEARU (2015). However, location of these cracks is uncertain and must be assumed. In a first attempt, cracks were located assuming the main source of infiltration will be due to the cracks between the window frame and the wall. Therefore, crack lengths were assumed to be the same as the window width in each room and the crack width was 3 mm so the infiltration result matches the 1.78 ach measured in the blower door test. A second option is to locate the cracks assuming the leakage is due to small holes and imperfections in the external walls. Thus, the crack lengths are defined according to exterior wall area keeping the 3 mm width calculated previously. Table 4.14 shows the dimension and location of the cracks according these two options.

Table 4.14: Crack dimensions and location

Crack location	Based on window width	Based on wall area
	Crack dimension	
Living room South	3mmx5.22m	3mmx2.2m
Kitchen North	3mmx2.3m	3mmx2m
Utility room North	3mmx1.68m	3mmx0.7m
Utility room East	-	3mmx1.4m
Cloak room North	-	3mmx0.7m
Cloak room East	3mmx1.04m	3mmx0.7m
Hall South	3mmx1.88m	3mmx0.7m
Hall East	-	3mmx0.7m
Main Bedroom South	3mmx3.54m	3mmx2.2m
Main Bedroom East	-	3mmx0.3m
Rear Bedroom North	3mmx1.88m	3mmx1.2m
Bathroom East	3mmx1.04m	3mmx0.9m
Bathroom North	-	3mmx0.7m
Upper hall East	-	3mmx1.4m

4.4.2. Temperature sensitivity analysis

In the case of the indoor temperature, the percentage of door opening area inside the house, the supply/extract flow rates, the temperature set-point and the crack distribution have a low level of evidence. Therefore, IC' are calculated for these parameters. To calculate the IC', the ranges of the inputs parameters must be identified. The feasible limits for the percentage of door opening area inside the house, the supply/extract flow rates and the crack distribution have already been described.

Temperature set-point

According to CIBSE Guide A (Chartered Institution of Building Services Engineers, 2015), recommended temperatures for dwellings range from 17 to 25 °C depending on the season and room type. Therefore, these values are taken as the minimum and maximum values for the temperature set-point to control the heating system.

4.5. Hierarchy of Influence Coefficients

For each factor (occupancy, infiltration and heating system), the CVRMSE and IC' are calculated for the lower and upper limits of the corresponding input variable (IP) according to Equation (3.3). Then, the IC' are ranked from the highest to the lowest. This gives the order in which the parameters must be adjusted to meet the calibration criteria. Table 4.15 to Table 4.20 show the rankings for the IC' for the CO_2 concentration and temperature in the living room and bedrooms.

Table 4.15. Hierarchy of Modified Influence Coefficients (IC') for CO_2 in the living room

	INPUT	IP_{BC}	$CVRMSE_{BC}$	IP	CVRMSE	IC'	Ranking
Occup.	Metabolic rate (W)	107.1	24.02%	50.0	25.04%	0.080	2
			24.02%	192.8	26.63%	0.136	
Infilt.	Opening area of doors inside the building (m^2)	0.21	24.02%	0.01	27.57%	0.157	1
			24.02%	1.70	23.12%	0.005	
	Supply rate (l/s)	12.25	24.02%	20.5	24.26%	0.015	3
			24.02%	15.7	24.02%	0.001	

Table 4.16: Hierarchy of Modified Influence Coefficients (IC') for CO_2 in the main bedroom

	INPUT	IP_{BC}	$CVRMSE_{BC}$	IP	CVRMSE	IC'	Ranking
Occup.	Metabolic rate (W)	62.7	26.29%	50.0	27.07%	0.148	1
			26.29%	112.9	25.48%	0.039	
Infilt.	Supply rate (l/s)	15.06	26.29%	20.1	27.35%	0.121	2
			26.29%	16.4	26.61%	0.143	

Table 4.17: Hierarchy of Modified Influence Coefficients (IC') for CO_2 in the rear bedroom

	INPUT	IP_{BC}	$CVRMSE_{BC}$	IP	CVRMSE	IC'	Ranking
Occup.	Metabolic rate (W)	55.4	16.63%	44.00	16.77%	0.043	1
			16.63%	99.72	21.50%	0.367	
Infilt.	Supply rate (l/s)	12.58	16.63%	16.41	16.94%	0.061	2
			16.63%	14.76	16.63%	0.002	

Table 4.18. Hierarchy *of Modified Influence Coefficients (IC') for temperature in the living room*

	INPUT	IP_{BC}	$CVRMSE_{BC}$	IP	CVRMSE	IC'	Ranking
Infilt.	Opening area of doors inside the building (m^2)	0.21	8.39%	0.012	26.37%	2.275	2
			8.39%	1.68	7.13%	0.021	
	Supply rate (l/s)	12.25	8.39%	20.49	8.82%	0.077	3
			8.39%	15.7	8.90%	0.217	
Heating system	Temperature set-point (°C)	20	8.39%	17	14.75%	5.061	1
			8.39%	25	13.59%	2.485	

Table 4.19. Hierarchy of Modified Influence Coefficients (IC') for temperature in the main room

	INPUT	IP_{BC}	$CVRMSE_{BC}$	IP	CVRMSE	IC'	Ranking
Infilt.	Supply rate (l/s)	15.1	20.11%	20.1	11.95%	1.220	2
			20.11%	16.4	15.39%	2.739	
Heating system	Temperature set-point (°C)	20	20.11%	17	7.83%	4.071	1
			20.11%	25	36.14%	3.189	

Table 4.20. Hierarchy of Modified Influence Coefficients (IC') for temperature in the rear bedroom

	INPUT	IP_{BC}	$CVRMSE_{BC}$	IP	CVRMSE	IC'	Ranking
Infilt.	Supply rate (l/s)	12.58	23.36%	16.41	14.46%	1.252	2
			23.36%	14.76	18.22%	1.269	
Heating system	Temperature set-point (°C)	20	23.36%	17	7.87%	4.421	1
			23.36%	25	39.60%	2.780	

According to the results in Table 4.15 to Table 4.20, the parameters that have the greatest impact on the CO_2 concentration are the metabolic rate for the bedroom and the opening area of indoor door for the living room. The one that has a greater impact on the indoor temperature is the temperature set-point to control the heating system. Therefore, these parameters will be adjusted first.

4.6. Model tested for acceptance

4.6.1. CO_2 concentration acceptance criterion

The British Standard BS EN 15251:2007 (BSI, 2007) recommends CO_2 concentration limits above outdoor concentration. The comfort zones for categories I, II, III and IV are shown in Table 4.21. It can be seen that the minimum amplitude difference between zones is 150 ppmv. Therefore, a maximum difference between the simulated and the measured percentile of 150 ppmv is considered acceptable for CO_2 calibration as the simulated and measured CO_2 concentrations will be included in the same IAQ zone category.

Table 4.21. Recommended criteria and categories for the indoor environment (BSI, 2007)

Category	Corresponding CO_2 above outdoors (ppmv)	Amplitude difference between categories (ppmv)
I	350	150
II	500	300
III	800	-
IV	> 800	-

Figure 4.26 to Figure 4.28 show the 50 %, 75 % and 90 % percentiles of the simulated and measured data for the living room and the bedrooms for CO_2 concentration assuming the ambient concentration is 600 ppmv.

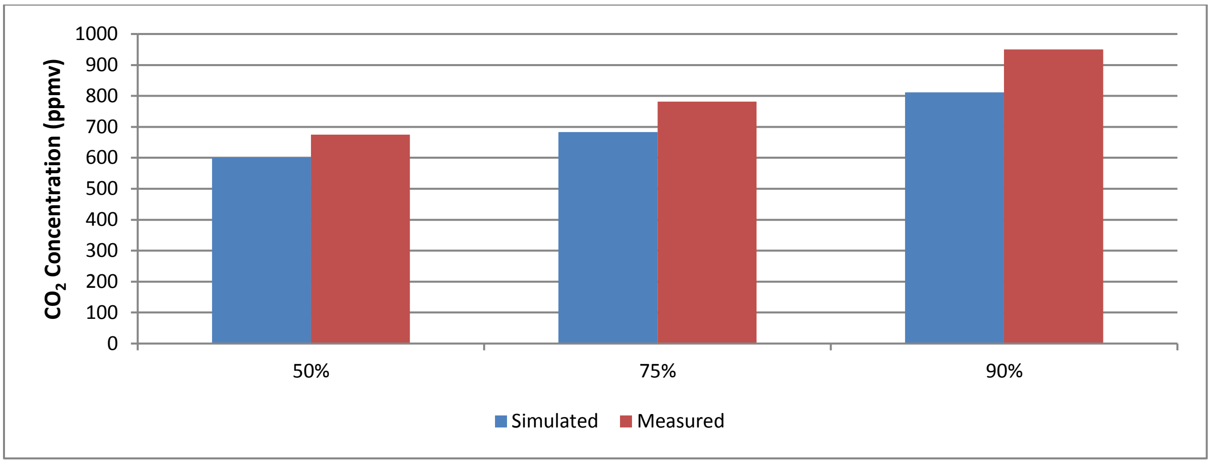

Figure 4.26. 50 %, 75 % and 90 % percentiles of both simulated and measured data for the living room for CO_2 concentration

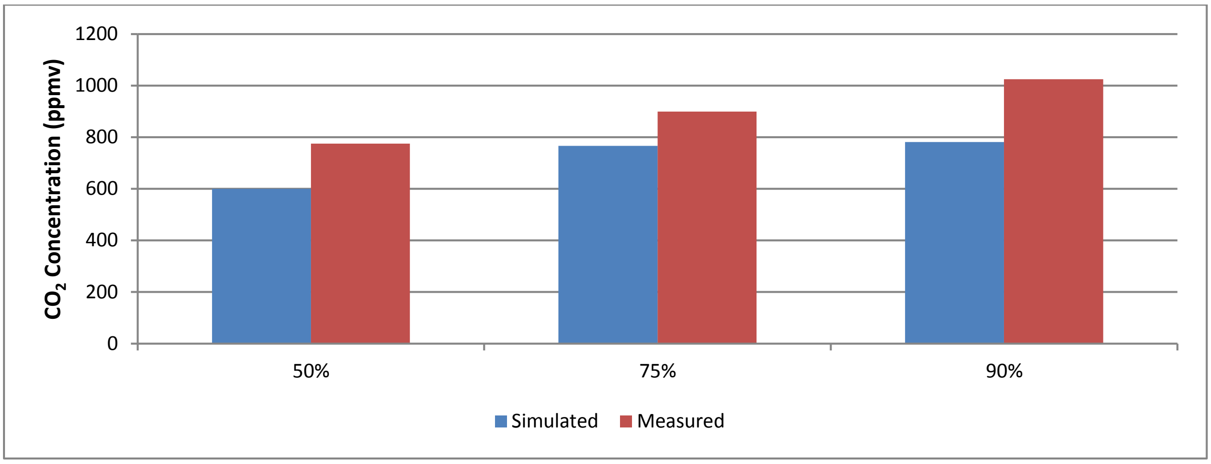

Figure 4.27. 50 %, 75 % and 90 % percentiles of both simulated and measured data for the main bedroom for CO_2 concentration

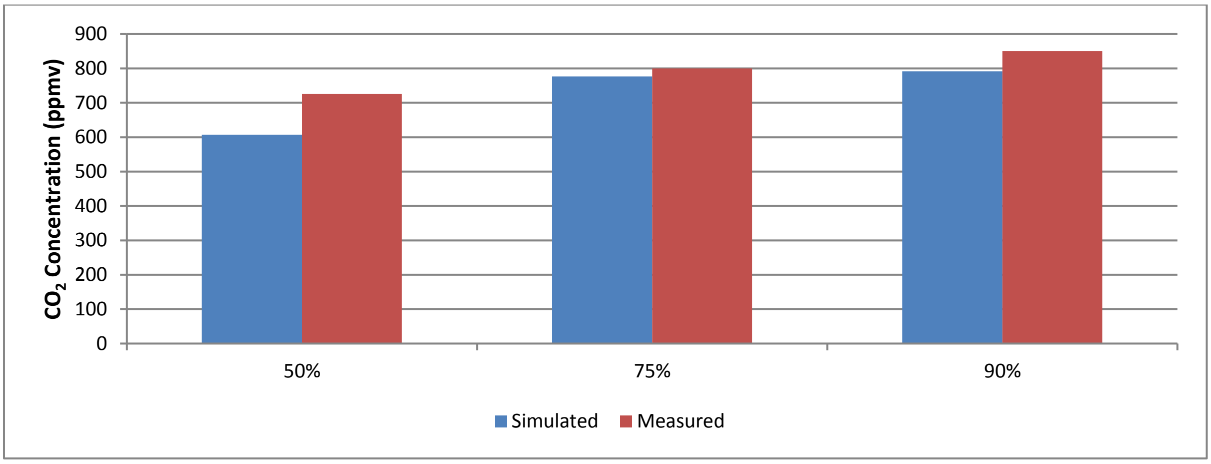

Figure 4.28. 50 %, 75 % and 90 % percentiles of both simulated and measured data for the rear bedroom for CO_2 concentration

The maximum difference between simulated and measured percentiles is 243 ppmv. This difference in the percentiles is greater than 150 ppmv, therefore, further adjustment of inputs will be carried out using the hierarchy of IC' previously explained and the multi-objective calibration.

4.6.2. Temperature acceptance criterion

According to the analysis of the SCATs project database (Nicol and Humphreys, 2002), where indoor conditions of 26 office buildings across Europe were measured, the range of temperatures at which discomfort will be acceptable is up to ± 2 °C from the comfort temperature. Therefore, the percentile comparison (50 %, 75 % and 90 %) should be within 2 °C to be considered acceptable for temperature calibration. Figure 4.29 to Figure 4.31 show the 50 %, 75 % and 90 % percentiles of the simulated and measured data for the living room and the two bedrooms for temperature of the initial model before the calibration.

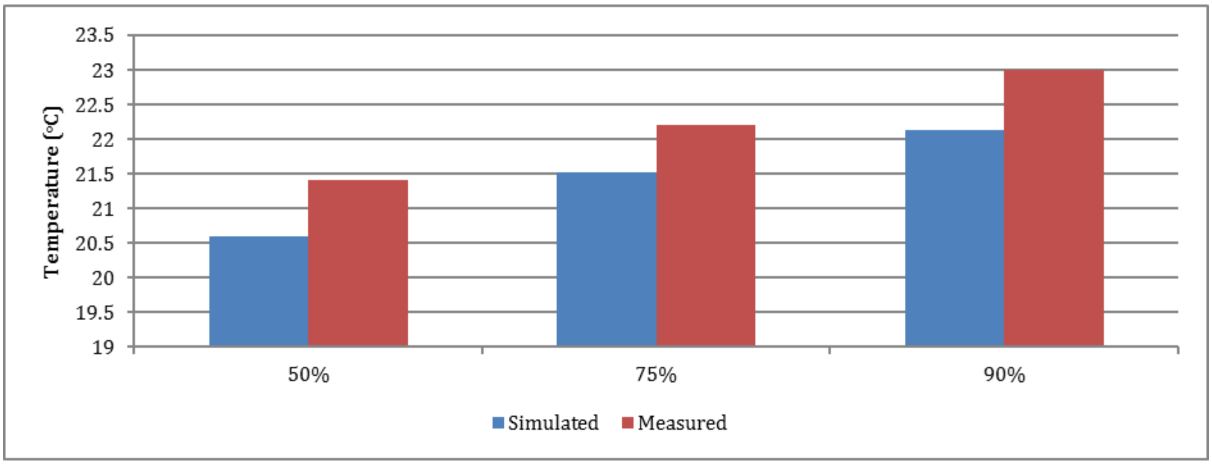

Figure 4.29. 50 %, 75 % and 90 % percentiles of both simulated and measured data for the living room for indoor temperature

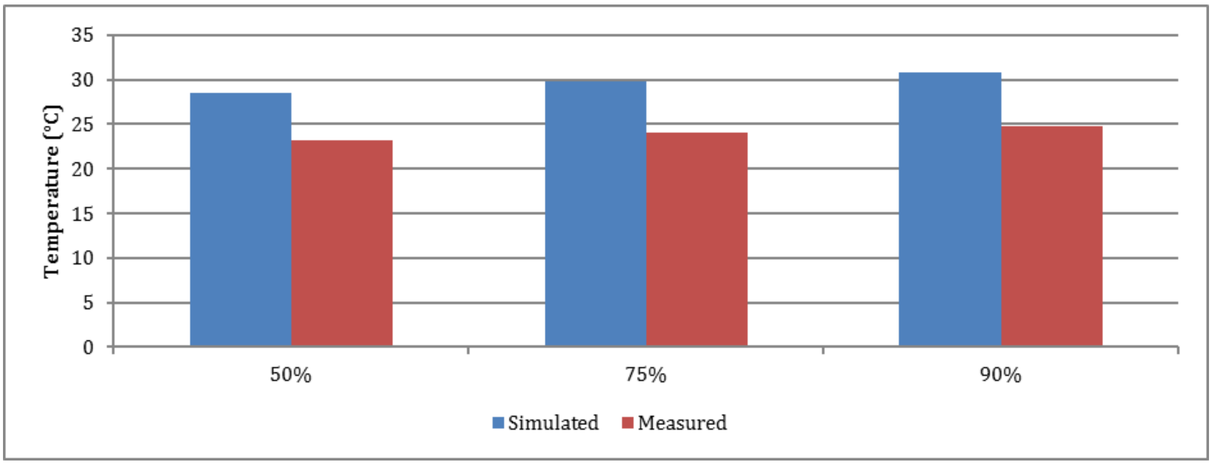

Figure 4.30. 50 %, 75 % and 90 % percentiles of both simulated and measured data for the main bedroom for indoor temperature

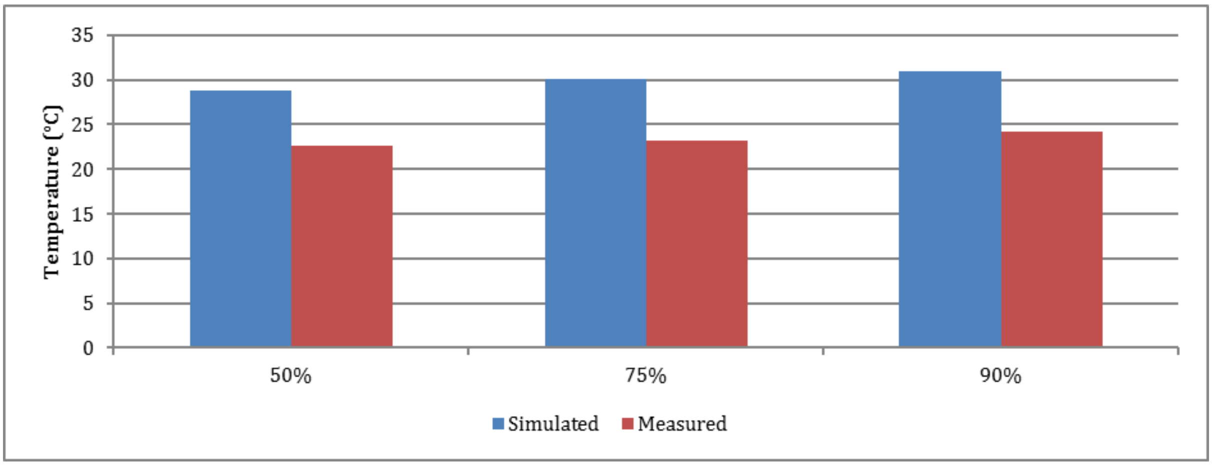

Figure 4.31. 50 %, 75 % and 90 % percentiles of both simulated and measured data for the rear bedroom for indoor temperature

The maximum difference between simulated and measured percentiles is 6.9 °C which is greater than 2 °C. Therefore, adjustment of inputs is needed.

4.7. Multi-objective calibration

To calibrate the model based on several parameters, a multi-objective function was defined as in Equation (3.4), and this function needed to be minimised. In this case, only temperature and CO_2 were used to calibrate the model as previously explained. Regarding the weighting factors, all were given the same value as the objective was the assessment of temporal and spatial distribution of overheating and poor IAQ within the house, and both temperature and CO_2 are considered equally important. Hence, the function that needs to be minimised is given in Equation (4.1).

$$f = \sum_{zones} (CVRMSE\ (CO_2) + \ CVRMSE(T)) \tag{4.1}$$

To facilitate the process of minimising the previous function, the focus will be on one of the objectives at a time. From the SA, the parameters that need to be adjusted first are the metabolic rate and the control temperature for the heating system. Metabolic rate will vary the CO_2 and temperature results while temperature control will only change the indoor temperature. Therefore, the easiest way to proceed in this case is to do the calibration focusing on CO_2 concentration first, and once there is a good agreement between the simulated results and measured data, the calibration based on temperature will be carried out.

4.8. Inputs adjusted

4.8.1. CO_2 concentration

According to the ranking, the parameter that has a greater impact on the CO_2 concentration is the metabolic rate for the bedrooms. Therefore, this is the first parameter to adjust. Table 4.22 shows the CV RMSE values for the CO_2 concentration results assuming different metabolic rates within the feasible limits.

Table 4.22: Impact of metabolic rate changes on CO_2 results

Base Case				**Changes**			
Metabolic rate (MR_{BC})	**CV $RMSE_{BC}$**			**Metabolic rate**	**CV RMSE**		
	Living	**Bed1**	**Bed2**		**Living**	**Bed1**	**Bed2**
Living=107.1 W Bed1=62.7 W Bed2=55.4 W	24.02%	26.29%	16.63%	1.8 * MR_{BC}	26.63%	25.48%	21.50%
				1.5 * MR_{BC}	25.11%	25.33%	18.83%
				1.2 * MR_{BC}	24.24%	25.72%	17.11%
				50 W	25.04%	27.07%	16.77%

Looking at these results, it can be seen that the metabolic rate that gives best results are 1.2*MR_{BC} for the living room, 1.5*MR_{BC} for the main bedroom and 50 W for the rear bedroom. Taking this as the new base case, the next parameter is adjusted. According to the ranking, the door opening area has a great impact on the CO_2 concentration in the living room. Therefore, this parameter is adjusted next. Table 4.23 shows the CV RMSE values for the CO_2 concentration results the living room assuming different door opening areas within the feasible limits.

Table 4.23. Impact of door opening area changes on CO_2 results in the living room

Door opening area (m^2)	CV RMSE
0.21	24.24%
0.01	31.43%
1.68	23.01%
0.84	23.40%

Results show that simulated CO_2 concentration in the living room matchs the measured data better when the internal doors are fully open. Finally, changing the crack distribution does not make a significant difference on the CO_2 results. After these changes, the maximum difference between simulated and measured percentiles is 174 ppmv, which is 16 % higher than the 150 ppmv criterion but it can be considered acceptable for the purposes of this study.

4.8.2. Temperature

According to the ranking, the parameter that has a greater impact on the temperature is the temperature set-point of the heating system. Table 4.24 shows the CV RMSE values for the temperature results assuming different temperature set-points.

Table 4.24: Impact of temperature set-point changes on temperature results

Temperature set-point (°C)	CV RMSE			
	Living	Bed1	Bed2	Total
16	19.68%	9.67%	8.34%	37.70%
17	15.71%	7.43%	8.61%	31.75%
18	12.14%	11.53%	14.12%	37.79%
19	9.07%	17.64%	20.72%	47.43%
20	7.09%	23.77%	27.10%	57.96%
21	6.68%	28.48%	31.90%	67.06%

Looking at the results from Table 4.24, it can be seen that the temperature set-point that gives best results is 17 °C. After changing this, the maximum difference between simulated and measured percentiles is 3.5 °C, which is 75 % higher than the 2 °C criterion and therefore, further adjustment of inputs is needed.

Once all the prioritised parameters have been adjusted, it is necessary to go back and look at the list of uncertain parameters identified in Table 4.9 and Table 4.10. Looking at these tables, it can be seen that there are three inputs with a high level of uncertainty that have not been adjusted: the internal solar protection and the spatial distribution of appliances and lighting. Hence, these are the next inputs that should be changed. First, simulations changing the use of internal solar protection (curtains) are run to minimise the CV RMSE and the percentiles differences. CVRMSE results are shown in Table 4.25.

Table 4.25. Impact of temperature set-point changes on temperature results

	CV RMSE			
	Living	**Bed1**	**Bed2**	**Total**
Curtains	15.71%	7.43%	8.61%	31.75%
No curtains	14.62%	7.45%	7.46%	29.53%

According to Table 4.25, best results are obtained when no curtains are assumed. After this change, the maximum difference between simulated and measured percentiles is 1.7 °C, which is lower than the 2 °C criterion and can be considered acceptable.

4.9. Model calibrated

After applying the calibration procedure, the maximum differences between simulated and measured percentiles are 174 ppmv and 1.7 °C for the CO_2 concentration and indoor temperature, respectively. Regarding the multi-objective function defined in (4.1), the values of CV RMSE that minimises it are shown in Table 4.26.

Table 4.26: CV RMSE Results for the calibrated model

	Living	Bed1	Bed2
CV RMSE (CO_2)	23.01 %	25.28 %	16.63 %
CV RMSE (T)	14.62%	7.45%	7.46%

Finally, this calibration process gives the results shown in Table 4.27, where it can be seen that the simulated results are in acceptable agreement with measured data in terms of average and standard deviation of indoor temperature and CO_2 concentrations in the living room and bedrooms. Some discrepancies persist after the calibration as shown in Figure 4.32 to Figure 4.37. However, these differences are considered acceptable for the purpose of this study as model calibration was not the main focus of the research but a tool to ensure the model is acceptable to investigate IEQ issues in low-energy houses.

Table 4.27: Monitored and simulated results for winter

			Living	Bed1	Bed2
Temperature (°C)	Average	Monitored	21.1	22.9	22.5
		Simulated	20.0	23.3	23.0
	Standard dev.	Monitored	1.7	1.5	1.4
		Simulated	0.9	1.0	1.0
CO_2 (ppmv)	Average	Monitored	719	789	716
		Simulated	686	685	658
	Standard dev.	Monitored	159	168	111
		Simulated	118	115	67

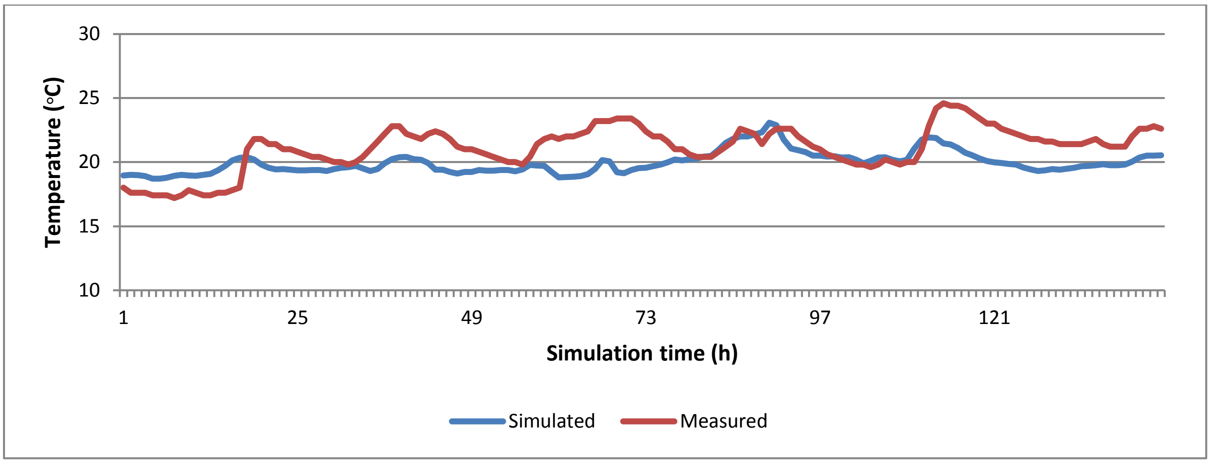

Figure 4.32: Simulated and measured temperature results for calibrated model in the living room

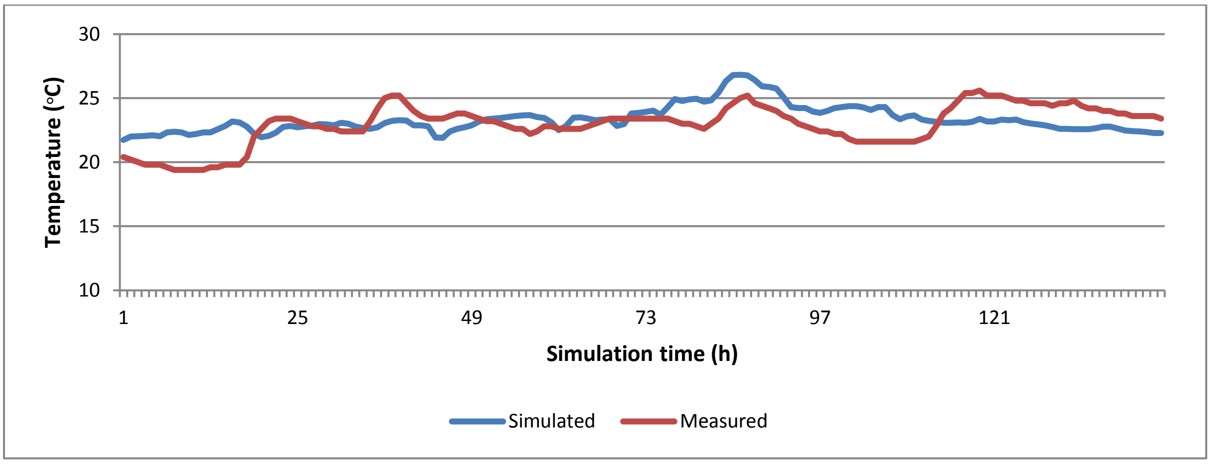

Figure 4.33: Simulated and measured temperature results for calibrated model in the main bedroom

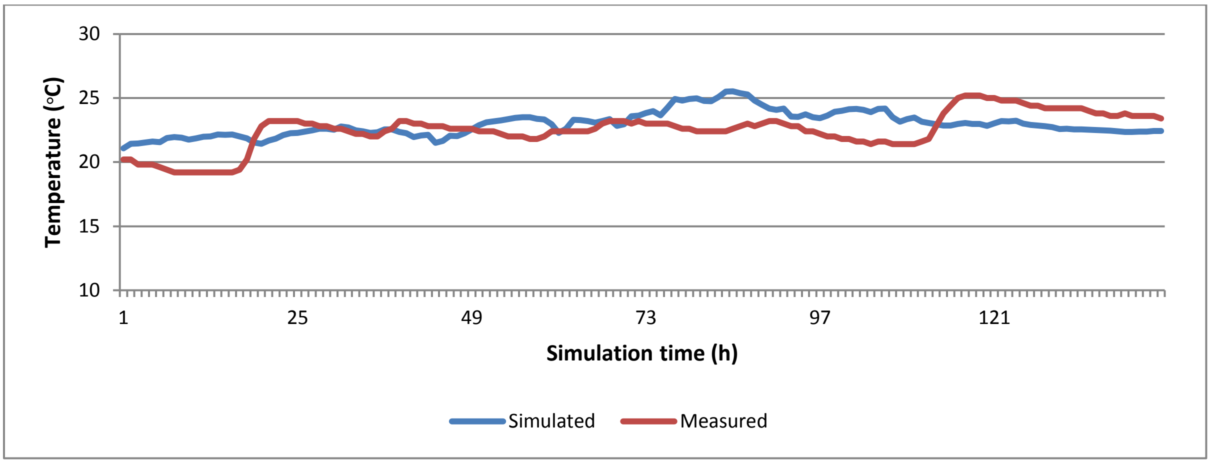

Figure 4.34: Simulated and measured temperature results for calibrated model in the rear bedroom

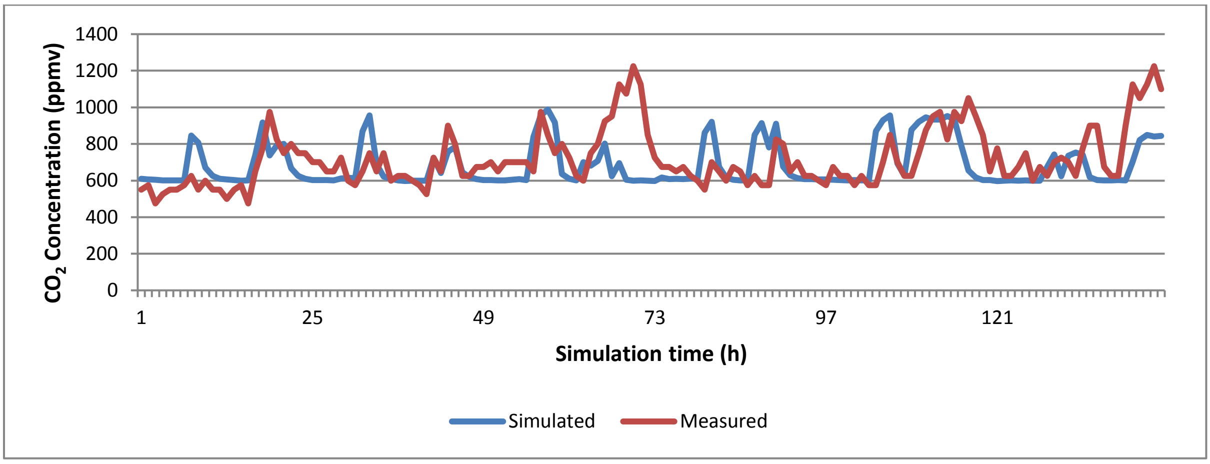

Figure 4.35: Simulated and measured CO_2 results for the calibrated model in the living room

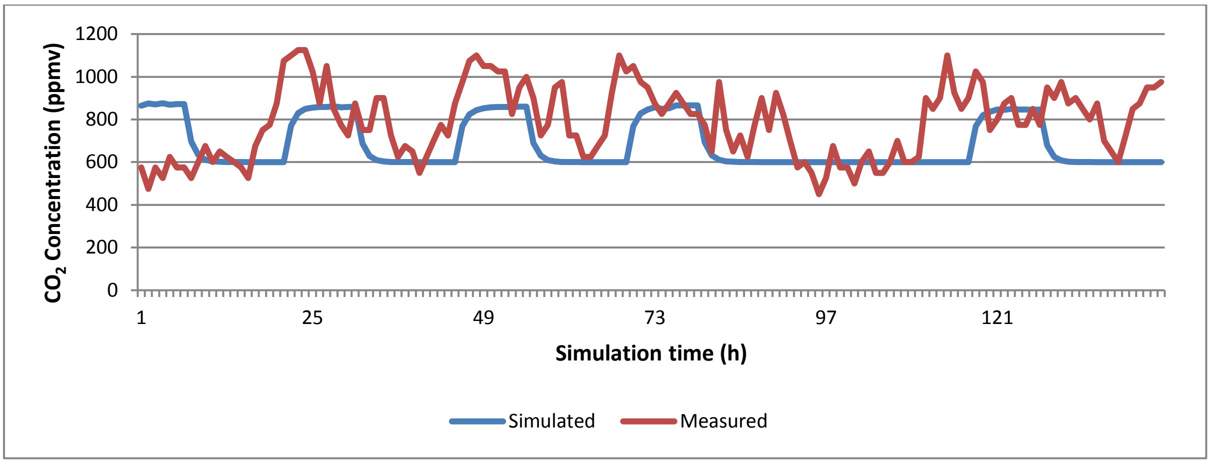

Figure 4.36: Simulated and measured CO_2 results for the base model in the main bedroom

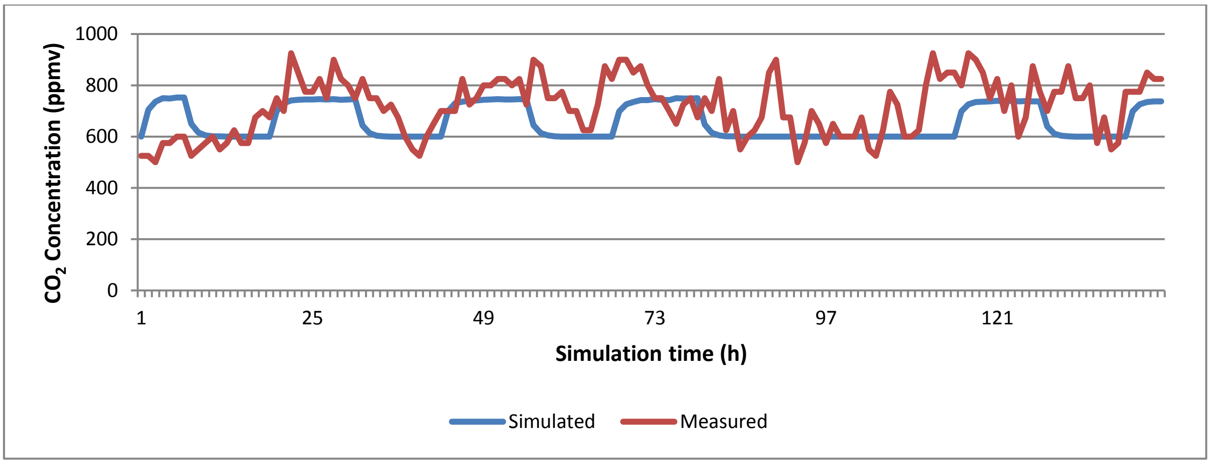

Figure 4.37: Simulated and measured CO_2 results for the base model in the rear bedroom

Once the model is calibrated, a check of RH results is needed to ensure the model is reasonable. Table 4.28 shows the values of CV RMSE for the RH results of the calibrated model and Table 4.29 shows the average and standard deviation of the RH results.

Table 4.28: CV RMSE for the RH results for the calibrated model

	Living	**Bed1**	**Bed2**
CV RMSE (RH)	20.44 %	13.29 %	13.40 %

Table 4.29: Monitored and simulated RH results for winter

		Living	Bed1	Bed2
Average	Monitored	27.1	22.0	22.0
	Simulated	33.0	21.4	21.0
Standard dev.	Monitored	3.3	3.5	3.4
	Simulated	9.6	7.0	6.7

A final check to prove that the simulated results are in acceptable agreement with measured data has been done by extending the simulation to a longer period (January 1st to March 31st), assuming the week used for the calibration is representative and there is no major change in occupants' behaviour. Comparison of simulated and measured results for CO_2 concentration and temperature in the living room and bedrooms is shown in Figure 4.38 and Figure 4.39. For these graphs, the IEQ criteria defined in Chapter 6 (Table 6.4) are used.

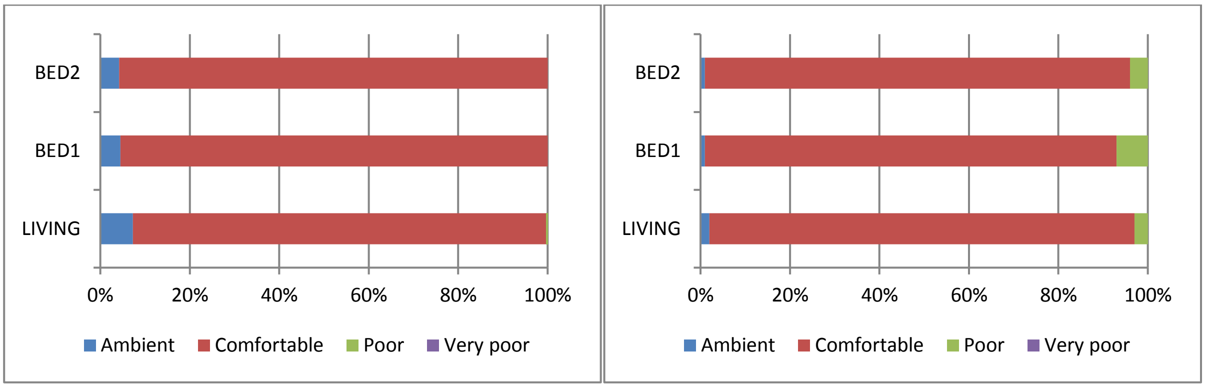

Figure 4.38. Simulated (left) and measured (right) CO_2 results for the calibrated model for a winter period (January 1st to March 31st)

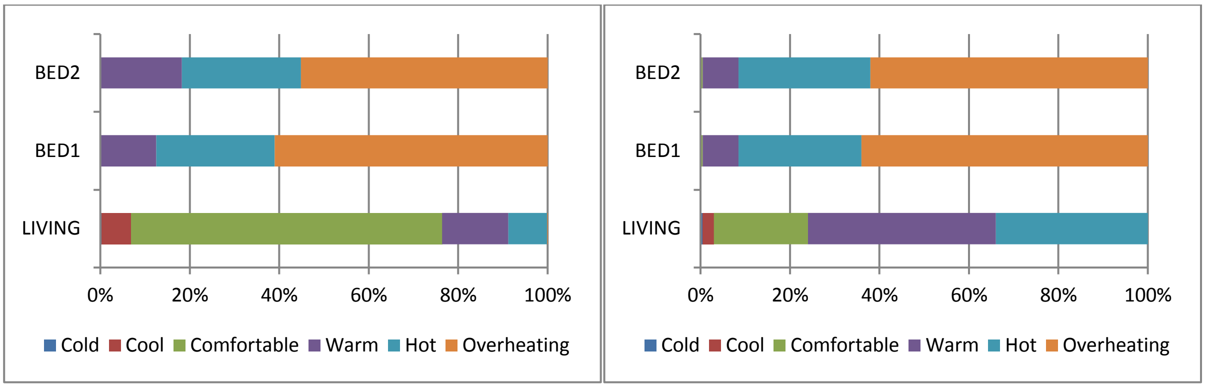

Figure 4.39. Simulated (left) and measured (right) temperature results for the calibrated model for a winter period (January 1st to March 31st)

4.10. Summary

The model of the case study selected has been described, explaining the different assumptions made when some information was missing. The characteristics of the building were related to the location and climate, geometry, materials and constructions, IHG, infiltration and ventilation, heating system and solar protection. Once the base model was built, the calibration methodology described in the previous chapter was applied. The calibration criteria to assess if indoor temperature and CO_2 concentration results are in acceptable agreement against measured data have been defined, addressing the current absence of specific guidelines for model calibration based on the indoor environment. These criteria have been defined using the British Standard BS EN 15251:2007 (BSI, 2007) recommendations and comfort data from previous monitoring studies. Maximum differences between the simulated and the measured percentiles of 150 ppmv and 2 °C were considered acceptable for CO_2 and temperature calibration respectively. Finally, results showed acceptable agreement between simulated and measured data regarding the indoor environment. Hence, predictions can be considered accurate enough to predict overheating and indoor air quality issues within this low-energy dwelling. Several assumptions regarding IHG, occupancy profile, MVHR ventilation rates, etc. will be made in Chapter 6 to adapt this model and generalise the analysis to other low-energy houses in mild climates.

Chapter 5. Implementation of pollutant models

Following the review of pollutant sources and sinks undertaken in Chapter 2, four emission models and a deposition and resuspension model were implemented in ESP-r. This chapter explains the implementation of these models, the assumptions made to simplify their implementation and the checks made to identify the impact of these assumptions on the simulation results. Finally, the limitations of these models are highlighted.

As mentioned in Chapter 1, ESP-r was selected for its capability to simulate dynamic variations of indoor environmental conditions within a building and being extensively validated (Strachan et al., 2008). In addition, there are a number of source and sink algorithms previously implemented in ESP-r by Samuel (2006). These algorithms are:

- Constant coefficient source
- Cut-off concentration source
- Exponential decay and generation
- Boundary layer diffusion model
- Time dependent constant mass
- Personal CO_2 emission

Following the review of commonly found pollutants and their impact on health undertaken in Chapter 2, the target pollutants selected were: CO_2, formaldehyde, NO_2, PM_{10}, $PM_{2.5,}$ radon and mould. However, as explained in Chapter 4, measurements of radon and mould were not included in the monitoring as the risk of high radon concentrations were negligible and risk of mould growth can be estimated from RH levels. Therefore, radon and mould are not included in the modelling and focus is on CO_2, formaldehyde, $PM_{2.5}$, PM_{10} and NO_2. As the emission model of CO_2 by building inhabitants was already implemented in ESP-r, a review of source and sink models regarding formaldehyde, $PM_{2.5}$, PM_{10} and NO_2 was carried, followed by their implementation when needed.

5.1. Pollutant emission models

5.1.1. Formaldehyde

A review of emission models for formaldehyde was carried out and, according to their detail and complexity, they can be classified into three categories:

- Constant emission models
- Time-dependent models
- Detailed models

The models in the first two categories are simple and easy to implement. They are usually developed using regression analysis of chamber test data (Liu and Little, 2012). Their main advantage is that they require less specific parameters than more detailed models, and these parameters are easily found in the literature. These models were retrieved from the PANDORA (a comPilAtioN of inDOor aiR pollutAnt emissions) database (Abadie and Blondeau, 2011) and are defined as follows:

Gas steady state model:

$$S = constant \tag{5.1}$$

where S is the emission rate (mg/m^2h). This model was already implemented in ESP-r.

Gas transient power law model:

$$S = a_1 \times t_p^{-a_2} \; if \; t \leq t_p \tag{5.2}$$

$$S = a_1 \times t^{-a_2} \; if \; t > t_p \tag{5.3}$$

where S is the emission rate (mg/m^2h), a_1 ($mg/m^2h^{(a2-1)}$), a_2 (-) and t_p (h) are specific parameters for the material.

Gas transient discrete emission data model:

$$S = a_i \; at \; t = t_i, \qquad i \in \mathbb{N} \tag{5.4}$$

where S is the emission rate (µg/gh or µg/m^{2}h) at different times t_i (h). For its implementation, the emission rate was assumed to be constant between intervals.

Gas transient peak model:

$$S = a_1 e^{-0.5\left(\frac{ln(t/t_p)}{a_2}\right)^2} \tag{5.5}$$

where S is the emission rate (mg/m^{2}h), a_1 (mg/m^{2}h), a_2 (-) and t_p (h) are specific parameters for the material.

Finally, regarding the third category, detailed models which estimate the emission rate based on physical parameters of building materials, their main advantage is that they are able to take into account the impact of the indoor environment (temperature, RH, air velocity etc.) on the emission rate. Previous studies have found that indoor environment conditions have a significant impact on formaldehyde and other VOCs' emissions (Haghighat and De Bellis, 1998; Liang et al., 2014; Liu and Little, 2012). Consequently, these models may obtain a better level of accuracy when indoor conditions differ from the fixed chamber test conditions used in more simple models.

Of the detailed models, the model chosen was the numerical model developed by Huang and Haghighat (2002) as it is one of the most accepted models for VOC, including formaldehyde, emission for dry materials (Liang, 2016; Liu et al., 2015; Wang and Zhang, 2009). The numerical solution of the model is:

$$R(t) = h\left(\frac{C_m(b,t)}{k} - C_a(t)\right) \tag{5.6}$$

where R(t) is the formaldehyde emission rate (µg/m^{2}s), h is the mean mass-transfer coefficient (m/s), C_m(b,t) is the formaldehyde concentration at the material surface (µg/m^3), k is the dimensionless material/air partition coefficient, C_a(t) is the formaldehyde concentration in the room air (µg/m^3), b is the material thickness (m) and t is the time (s).

This model assumes that the formaldehyde is completely mixed in the room air and the initial concentration inside the material is homogenous. As a boundary condition, it is assumed that no formaldehyde is passing through the bottom surface of the material.

Parameter calculation:

The mean mass-transfer coefficient can be calculated using the following expression:

$$Sh = \frac{h\,l}{D_a} \tag{5.7}$$

where Sh is the Sherwood number (ratio of convective mass transfer rate and mass diffusion rate), l the characteristic length (m) and D_a the diffusion coefficient of the air (m^2/s). The characteristic length (l) is the length of the material in the direction of the airflow as shown in Figure 5.1.

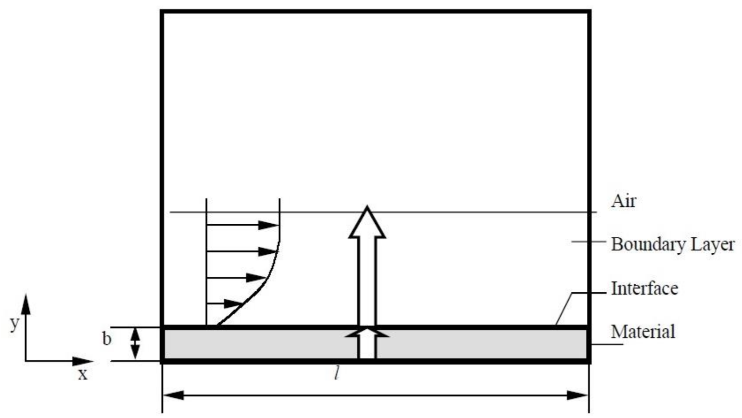

Figure 5.1: Formaldehyde emission from dry building materials (modified from Huang & Haghighat 2002)

The diffusion coefficient of the air (D_a) can be estimated using the method of Fuller, Schettler and Giddings (FSG Method) which is based on the following correlation (Lyman, 1990):

$$D_a = \frac{10^{-7} T^{1.75} \sqrt{M_r}}{P \left(V_a^{1/3} + V_{formald}^{1/3} \right)^2} \tag{5.8}$$

where T is the absolute temperature (K), P is the atmospheric pressure (atm), V_a is the air molar volume (cm^3/mol), $V_{formald}$ is the formaldehyde molar volume (cm^3/mol) and M_r is calculated as:

$$M_r = \frac{\left(M_a + M_{formald} \right)}{M_a M_{formald}} \tag{5.9}$$

where M_a and $M_{formald}$ are the molecular weight of the air and formaldehyde respectively (g/mol).

The Sherwood number can be obtained as a function of the Schmidt number (Sc) and the Reynolds number (Re).

$$Sc = \frac{\upsilon}{D_a} \tag{5.10}$$

$$Re = \frac{u\, l}{\upsilon} \tag{5.11}$$

where υ is the kinematic viscosity of the air (m^2/s) and u is the mean air velocity over the material (m/s).

To calculate the mean air velocity over the material (u), the simplified method used by Bourdin et al. (2014) can be applied. This approach assumes that the mean air velocity over a material is equal to the mean air velocity inside the room, and therefore, it is the same for all the materials within the room. This will underestimate the air velocity near the inlet and overestimate it in other parts of the room. Bourdin at al. (2014) developed a CFD model and compared it to measurements finding it was a good approximation for classrooms with high ventilation rates (3.3 h^{-1}). However, analysis of lower ventilation rates was not undertaken. Therefore, more measurements are needed for different environments and care should be taken when using this approximation. SA of air velocity is done at the end of this chapter in order to investigate the impact of this assumption.

Assuming that the geometry of the room can be considered as a rectangular parallelepiped (see Figure 5.2), the mean air velocity over the material (u) can be estimated using the following expression:

$$u = \frac{V \times N}{H \times W} \tag{5.12}$$

where H and W are the height and the width of the room respectively (m), V is the volume of the room (m^3) and N is the air exchange rate (s^{-1}).

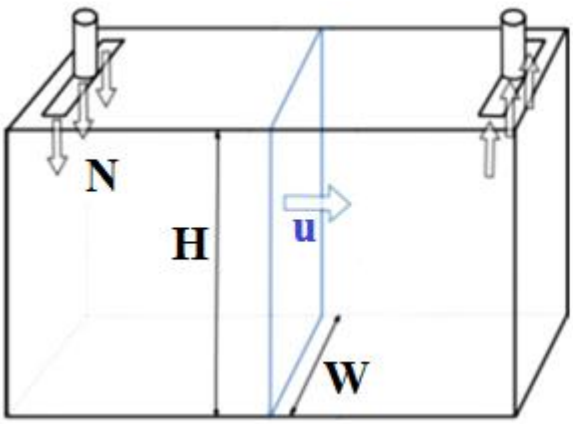

Figure 5.2: Determination of the mean air velocity over the material (u). Modified from Bourdin et al. (2014)

There are two different correlations to obtain Sh for flow on flat plates (NPTEL, 2015):

- Laminar flow (Re < 300,000)

$$Sh = 0.664\, Sc^{1/3} Re^{1/2} \tag{5.13}$$

- Turbulent flow (Re ≥ 300,000)

$$Sh = 0.036\, Sc^{1/3} Re^{4/5} \tag{5.14}$$

The formaldehyde concentration at the material surface was also developed by Huang and Haghighat and it is given in Equation (5.15).

$$\left(\frac{D_m}{\delta y} + \frac{\Delta y}{\Delta t} + \frac{h}{k} - \frac{Lh^2 \Delta t}{k(N\Delta t + Lh\Delta t + 1)}\right) C_m(b,t) = \frac{D_m}{\delta y} C_m(b - \delta y, t) + \frac{\Delta y}{\Delta t} C_m(b, t - \Delta t) + \frac{h}{(N\Delta t + Lh\Delta t + 1)} C_a(t - \Delta t) \tag{5.15}$$

where D_m is the formaldehyde diffusion coefficient of the material (m^2/s), δy is the distance between two grid points in the direction y, in which formaldehyde diffusion takes place (m), Δy is the y dimension of the control volume inside the material (m), Δt is the calculation time step (s), and L is the material loading factor, which is the ratio of the material emitting surface area and room air volume (m^2/m^3) (Bluysse et al., 1997).

Figure 5.3 and Figure 5.4 show the distribution of the grid points inside the material and the control volumes defined according to their position in the material (bottom, internal grid point or surface).

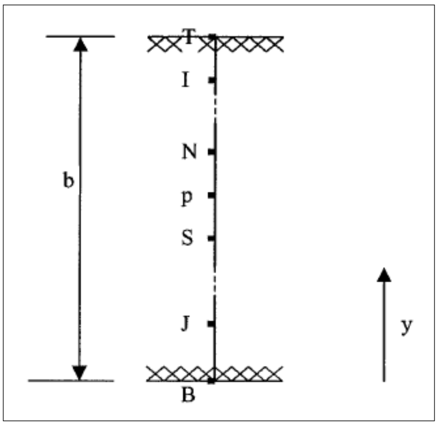

Figure 5.3: Material internal and boundary grid points (Huang, 2003)

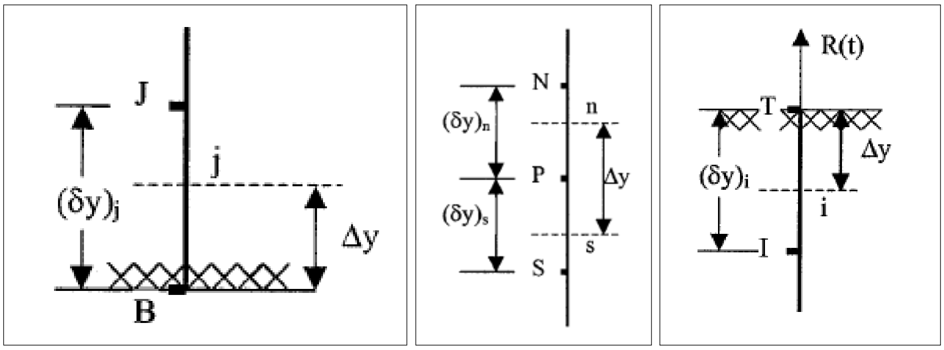

Figure 5.4: Control volumes inside the material: bottom (left), internal grid point (centre) and surface (right) (Huang, 2003)

There are three key parameters in this model that influence the emission rate of materials and are dependent on the environmental conditions. These parameters are:

- Initial emittable concentration, C_0 or $C_m(b,0)$
- Diffusion coefficient of the material, D_m
- Material/air partition coefficient, k

There are different correlations to determine these parameters depending on the indoor conditions. A correlation that takes into account the combined effects of air temperature T (K) and RH (%) on the initial emittable formaldehyde concentration was derived by Liang et al. (2016):

$$C_0 = (1 + C_1 \times RH) C_2 T^{-0.5} e^{\left(-\frac{C_3}{T}\right)} \qquad (5.16)$$

where C_1, C_2 and C_3 are constants which cannot be directly calculated based on physical properties of the material and therefore, they need to be determined experimentally. Previous studies found that the D_m and k dependence on RH was not significant and consequently, correlations of these parameters depending on temperature would give satisfactory results (Liang et al., 2016; Xu and Zhang, 2011).

Deng et al. (2009) developed a correlation to estimate D_m and Zhang et al. (2007) developed a correlation to estimate k, giving the following expressions:

$$D_m = B_1 T^{1.25} e^{\left(\frac{B_2}{T}\right)} \tag{5.17}$$

$$k = A_1 T^{0.5} e^{\left(\frac{A_2}{T}\right)} \tag{5.18}$$

where A_1, A_2, B_1 and B_2 are constants.

5.1.2. Particulate Matter and Nitrogen Dioxide

A review of emission models for Particulate Matter (PM) and Nitrogen Dioxide (NO_2) was carried out and it was found that most studies assume constant emission rates, explained previously for formaldehyde in Equation (5.1) (Dimitroulopoulou et al., 2000; He et al., 2004; Ozkaynak et al., 1997). Additionally, the transient discrete emission data model, explained previously for formaldehyde in Equation (5.4), is also applicable for PM and NO_2 emissions for activities such as burning candles or incense (Abadie and Blondeau, 2011).

5.2. Pollutant deposition and resuspension model

A review of particle deposition and resuspension models was undertaken and it was found that a number of studies used the standard single-compartment box model (Long et al., 2001) which estimates the steady-state indoor concentration of particles depending on the penetration efficiency, air change rate and deposition rate. A dynamic model that takes into account deposition and resuspension mechanisms more accurately is the one used in CONTAM (Dols and Polidoro, 2015). This model was implemented in ESP-r and is defined as follows:

$$R_{PM}(t) = k_d V_z \rho_{air} C_{PM}(t) \tag{5.19}$$

$$S_{PM}(t) = r A_r L_{PM}(t) \tag{5.20}$$

where $R_{PM}(t)$ is the removal rate (kg_{PM}/s), k_d is the deposition rate (s^{-1}), V_z is the zone volume (m^3), ρ_{air} is the density of the air (kg/m^3), $C_{PM}(t)$ is the PM concentration (kg_{PM}/kg_{air}), S_{PM} is the particle resuspension rate (kg_{PM}/m^2), r is the resuspension rate (s^{-1}), A_r is the resuspension surface area (m^2), $L_{PM}(t)$ is the concentration of PM on the deposition surface (kg_{PM}/m^2) and t is time. It should be noted that this removal rate (R_{PM}) includes only the removal rate by deposition and not by ventilation.

5.3. Modelling checks

5.3.1. Formaldehyde emission models

First, checks were made using Excel spreadsheets, and simulations replicating the results from Huang & Haghighat (2002) were run to confirm that the calculations carried out in ESP-r were implemented correctly. Secondly, the impact of the assumptions made to simplify the implementation of Huang and Haghighat's model (Equations (5.6) to (5.18)), needed to be checked. Therefore, a SA for several parameters was undertaken. This was done by changing these parameters in a range that is realistic and commonly found in buildings. Finally, to check the relevance of detailed modelling of formaldehyde emission rates depending on prevailing temperature and RH, simulation results assuming a constant indoor temperature of 23 °C, a constant RH of 50 %, and variable values for temperature and RH, were compared.

Huang and Haghighat's emission model implementation checks:

To check the correct implementation of Huang and Haghighat's emission model in ESP-r, simulations were run replicating the results from the SA they carried out in their study (Huang & Haghighat 2002). A carpet containing VOCs, specifically nonane, was located in a room of 27 m^3. The dimensions of the carpet were 2x1.5 m^2 and the initial concentration was assumed to be $1x10^7$ µg/m^3. The temperature of the room was 23 °C and 100 grid points were assumed inside the material.

The following graphs show the comparison of the results from ESP-r simulations and Huang and Haghighat's study:

- Figure 5.5 and Figure 5.6 show the nonane concentration in the carpet at different depths.

- Figure 5.7 and Figure 5.8 show the concentration of nonane at the surface of the carpet for different air velocities.
- Figure 5.9 and Figure 5.10 show the nonane emission rate for different air velocities.

These graphs show that ESP-r results are in good agreement with the results of Huang and Haghighat's study and therefore, the model was implemented correctly.

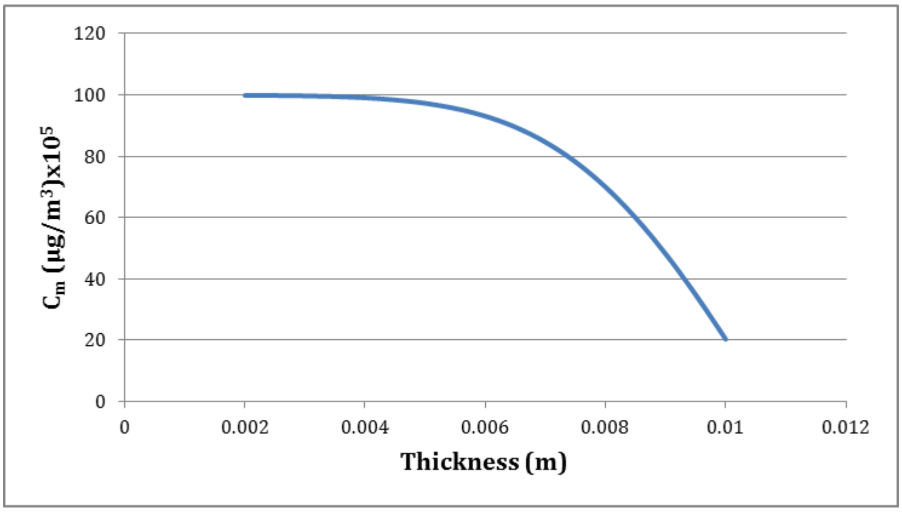

Figure 5.5: Nonane concentration distribution in the carpet from ESP-r 2 days after the start of the emission

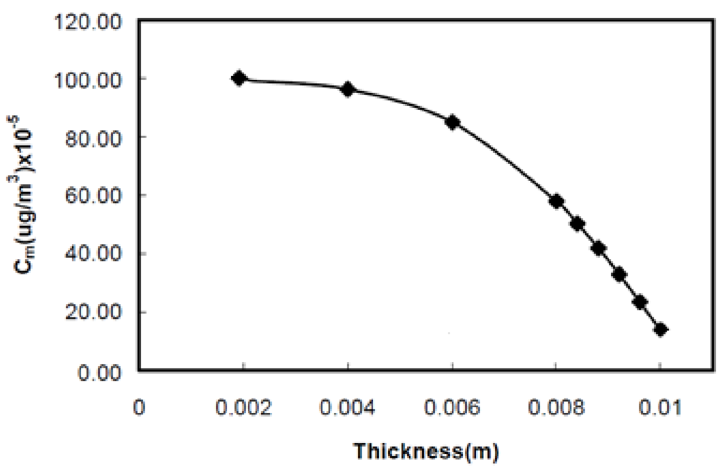

Figure 5.6: Nonane concentration distribution in the carpet from Huang and Haghighat's study 2 days after the start of the emission (2002)

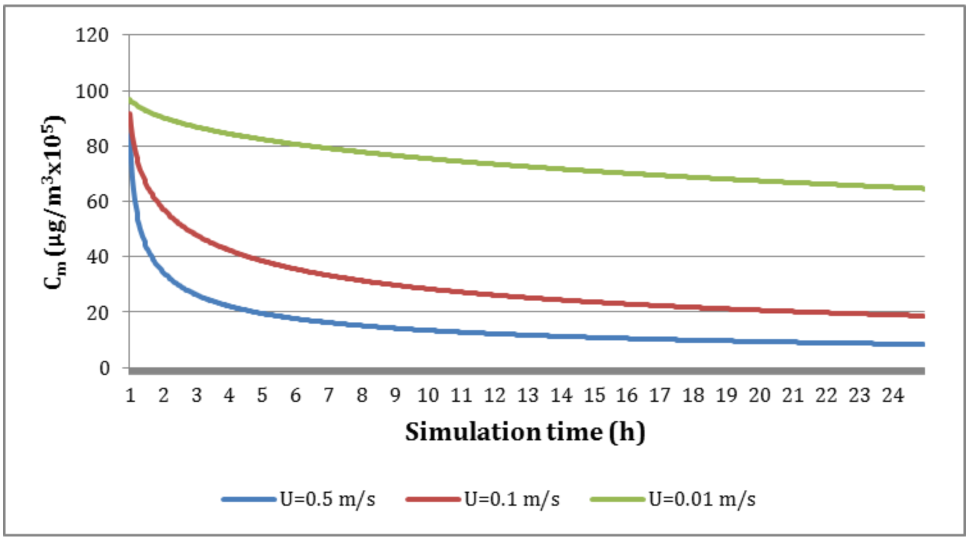

Figure 5.7: Comparison of nonane concentration at the carpet surface from ESP-r

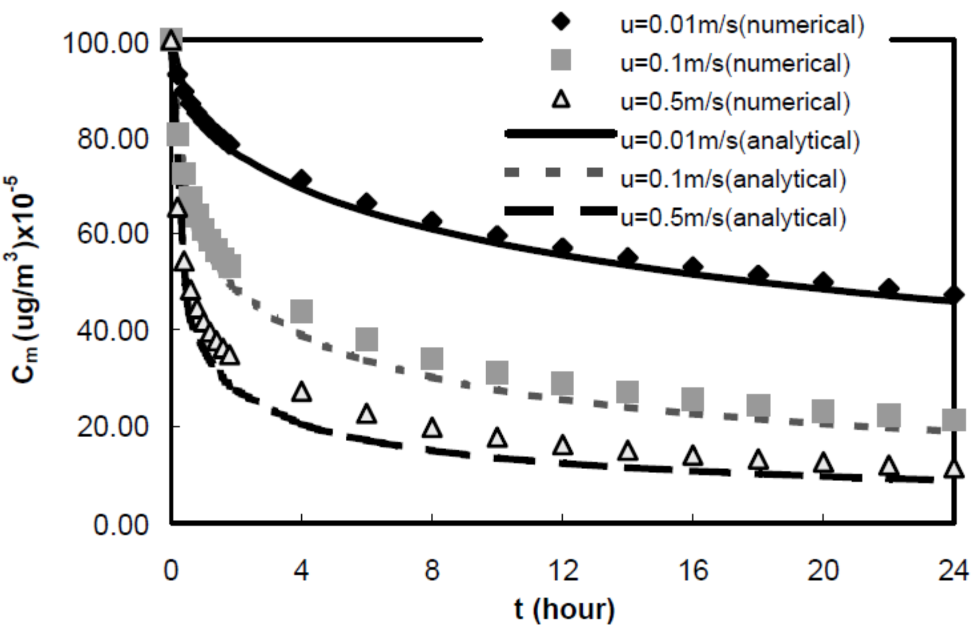

Figure 5.8: Comparison of nonane concentration at the carpet surface from Huang and Haghighat's study (2002)

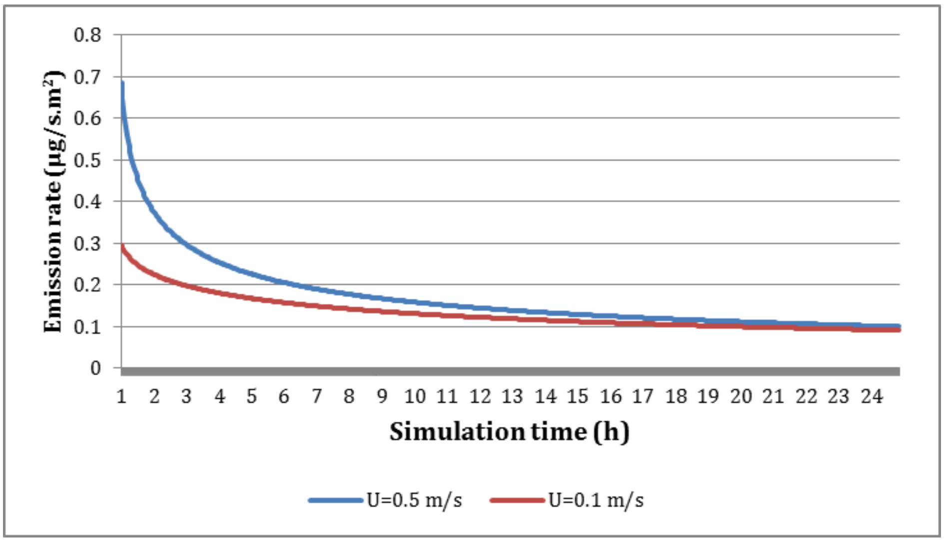

Figure 5.9: Comparison of nonane emission rate from ESP-r

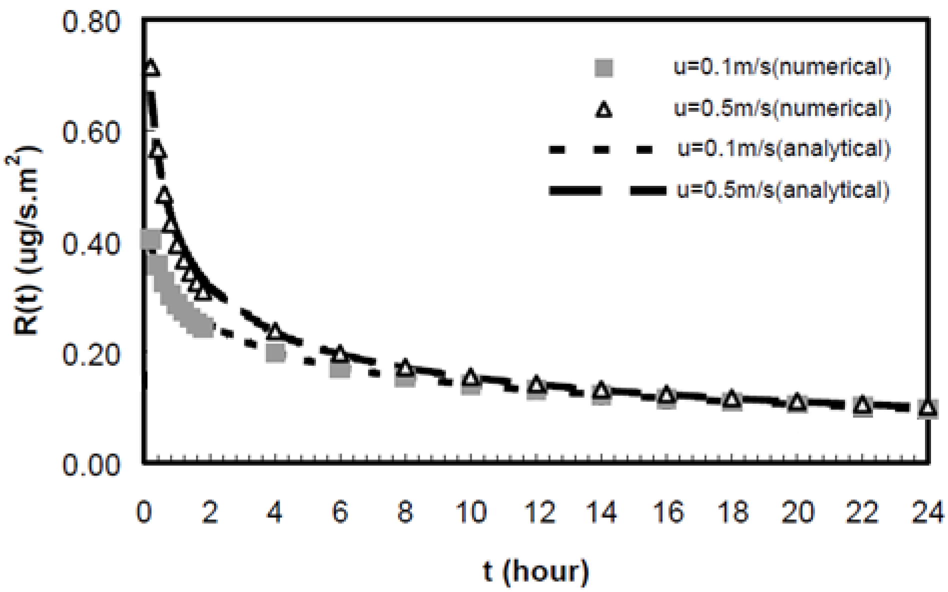

Figure 5.10: Comparison of nonane emission rate from Huang and Haghighat's study (2002)

SA of Huang and Haghighat's emission model parameters

To check the impact of the assumptions made to simplify the implementation of Huang and Haghighat's model, a SA for the air velocity over the material surface, the distance between two grid points inside the material and the simulation time step, was done by changing these parameters in a range that is realistic and commonly found in buildings. For this, a simple 1-zone model was defined and a medium-density fibreboard (MDF) surface was assumed to be the only formaldehyde indoor source. The emission is assumed to start on 2nd January. The dimensions of the zone were 10x10x2.4 m^3 and the dimensions of the MDF surface were 1.95x1.27x0.025 m^3. An almost perfectly sealed room was assumed, defining just two small cracks in the model in order to define the airflow network for contaminant simulation.

Air velocity over the material, u:

Simulations were carried out for three different air velocities: 0.01, 0.1 and 0.5 m/s. These velocities were selected to match those analysed by Huang & Haghighat (2002). Figure 5.11 compares the formaldehyde emission rate for a short period (one day). It can be seen that the air velocity has a great impact on the emission rate at the beginning of the emission, when the emission rate at 0.5 m/s is around five times greater than the emission rate at 0.01 m/s. However, this effect decreases rapidly with time, with only 10 % difference after four hours.

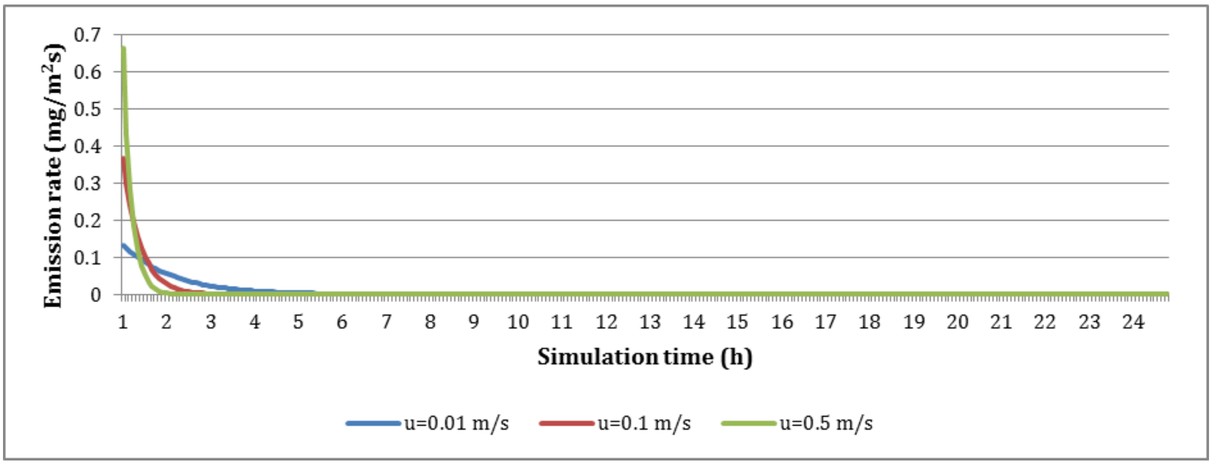

Figure 5.11: Comparison of formaldehyde emission rate for different air velocities for one day

Figure 5.12 compares the formaldehyde concentration at the material surface for a short period. It can be seen that the concentration decreases faster in the case of higher air velocities due to the higher emission rates, as expected.

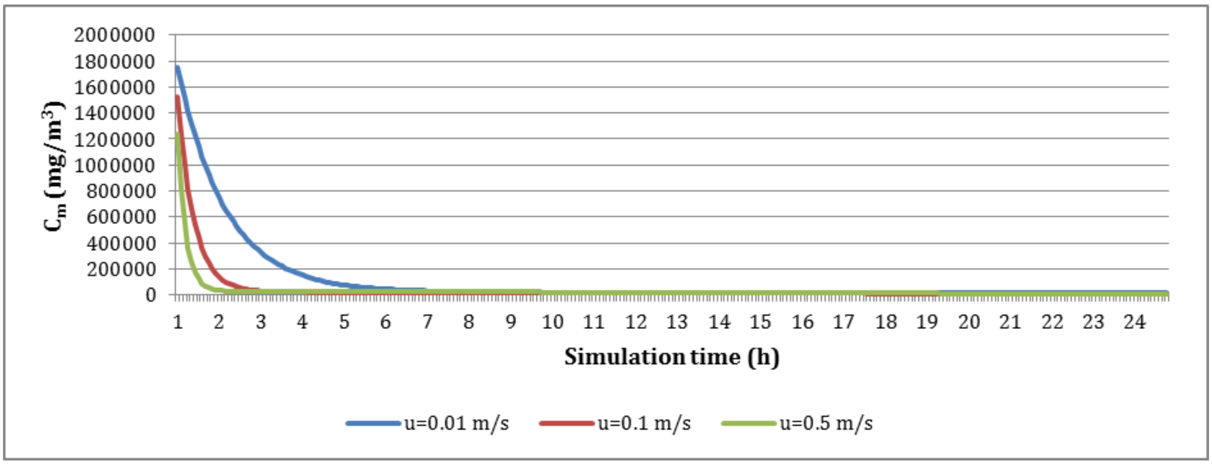

Figure 5.12: Comparison of formaldehyde concentration at the material surface for different air velocities for one day

Figure 5.13 and Figure 5.14 show the formaldehyde concentration of the indoor air for different air velocities for a short period (24 hours) and a long one (3 months). These results indicate that the impact of different air velocities on the IAQ is significant at the start of the emission. However, four days after the emission starts, formaldehyde concentrations in the air are identical in all cases. Thus, air velocity has little influence on IAQ in the long term.

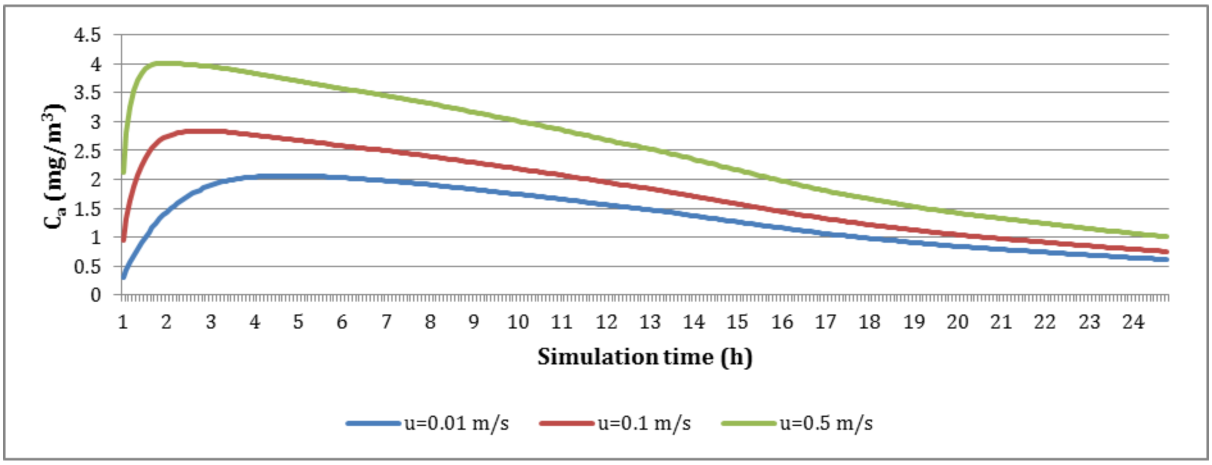

Figure 5.13: Comparison of formaldehyde concentration in the indoor air for different air velocities for one day

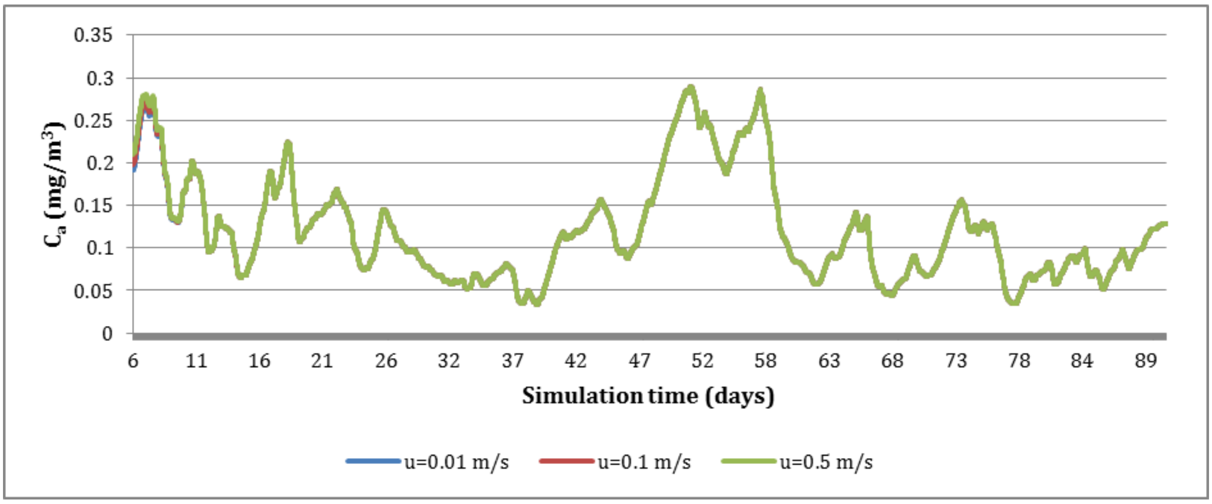

Figure 5.14: Comparison of formaldehyde concentration in the indoor air for different air velocities for three months

Distance between two grid points inside the material, δy:

Simulations were carried out for five different grid sizes, dividing the material thickness between 5, 10, 50, 100 and 200 grid points, to check its impact on the calculated emission rate.

Figure 5.15 to Figure 5.20 compare the formaldehyde emission rate, concentration at the material surface and concentration in the indoor air for a short period (one day) and a long period (three months). It can be seen that the grid size has a great impact on the emission rate and concentration in the material and air during the entire simulation period. However, this effect decreases with increasing number of grid points, as the numerical solution would tend to the analytical one (Liang, 2018), and for 50 grid points and above the differences are negligible after 3 months.

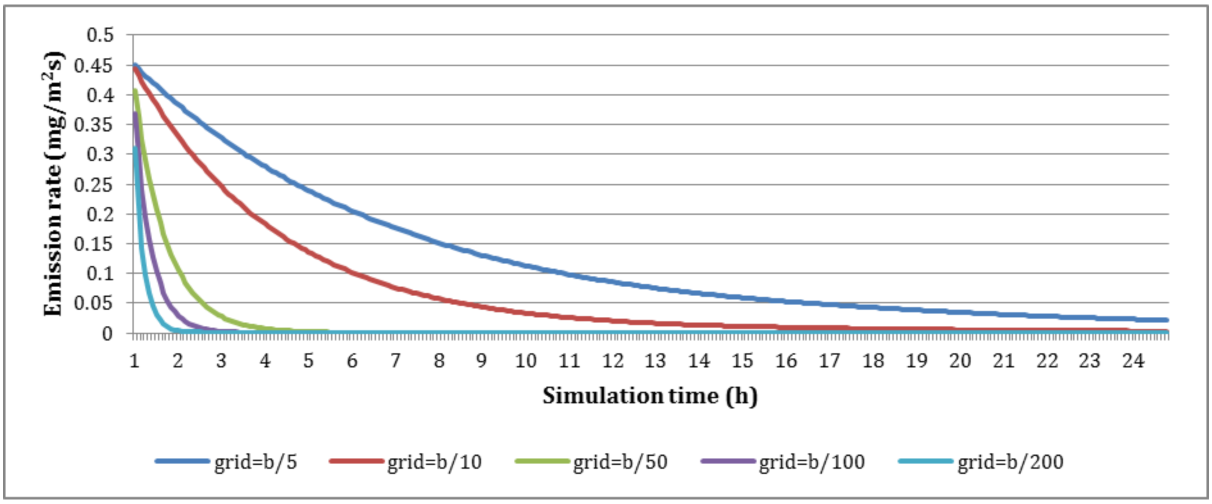

Figure 5.15: Comparison of formaldehyde emission rate for different grid sizes for one day

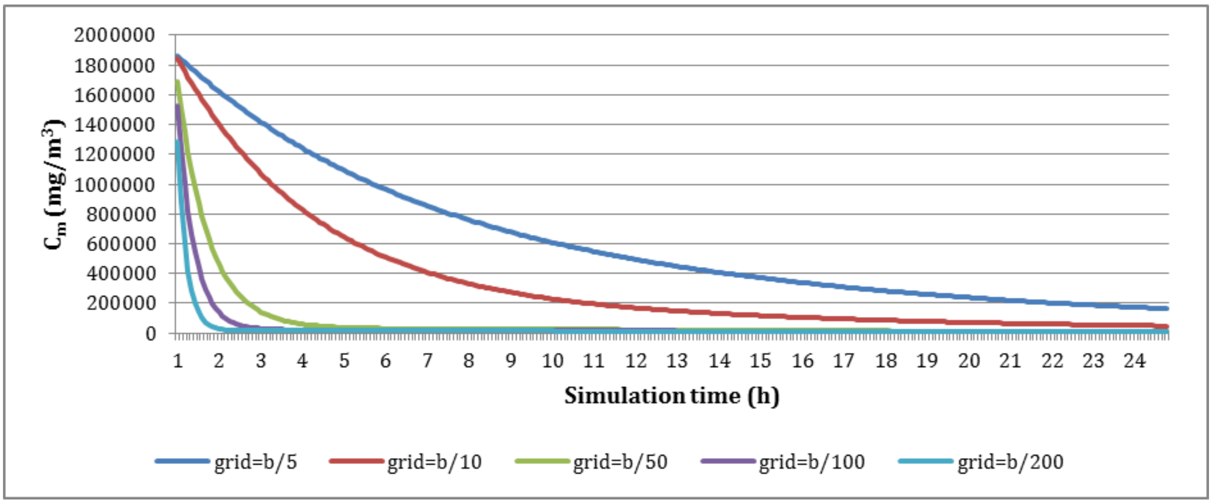

Figure 5.16: Comparison of formaldehyde concentration at the material surface for different grid sizes for one day

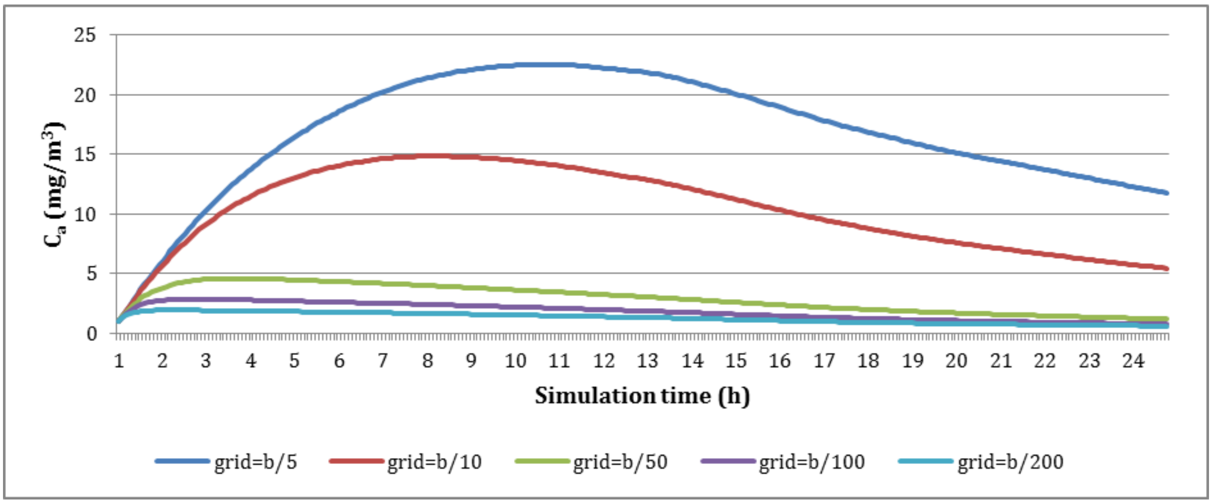

Figure 5.17: Comparison of formaldehyde concentration in the indoor air for different grid sizes for one day

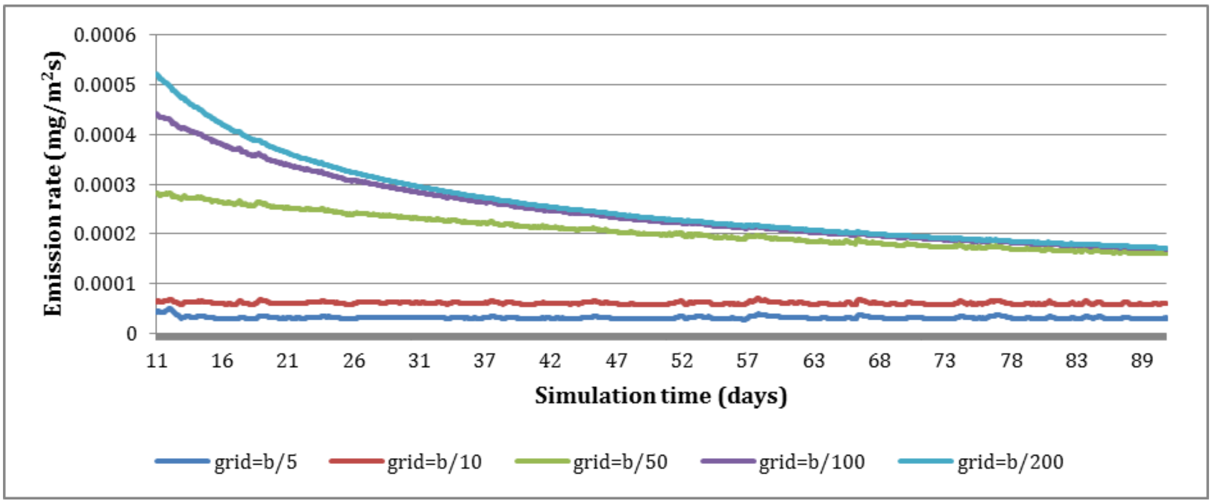

Figure 5.18: Comparison of formaldehyde emission rate for different grid sizes for three months

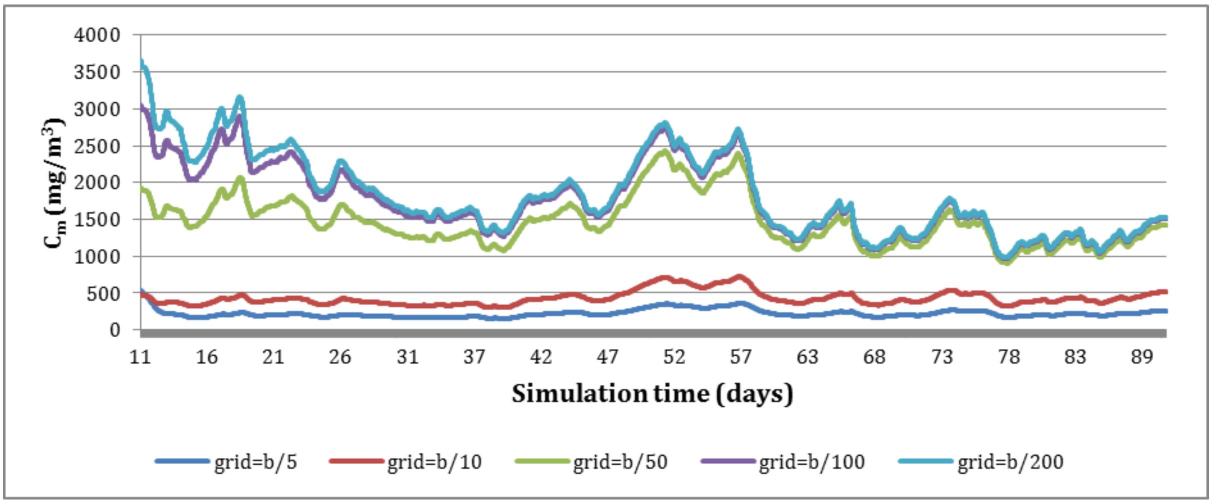

Figure 5.19: Comparison of formaldehyde concentration at the material surface for different grid sizes for three months

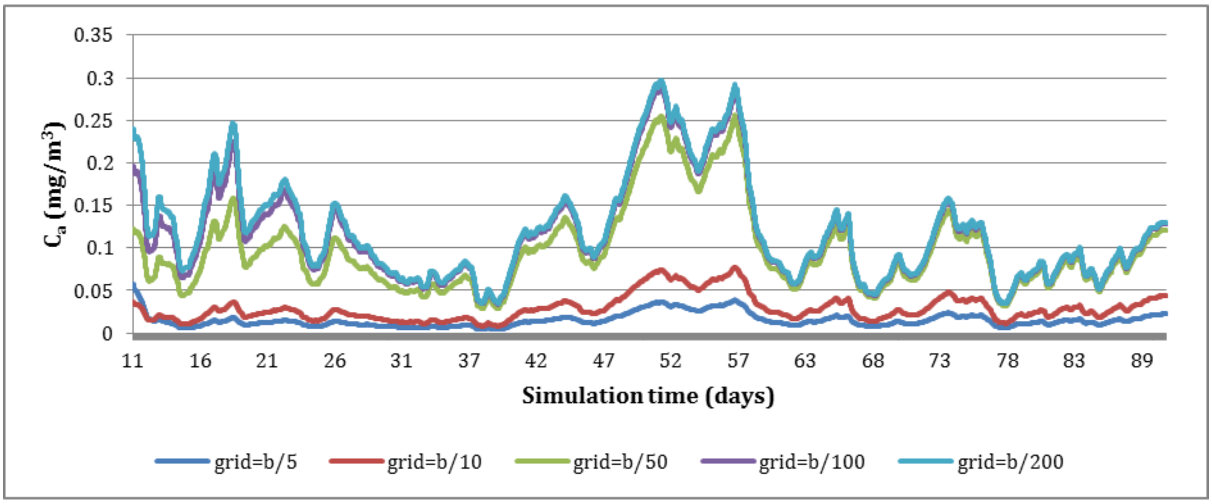

Figure 5.20: Comparison of formaldehyde concentration in the indoor air for different grid sizes for three months

A possible explanation for this result is the slow diffusion of formaldehyde through the material with a diffusion coefficient of 3.31×10^{-14} m^2/s. To check this hypothesis, simulations assuming a diffusion coefficient of 10^{-10} m^2/s were carried for different grid sizes (see Figure 5.21). Results still show some discrepancies but they are much smaller than in the previous graphs, suggesting that effectively, the slow diffusion of formaldehyde through the material makes the selection of the grid size important.

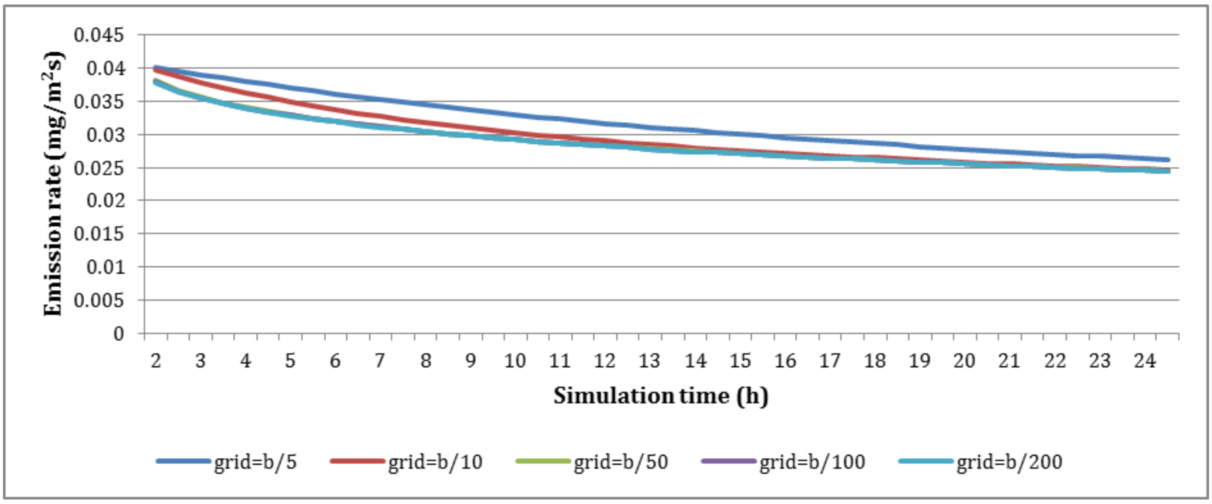

Figure 5.21: Comparison of formaldehyde emission rate for different grid sizes for one day using a diffusion coefficient of 10^{-10} m^2/s

Simulation time step, Δt:

Simulations were carried out for two different time steps: 2 and 30 minutes. Results show that choosing different time steps for the simulation do not significantly change the results (see Figure 5.22 and Figure 5.23).

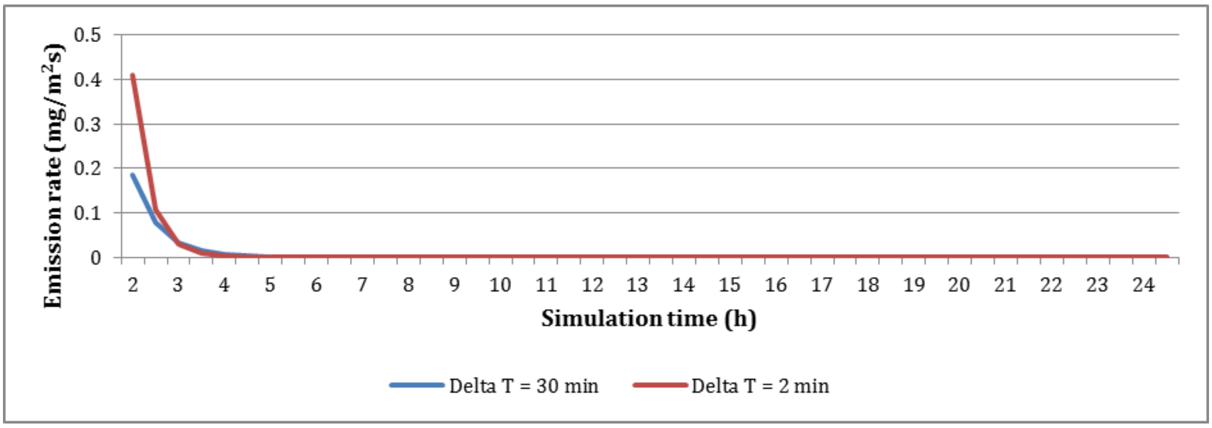

Figure 5.22: Comparison of formaldehyde emission rate for different time steps for one day

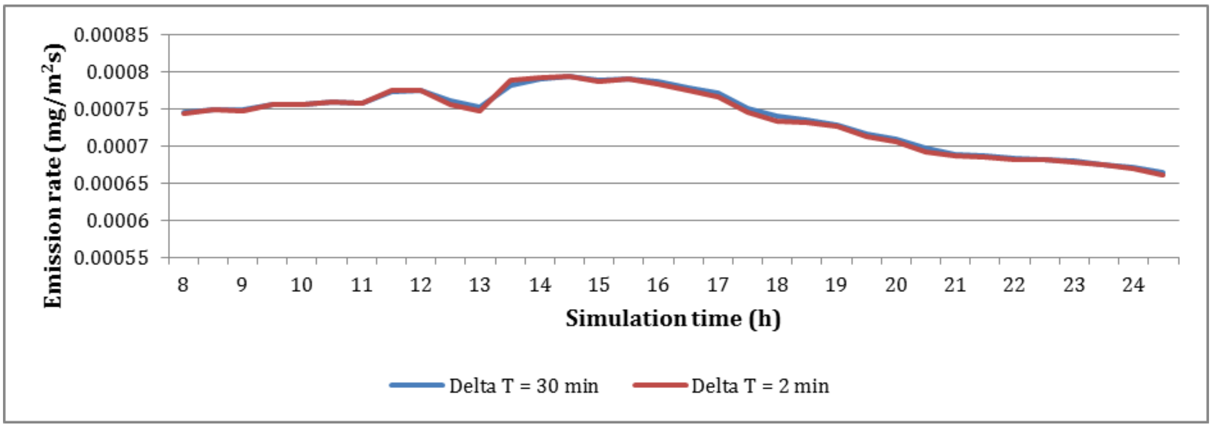

Figure 5.23: Comparison of formaldehyde emission rate for different time steps 6 to 24 hours after the start of the emission

Environmental conditions:

To check the relevance of detailed modelling of formaldehyde emission rates depending on prevailing temperature and RH, simulation results assuming an indoor temperature of 15, 23 and 30 °C, and a constant RH of 50 % were compared. In the same way, simulations assuming a RH of 20, 50 and 80 %, and a constant temperature of 23 °C were also carried out. For this, the same 1-zone model defined for the SA was used. 100 grid points inside the material were used and the air velocity over the material surface was assumed as 0.028 m/s.

Temperature (T)

Figure 5.24 to Figure 5.27 show that a temperature change from 15 to 30 °C would increase the emission rate four times and it would double the emittable concentration at the material surface. Therefore, the emission rate and the emittable formaldehyde concentration at the material surface increase greatly with temperature.

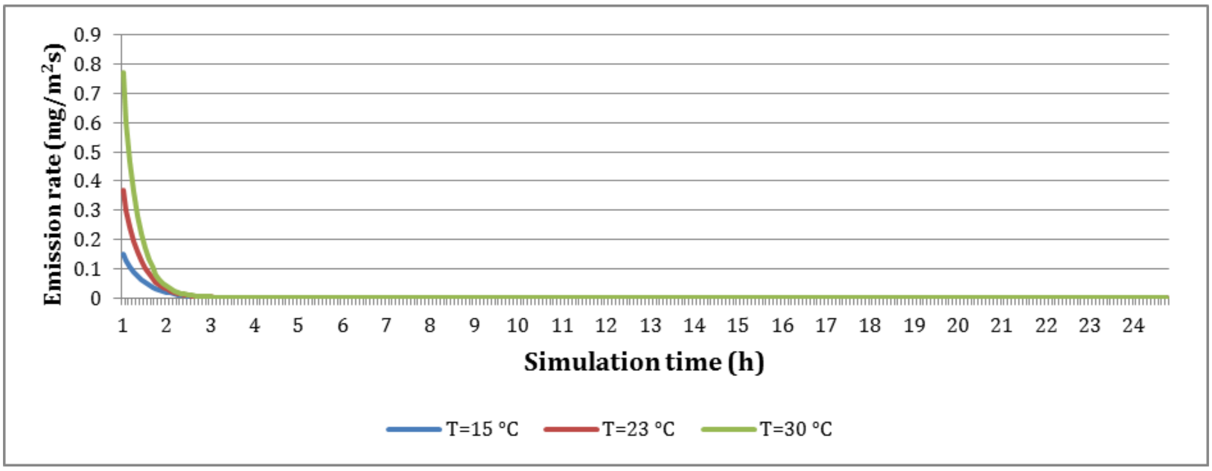

Figure 5.24: Comparison of formaldehyde emission rate for different indoor temperatures for one day

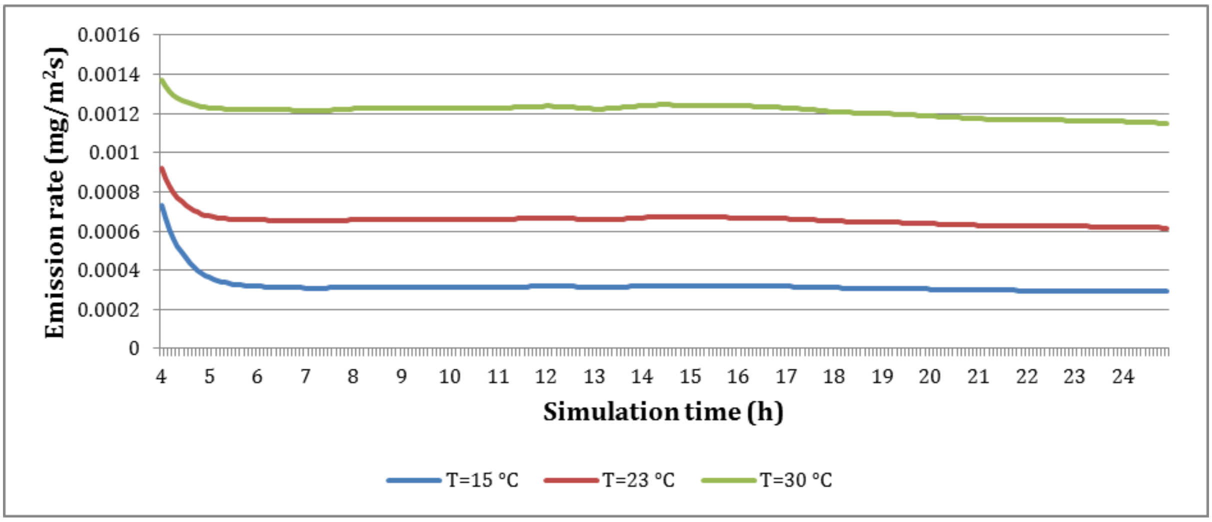

Figure 5.25: Comparison of formaldehyde emission rate for different indoor temperatures 4 to 24 hours after the start of the emission

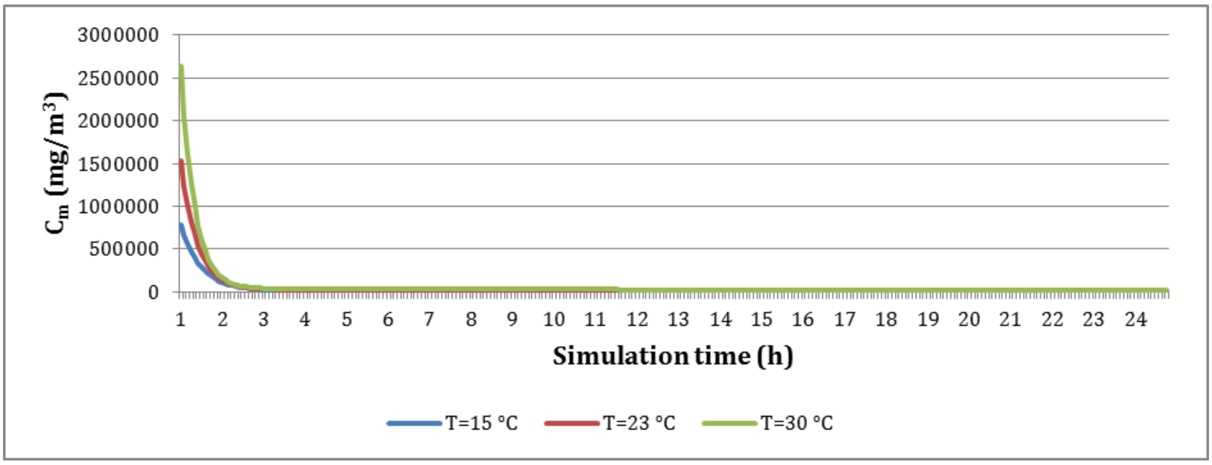

Figure 5.26: Comparison of formaldehyde concentration at the material surface for different indoor temperatures for one day

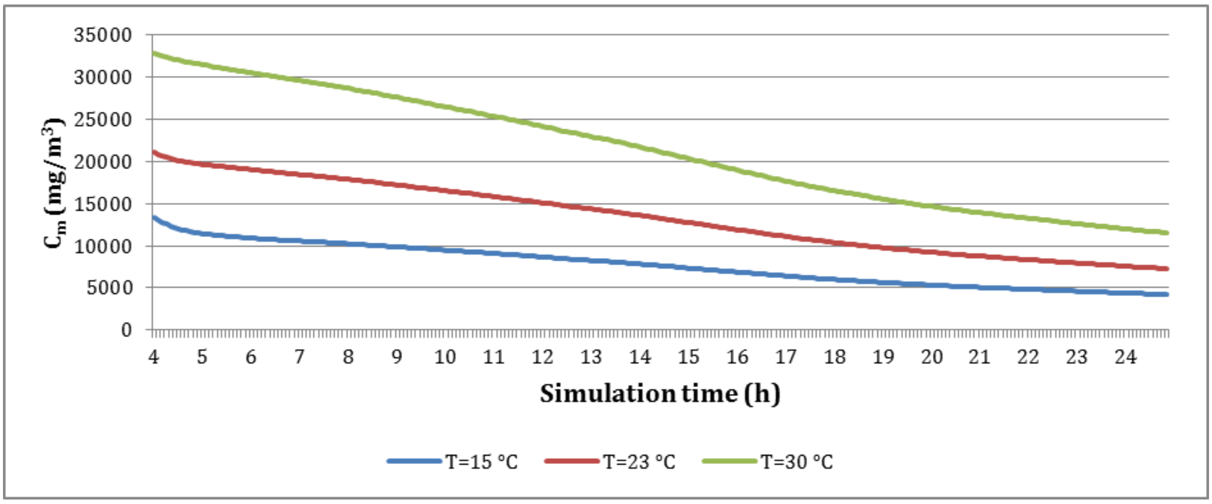

Figure 5.27: Comparison of formaldehyde concentration at the material surface for different indoor temperatures 4 to 24 hours after the start of the emission

Figure 5.24 and Figure 5.26 show that both the emission rate and the emittable concentration at the material surface decrease abruptly three hours after the emission starts. Thus, to check if the impact of temperature changes become insignificant for the IAQ levels after this time, Figure 5.28 and Figure 5.29 show the formaldehyde concentration of the indoor air for different temperatures for a short period (24 hours) and a long one (3 months). Results confirm that indoor temperature will influence the formaldehyde concentration in the room even after 3 months from the start of the emission. Hence, detailed modelling and simulation of formaldehyde emission is important in order to assess the IAQ accurately. Looking at Figure 5.29, it can be seen that formaldehyde concentrations suffer identical fluctuations for all the temperatures. This pattern is repeated again for different levels of RH. This is due to infiltration changes due to the two small cracks included in the model.

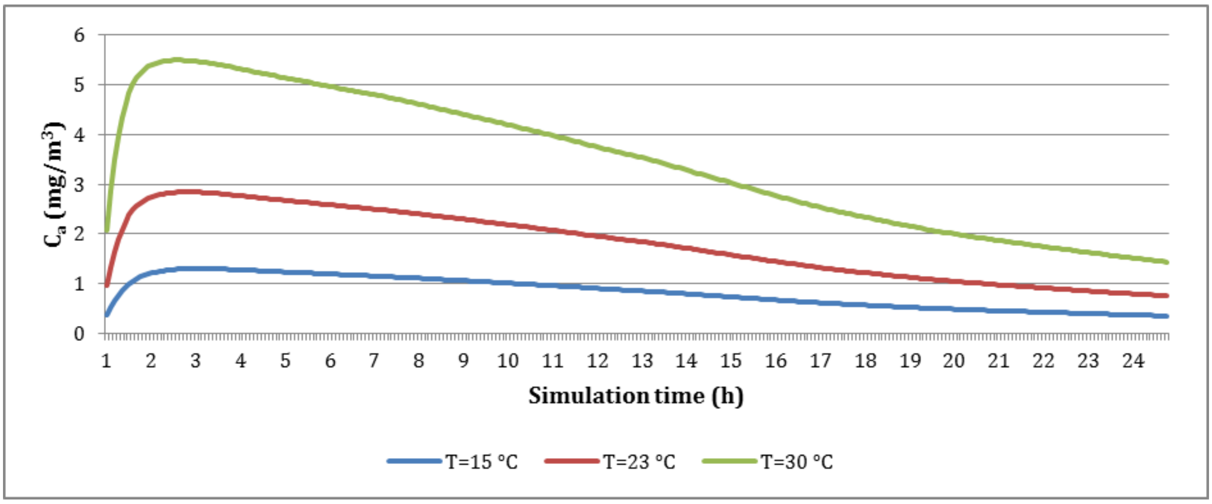

Figure 5.28: Comparison of formaldehyde concentration in the indoor air for different indoor temperatures for one day

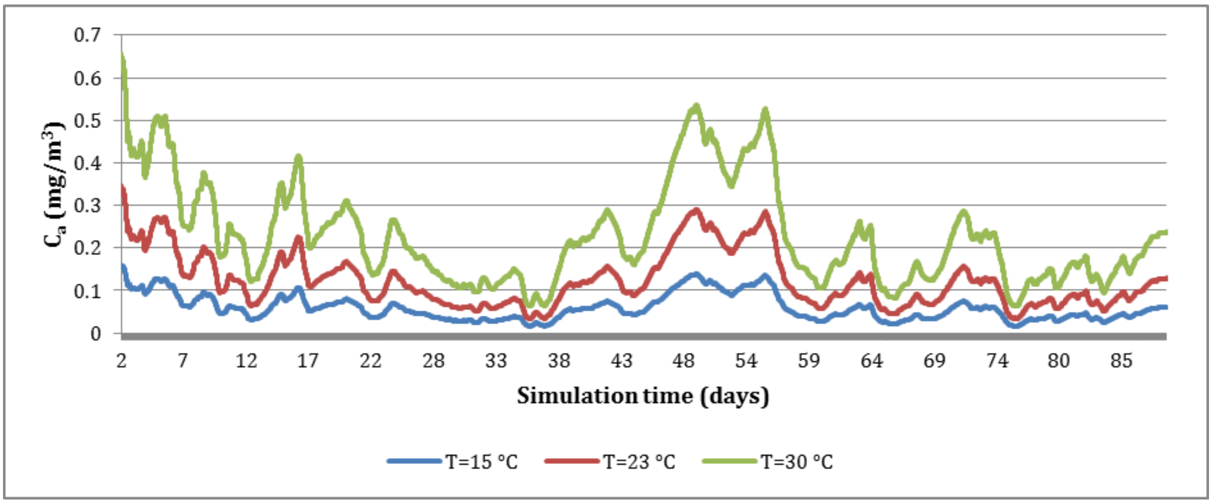

Figure 5.29: Comparison of formaldehyde concentration in the indoor air for different indoor temperatures for three months

Relative humidity

In this case, results for the first three hours after the emission starts are omitted since they follow the same trend as previously seen for the temperature. Figure 5.30 and Figure 5.31 show that a RH change from 20 to 80 % would increase the emission rate and the emittable concentration at the material surface around 20 %. Therefore, the emission rate and the emittable formaldehyde concentration at the material surface increase with RH but the change is less significant than for the case of temperature.

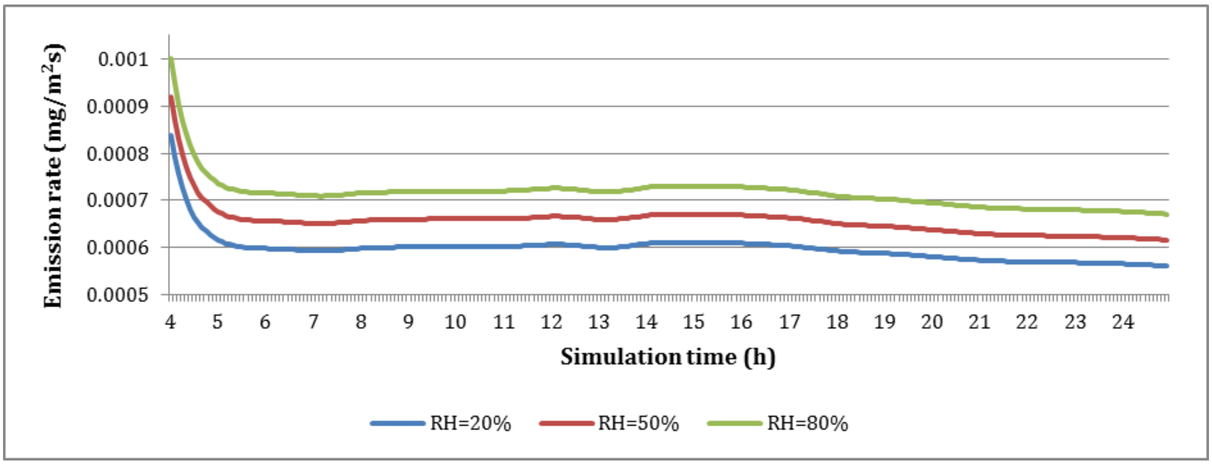

Figure 5.30: Comparison of formaldehyde emission rate for different RH levels 4 to 24 hours after the start of the emission

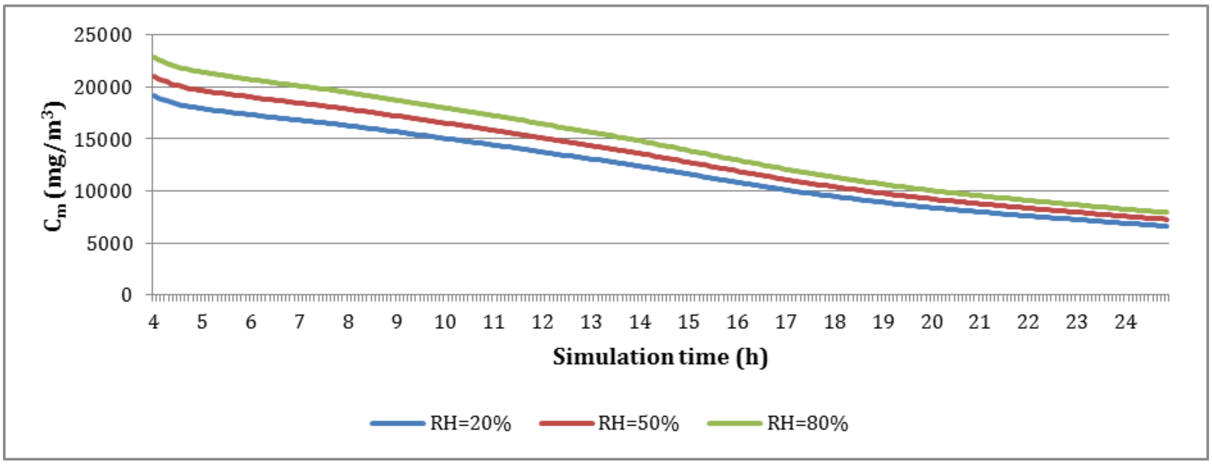

Figure 5.31: Comparison of formaldehyde concentration at the material surface for different RH levels 4 to 24 hours after the start of the emission

To check the impact of RH changes on IAQ in the short and long term, Figure 5.32 and Figure 5.33 show the formaldehyde concentration of the indoor air for different RH levels for a short period (24 hours) and a long one (3 months). These graphs confirm that the impact of RH on IAQ is less important than the impact of temperature, but still causes changes in the indoor concentration of formaldehyde, which may be important in rooms with several sources of formaldehyde.

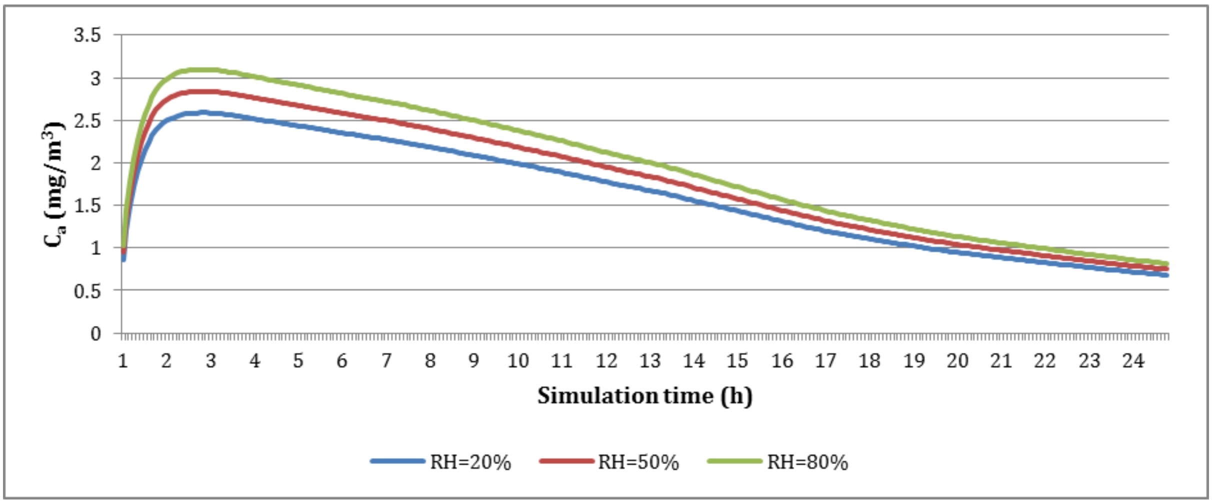

Figure 5.32: Comparison of formaldehyde concentration in the indoor air for different RH levels for one day

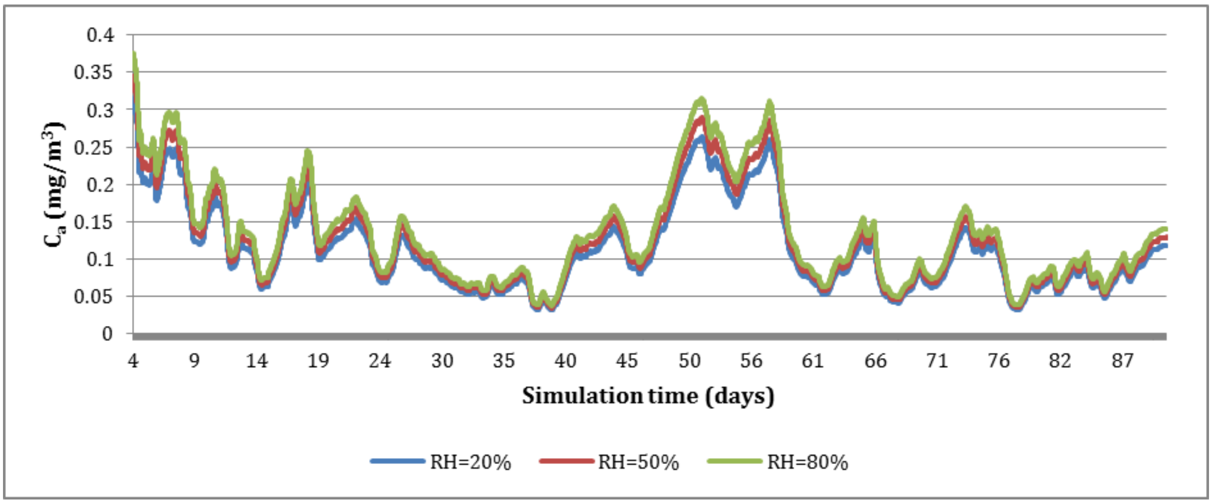

Figure 5.33: Comparison of formaldehyde concentration in the indoor air for different RH levels for three months

5.3.2. PM and NO_2 deposition and resuspension

To check the relevance of modelling deposition and resuspension of particles, defined in Section 5.2, simulations using different deposition and resuspension rates and surface areas were carried out for a period of three months. For this, a simple 1-zone model was defined and a constant ambient concentration of 9 μg/m^3 of PM_{10} was assumed to be the only particle source. The dimensions of the zone were 10x10x2.4 m^3 and the ventilation rate was 0.6 ach.

Deposition and resuspension rates

The deposition rates considered were 0.37, 0.65 and 0.93 h^{-1}, which are the minimum, average and maximum PM_{10} deposition rates reported by the Particle TEAM (PTEAM) Study (Ozkaynak et al. 1997). The resuspension rates considered were zero, 10^{-4} and 10^{-3} h^{-1}, which correspond to no activity, moderate and active activity respectively (Healy, 1971). Finally, simulations assuming no deposition and no resuspension were also undertaken. The deposition and resuspension surface areas were assumed to be the room floor area.

Figure 5.34 to Figure 5.37 show the removal rate, particle resuspension rate, PM_{10} concentration on the deposition surface and PM_{10} concentration in the air for the different deposition and resuspension rates considered. It can be seen that changes in the deposition and resuspension rate have a great impact on the results. A change of the deposition rate from 0.37 to 0.93 h^{-1}, keeping a constant resuspension rate, increases the particle removal rate 56 %. On the other hand, changing the resuspension rate from 0 to 0.001 does not change the removal rate at the beginning of the simulation since the concentration of particles on the deposition surface is zero (see Figure 5.35 and Figure 5.36). However, as time passes, the impact of increasing the resuspension rate becomes more significant and after three months the removal rate assuming the maximum resuspension rate is 80 % higher than the removal rate assuming no resuspension. Regarding the particle resuspension rate, it is seven times higher assuming a resuspension rate of 10^{-3} h^{-1} compared to a resuspension rate of 10^{-4} h^{-1}.

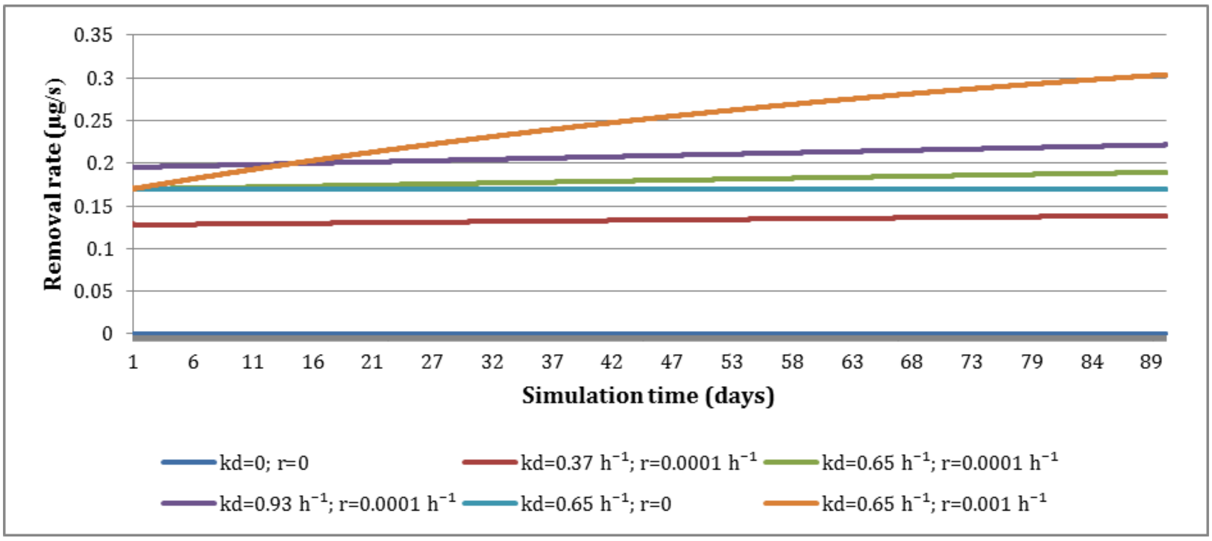

Figure 5.34: Comparison of PM_{10} removal rate for different deposition and resuspension rates for three months

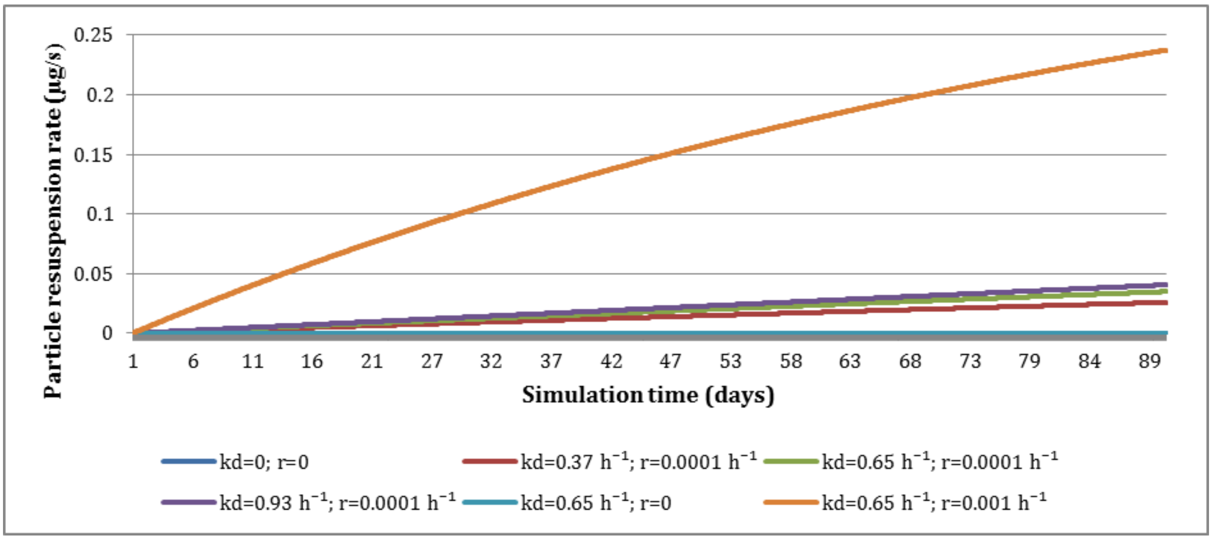

Figure 5.35: Comparison of PM_{10} resuspension rate for different deposition and resuspension rates for three months

Regarding the PM_{10} concentration on the deposition surface, Figure 5.36 shows that the greater concentrations are obtained when the deposition rate increases and the resuspension rate decreases, as expected.

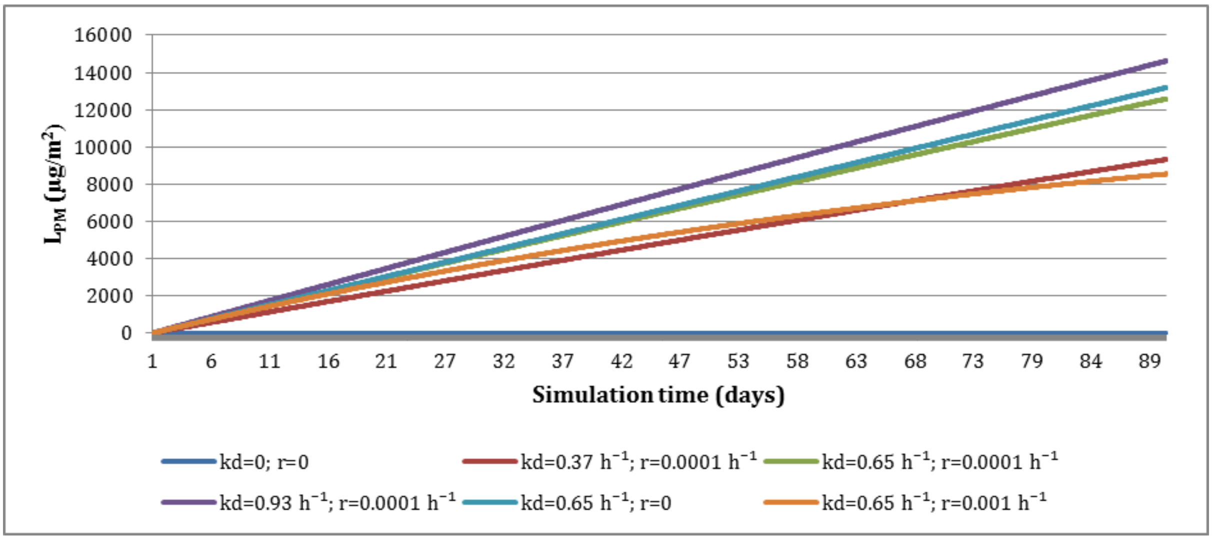

Figure 5.36: Comparison of PM_{10} concentration on the deposition surface for different deposition and resuspension rates for three months

Finally, the impact of different deposition and resuspension rates on the PM_{10} concentration in the air is shown in Figure 5.37. Results show that the PM_{10} concentration in the air decreases when the deposition rate increases and the resuspension rate decreases, as expected. It can be noticed that not taking into account the deposition and resuspension mechanisms in the simulation (k_d=0; r=0) in this case lead to a concentration three times higher than it should be. Therefore, it is important to include deposition and resuspension processes in the model in order to increase the accuracy of the results.

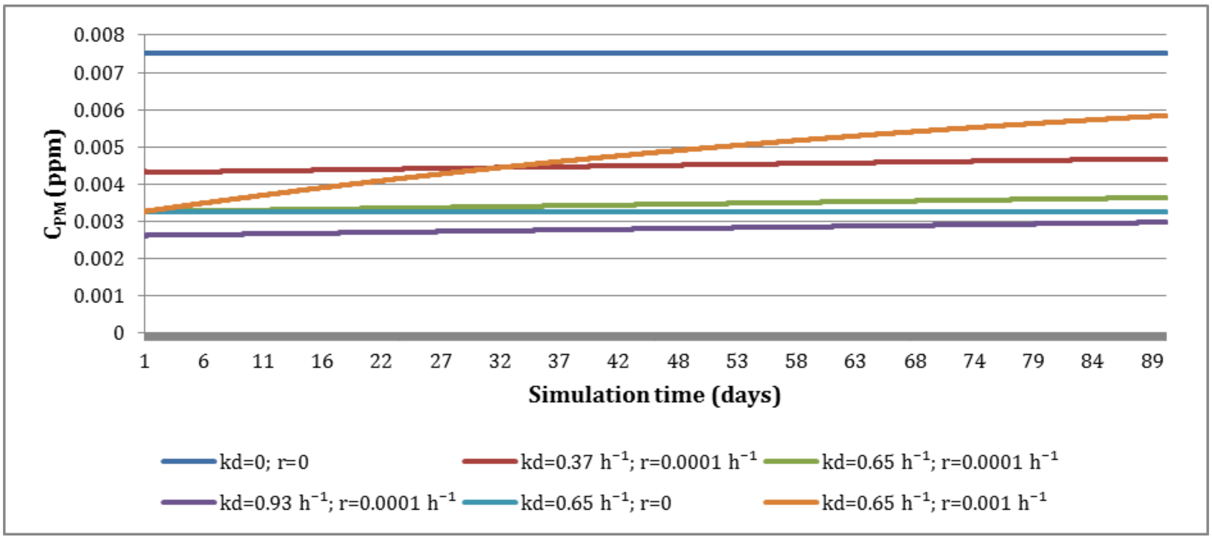

Figure 5.37: Comparison of PM_{10} concentration in the indoor air for different deposition and resuspension rates for three months

Deposition and resuspension surface area

Previous studies have investigated the impact of deposition and resuspension surface areas on the indoor particle concentration. Thatcher et al. (2002) carried out an experimental study of particle deposition in a fully furnished (carpet, table, book shelf, chairs and curtains) room and the same room but unfurnished, with only the carpeted floor. The deposition surface areas were estimated and it was found that the fully furnished room had a deposition area 30 % greater than the unfurnished room. In addition, other previous studies have found a ratio between total deposition surface to room volume of around 3 m^{-1} (Hussein et al., 2006). Therefore, the deposition areas considered for the SA were the floor area (100 m^2), 130 m^2, and 720 m^2.

The resuspension surface area is a difficult parameter to predict (Qian et al., 2014). Schneider et al. (1999) considered the resuspension surface area as the floor area even though in reality, the resuspension surface area will be smaller. Data to statistically estimate the fraction of floor area that is actually disturbed is missing. However, there have been some studies that have estimated the resuspension area, like Qian et al. (2008), who carried out resuspension experiments in a single-family residence and built a model, estimating the ratio of resuspension area to room volume as around 0.11 m^{-1}. Therefore, the resuspension areas that will be considered for the SA are the floor area (100 m^2) and 26.4 m^2.

Figure 5.38 to Figure 5.41 show the removal rate, particle resuspension rate, PM_{10} concentration on the deposition surface and PM_{10} concentration in the air for the different deposition and resuspension surface areas considered. Results show an increasing line tendency for all the graphs since the PM_{10} concentration in the room is lower than the ambient concentration. However, this tendency would be expected to change once the concentration in the room reaches the ambient concentration. Nevertheless, it can be seen that both the deposition and resuspension surface areas have a significant impact on the indoor PM concentrations simulated. Therefore, more information on how to estimate these areas or typical values that could be used according to different building configurations would help to obtain more accurate results.

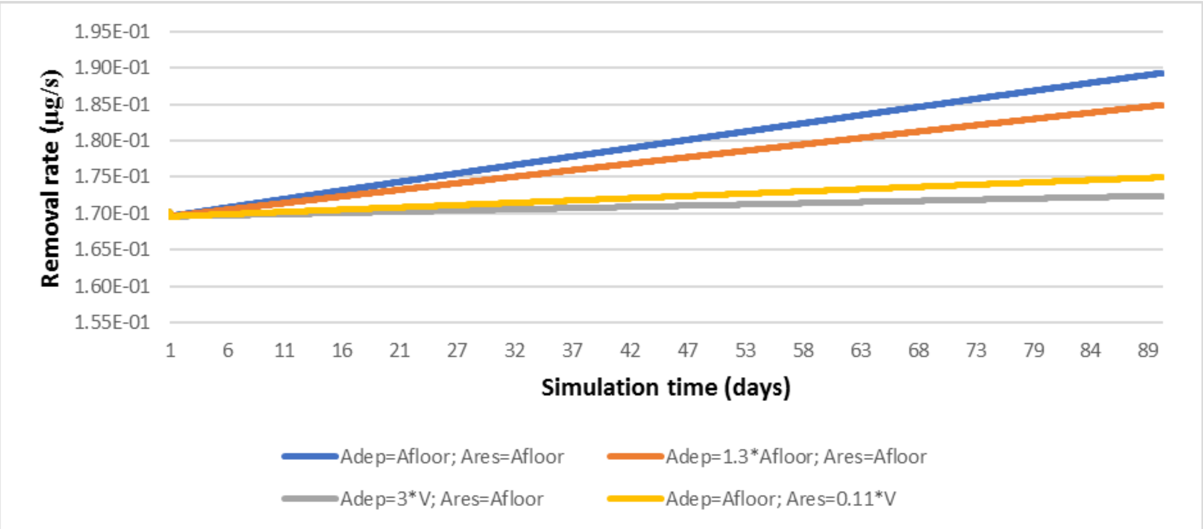

Figure 5.38: Comparison of PM_{10} removal rate for different deposition and resuspension surface areas for three months

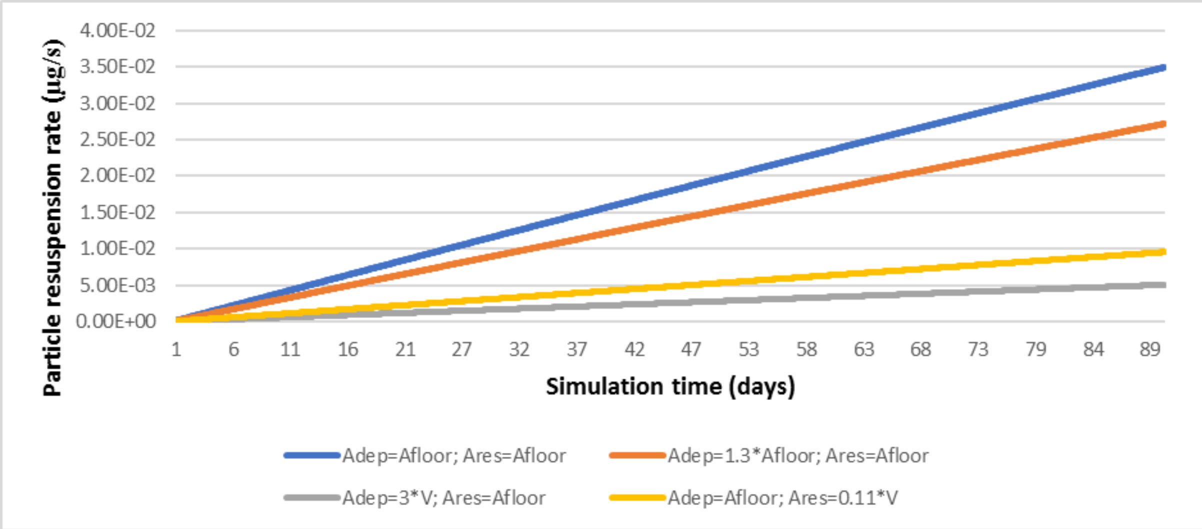

Figure 5.39: Comparison of PM_{10} resuspension rate for different deposition and resuspension surface areas for three months

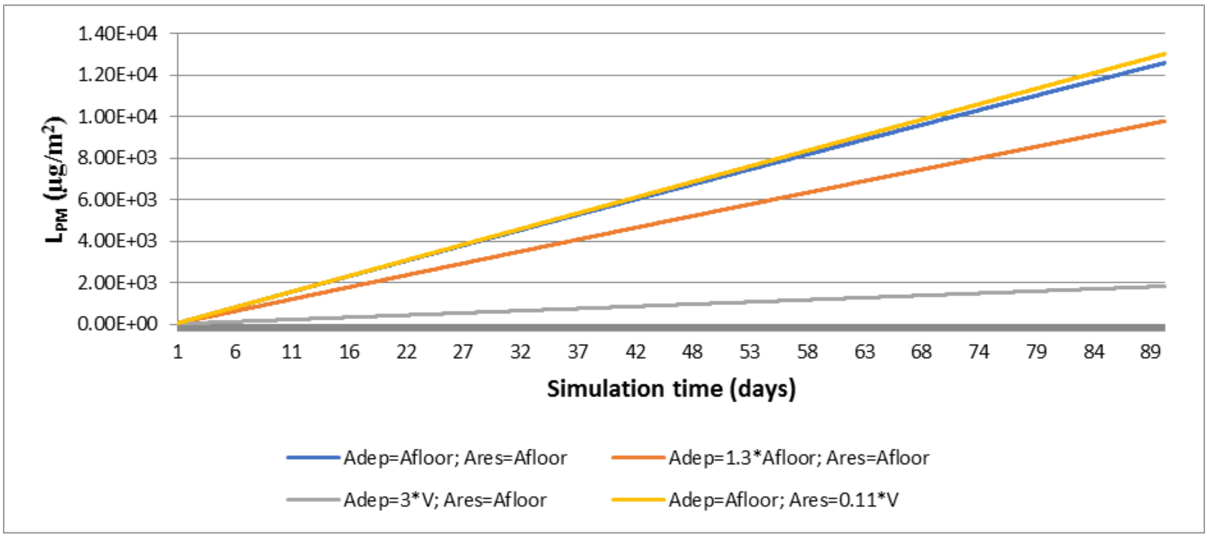

Figure 5.40: Comparison of PM_{10} concentration on the deposition surface for different deposition and resuspension surface areas for three months

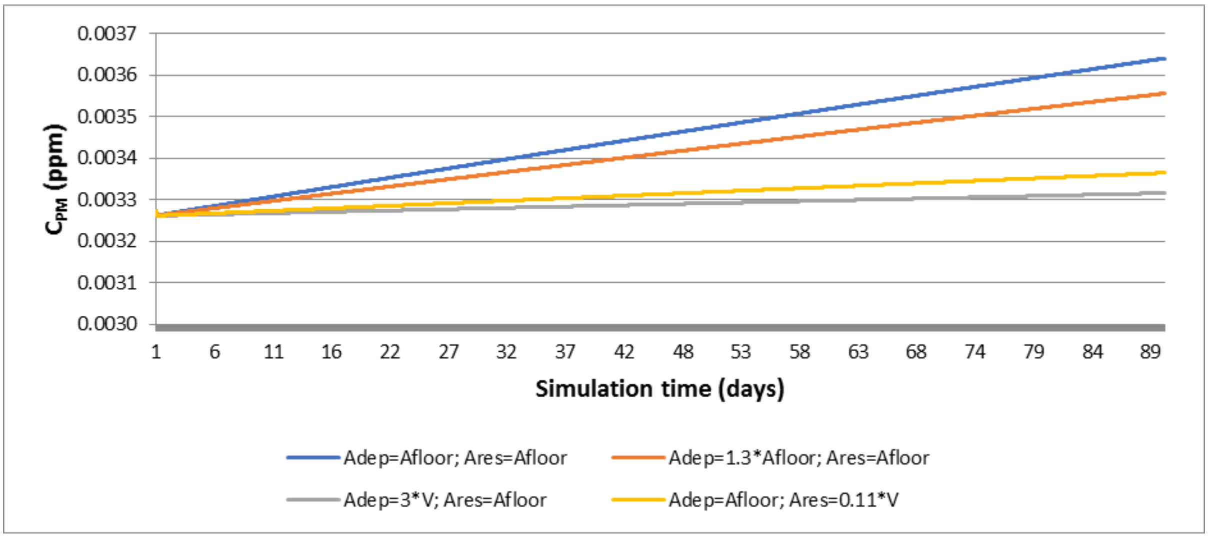

Figure 5.41: Comparison of PM_{10} concentration in the indoor air for different deposition and resuspension surface areas for three months

5.4. Formaldehyde emission model comparison

In this section, a comparison between the different models described in Section 5.1 is undertaken. This comparison needs to be done for the same material. For this, a simple 1-zone model was defined at 20 °C, 50 % RH and an air change rate of 1 h^{-1}. The MDF studied by Liang et al. (2016) was assumed to be the only formaldehyde indoor source and the emission is assumed to start on 2nd January. The dimensions of the zone were 10x10x2.4 m^3 and the dimensions of the MDF surface were 1.95x1.27x0.025 m^3. The emission parameters of Equations (5.1) to (5.5) were derived using the two-week emission data from Huang's model two weeks after the emission starts, to avoid defining the different models based on the initial high emission period. Figure 5.42 shows the emission rate for the different emission models calculated. The model correlations are defined in Equations (5.21) to (5.27). Finally, the parameters derived by Liang et al. (2016) are listed.

Gas steady state model:

$$S = 0.3178 \tag{5.21}$$

where S is the last emission rate value (mg/m^2h) estimated by Liang et al. (2016).

Gas transient power law model:

$$S = 0.5506 \qquad if\ t \leq 1\text{ h} \tag{5.22}$$
$$S = 0.5506 \times t^{-0.075} \qquad if\ t > 1\text{ h} \tag{5.23}$$

where S is the emission rate (mg/m^{2}h) and t is the time (h).

Gas transient discrete emission data model:

$$S = 0.3644\ \ if\ t \leq 168\text{ h} \tag{5.24}$$
$$S = 0.3228\ \ if\ 168 < t \leq 336\text{ h} \tag{5.25}$$
$$S = 0\ \ if\ t > 336\text{ h} \tag{5.26}$$

where S is the emission rate (mg/m^{2}h) and t is the time (h).

Gas transient peak model:

$$S = 0.4641e^{-0.5\left(\frac{ln(t)}{7.07}\right)^2} \tag{5.27}$$

where S is the emission rate (mg/m^{2}h) and t is the time (h).

Huang model parameters (Liang et al. 2016):

$$C_0 = 3.8 \times 10^6 mg/m^3$$
$$D_m = 3.5 \times 10^{-14} m^2/\text{s}$$
$$k = 5340$$

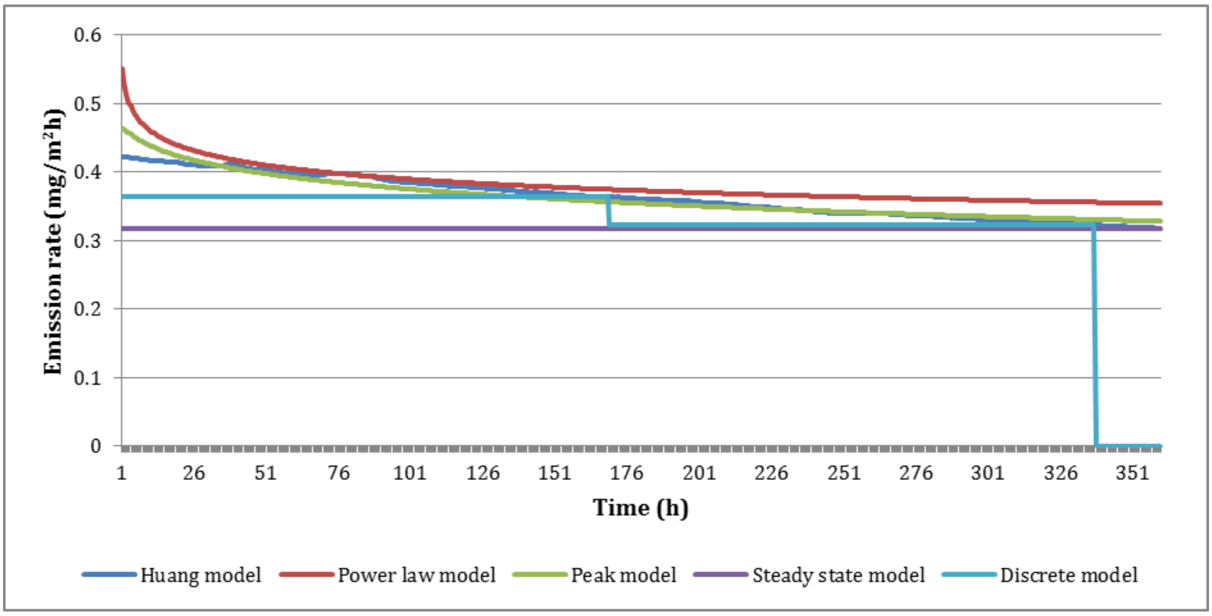

Figure 5.42: Formaldehyde emission models for MDF

Simulations were run using the Dormont PH model described in Chapter 4, focusing on the main bedroom, and a MDF surface of 7.4 m^2 was assumed to be the only formaldehyde indoor source. The emission is assumed to start on 2nd January and the simulations were run for three months.

Figure 5.43 and Figure 5.44 show the indoor temperature, RH and mean air velocity results in the main bedroom, which differ from the environmental conditions used in the environmental chamber and thus, from the ones used to define the simplified models. The temperature in the main bedroom is mainly above 20 °C while the RH is mainly below 50 %. Regarding the air velocity in the main bedroom (u), it oscillates above and below the value assumed to define the simplified models (u_o), which matches the average air velocity in the bedroom.

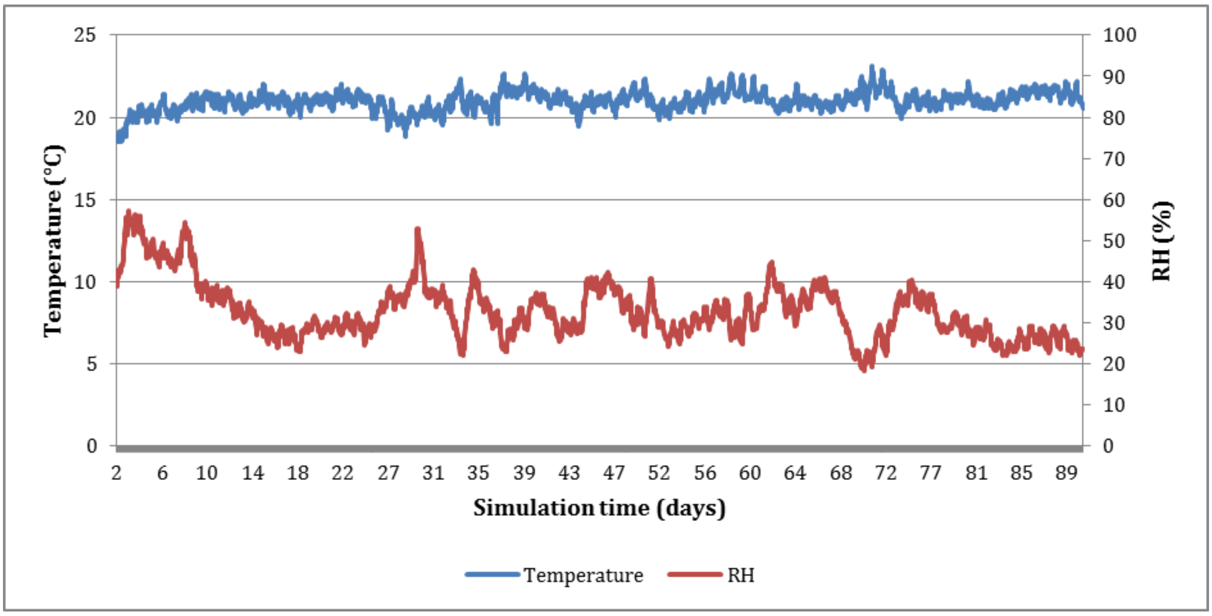

Figure 5.43: Temperature and RH results in the main bedroom

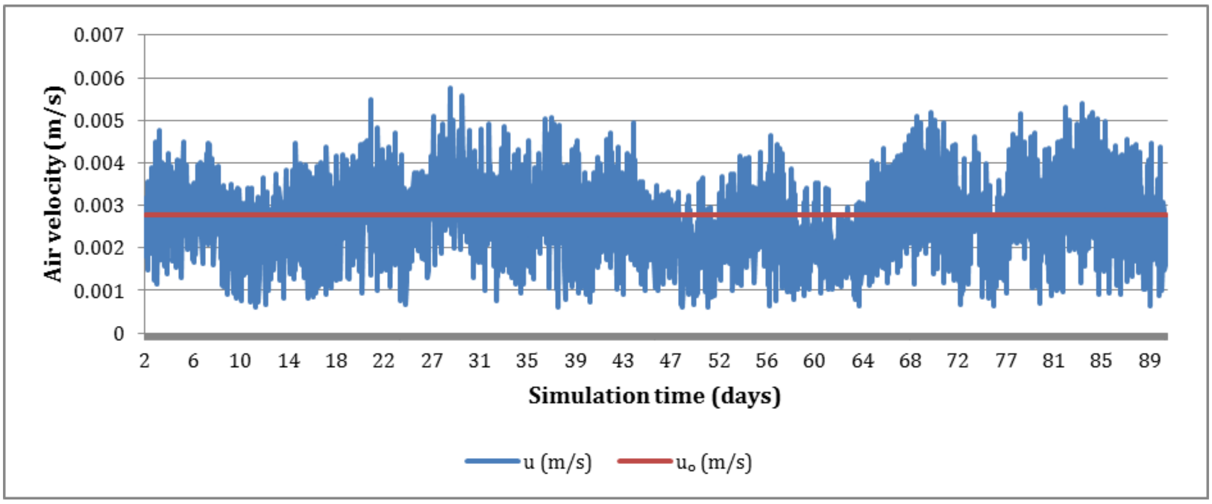

Figure 5.44: Mean air velocity over the material in the main bedroom

Figure 5.45 shows the formaldehyde emission rates for the different models. All the models assume 7.4 m^2 source area and the environmental conditions shown in Figure 5.43. It can be seen that two weeks after the start of the emission, the emission rate estimated by the power law, peak and steady state model are in good agreement with Huang's model since the models were derived from the emission data two weeks after the emission starts. However, as time passes, the emission rate estimated by Huang's model decreases more rapidly and falls below the emission rates estimated by the other models. Finally, it should be noticed that the discrete emission rate is zero as it has been defined using two-week data.

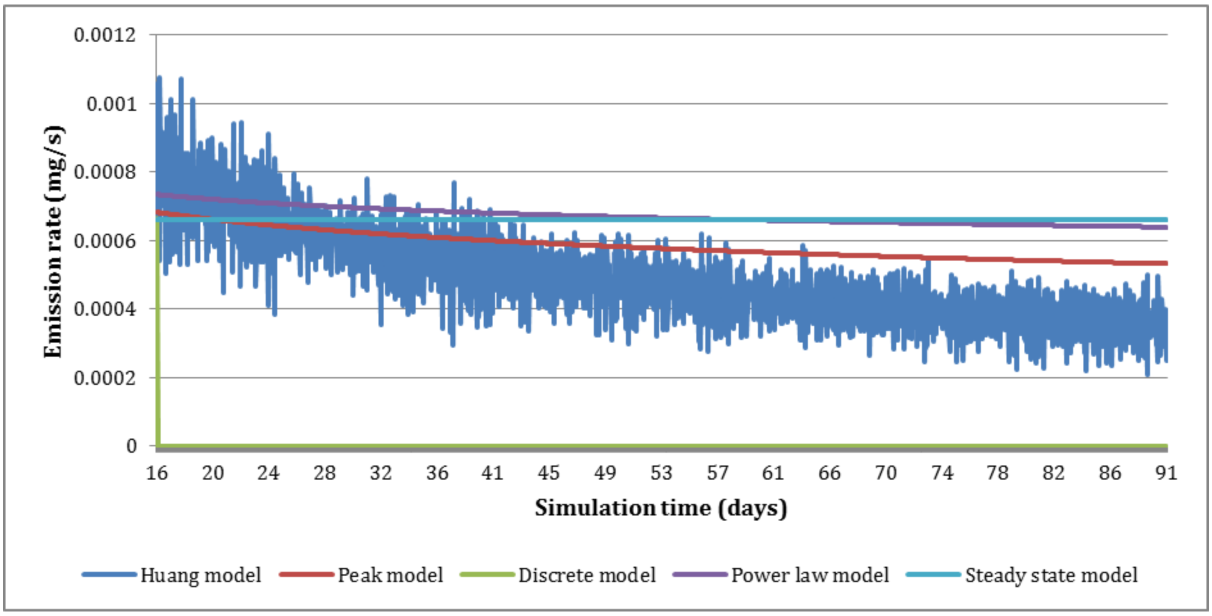

Figure 5.45: Comparison of formaldehyde emission rates for different models two weeks after the start of the emission

An analogous situation is found when looking at the formaldehyde concentration results in the indoor air (Figure 5.46). In this case, using the simplified models underestimates the formaldehyde concentration in the indoor air at the beginning of the emission when the concentration in the material is very high and it overestimates the concentration afterwards. To know how these differences would impact the IAQ assessment, the poor IAQ limit defined in Chapter 6 (Table 6.4) has been included in Figure 5.46. In addition, Figure 5.47 shows the IAQ assessment based on formaldehyde concentrations using the different models, highlighting that the power law, peak and steady state model give similar results. Huang's model gives better levels of IAQ than these simplified models. Finally, the discrete model gives good levels of IAQ as the emission rate is zero after two weeks. These results show the importance of detailed emission modelling when assessing IAQ.

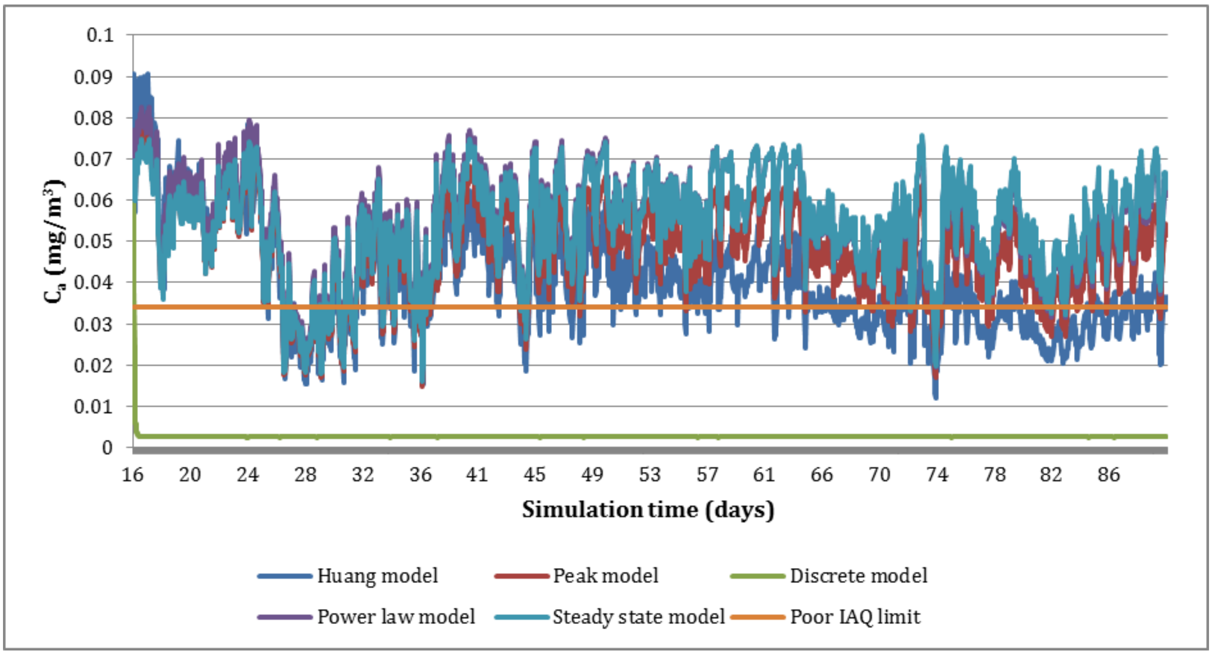

Figure 5.46: Comparison of formaldehyde concentration in the indoor air for different models two weeks after the start of the emission

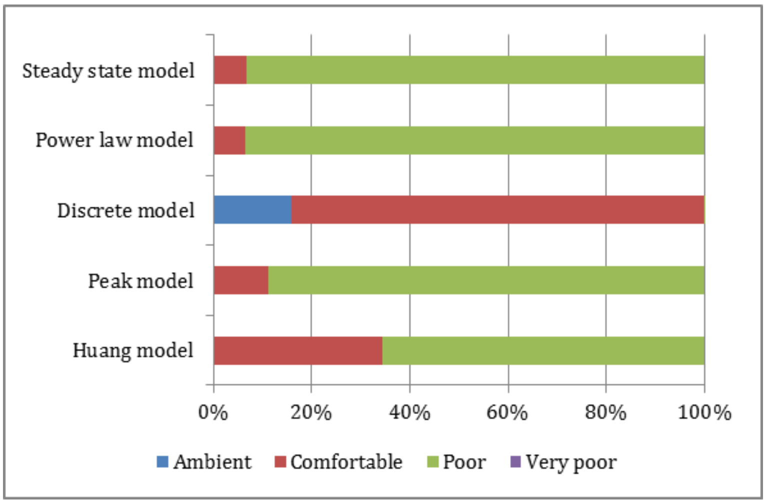

Figure 5.47: Comparison of IAQ assessment for different models two weeks after the start of the emission

5.5. Modelling limitations

The contaminant models implemented in ESP-r have a series of limitations that could be addressed in order to model IAQ in buildings more accurately. Some of these limitations are as follows.

5.5.1. Formaldehyde

The model by Huang and Haghighat assumes that the formaldehyde is completely mixed in the room air and the initial concentration inside the material is homogenous. In addition, it is assumed that no formaldehyde is passing through the bottom surface of the material. If more accurate predictions are needed for cases where, for example, there are many localised sources and the ventilation rate is not sufficient to completely mix the air in the room, a more complicated emission model would be required. Also, in practice, the initial concentration inside the material would not likely be homogeneous when it is installed in the house, as the main emissions from the near surface will take place immediately after manufacture.

In addition, this model needs to calculate the initial emittable concentration of the material, which is influenced by the temperature and RH at the start of the emission. Thus, the emission needs to start within the simulation period. This makes difficult the assessment of emission rates in the long term.

Correlations to estimate the initial emittable concentration, the diffusion coefficient of the material and the material/air partition coefficient, depending on temperature and RH, are not available in the literature for different materials, apart from the MDF studied by Liang et al. (2016), and therefore cannot be implemented in the model.

Finally, a CFD model would be needed in order to get better estimations of air velocities at the materials' surfaces in buildings with a low ventilation rate for periods shorter than three months after the beginning of the emission, as the emission rate changes greatly with air velocity during that time.

Despite these limitations, the model implemented is the best available at present, until more detailed model and measured data from different materials become available.

5.5.2. Particulate Matter

Deposition and resuspension rates are assumed to be constant and do not change depending on air velocity or occupant activity level. Thus, correlations of the deposition and the resuspension rate would help to increase the accuracy of the model.

5.6. Summary

Five different emission models were implemented in ESP-r: the gas steady state model, the gas transient power law model, the gas transient discrete emission data model, the gas transient peak model and Huang and Haghighat's model. In addition, the deposition and resuspension model from CONTAM was implemented. These models have been described in detail together with the assumptions made for their implementation. The correct implementation was checked using Excel spreadsheets and running simulations replicating the results from Huang & Haghighat (2002).

A sensitivity analysis for several parameters in Huang and Haghighat's model was undertaken. This analysis found that the air velocity has little influence on IAQ in the long term. The grid size has a great impact on the emission rate and concentration in the material and air during the entire simulation period. However, this effect decreases with increasing number of grid points, and for 50 grid points and above the differences are negligible after 3 months. Finally, choosing different time steps for the simulation do not significantly change the results.

To check the relevance of detailed modelling of formaldehyde emission rates depending on prevailing temperature and RH, simulation results assuming a constant indoor temperature, a constant RH and variable values for temperature and RH, were compared. It was found that the emission rate and the emittable formaldehyde concentration at the material surface increase greatly with temperature. The impact of RH on IAQ is less evident but it still causes changes in the indoor concentration of formaldehyde. Hence, detailed modelling and simulation of formaldehyde emission is important in order to assess the IAQ accurately.

The relevance of including deposition and resuspension mechanisms in the model was checked. Results show that the particle concentration in the air decreases when the deposition rate increases and the resuspension rate decreases as expected. It was concluded that it is important to include deposition and resuspension processes in the model in order to increase the accuracy of the results.

From the comparison of the formaldehyde emission models, it was found that, in the current case study, using the simplified models underestimates the formaldehyde concentration in the indoor air at the beginning of the emission when the concentration in the material is very high and it overestimates the concentration afterwards, except for the discrete model, as the emission rate was defined using two-week data only.

Finally, the limitations of these models in ESP-r were highlighted.

Chapter 6. Scenario Modelling

The use of scenarios began in the military context and has expanded to other areas since 1960s. Researchers use scenarios to gain knowledge of the interactions between different parameters in complex problems where there are many uncertainties. Hence, they are not used to predict the future but to help decision-making under different circumstances (Moss et al., 2010). This chapter describes the scenarios that have been defined to investigate typical design questions and the impact that common ventilation issues have on the indoor environment. Common assumptions to all scenarios regarding occupancy and IHG are described and so are the IEQ criteria that will be used to assess the results from the simulations. The questions investigated and the ventilation scenarios defined for each of them are listed.

Question 1 investigates whether MVHR without summer bypass can lead to significant overheating risk in mild climates and whether providing boost control to the system and assuming window opening can solve the overheating issue. This question also compares the performance of this system against the use of summer bypass. Question 2 investigates the consequences of a fault of the MVHR system and whether occupants opening windows could counteract them. Question 3 investigates the impact that the use of the kitchen hood while cooking has on IAQ and thermal comfort levels. The consequent energy increase is also investigated. Question 4 investigates whether trickle vents in the living room, bedrooms and wet rooms, and continuous mechanical extract fans in the wet rooms, can assure good IAQ and thermal comfort. The impact of providing boost control to the system and assuming window opening based on adaptive comfort is also explored. In addition, this question compares the performance of this system against the use of an MVHR system. Finally, Question 5 investigates the performance of a constant ventilation rate system compared with DCV control strategies based on RH or CO_2, and assuming window opening based on adaptive comfort.

The results that will be gathered are the operative temperature, RH and pollutant concentrations (CO_2, formaldehyde, $PM_{2.5}$, PM_{10} and NO_2) in the living room, kitchen and bedrooms. In addition, the heating demand in the whole building will be retrieved for some cases. Analysis of these results against the IEQ criteria should highlight the benefits and drawbacks of different ventilation strategies regarding the indoor environment and heating demand. Understanding of the impacts of different parameters and control systems should contribute to the development of guidelines to help designers, educate occupants on the importance of the proper use of the ventilation system and update Building Standards requirements.

Since there are a large number of pollutant sources, i.e. cleaning products, occupants' activities, building materials, etc., and a large uncertainty in the emission rates from them, it is impossible to define a "typical" pollutant profile. Therefore, in order to make realistic assumptions, it was decided to use the calibrated model from Chapter 4 and adjust the different pollutant sources to obtain similar pollutant concentrations to the ones measured in the building. This way, the pollutant cases defined can be considered adequate to assess IAQ issues in low-energy houses. One pollutant case was assigned to each of the questions investigated according to the main focus of each question.

All the scenarios were defined for two different situations; one assuming internal doors are open and another one assuming internal doors remain shut. The model assumes 15 mm door undercuts as an ideal case even though in real situations these may not exist or be blocked by carpets. In addition, the use of blinds was assumed when the indoor temperature exceeds comfort levels.

6.1. Occupancy profile and IHG

To generalise the analysis to a three member family, a profile, differentiating between weekdays, Saturdays and Sundays, has been assumed based on data from the UK Time Use Survey (TUS) 2000 (ONS, 2003) and a statistical model developed by Flett (2017). The family consists of one working adult, one unemployed adult and one child under 5 years old. The working adult stays out for work during the mornings, while the non-working adult and the child stay at home all day. It was considered that the use of statistical data to define the occupancy profile would lead to a more realistic analysis rather than using fixed profiles commonly used in modelling studies. However, it must be noted that this profile does not try to emulate a “typical” family behaviour as different families will behave differently. Nevertheless, it is believed that this profile is acceptable for assessing the building’s capability to keep good IEQ at any time since this lengthy occupied profile is conservative and agrees with the recommendation stated in the CIBSE TM59: “Design methodology for the assessment of overheating risk in homes” (CIBSE, 2017).

The occupants were then distributed within the building based on common behaviour assumptions. Then, the total heat generation by occupants was calculated using the Table 1.4 of CIBSE Guide A, *Typical metabolic rate and heat generation per unit area of body surface for various activities* (Chartered Institution of Building Services Engineers, 2015). The heat gain per unit body surface area assumed for each activity is shown in Table 6.1. These values were multiplied by 1.8 m^2, the average body surface area for an adult body. For the child, the heat gain was assumed to be 75 % of an adult according to the ASHRAE Handbook (ASHRAE, 2009). The occupancy heat gain profile during weekdays is shown in Figure 6.1.

Table 6.1: Heat gain assumed for each activity based on CIBSE Guide A (Chartered Institution of Building Services Engineers, 2015)

Activity	**Heat Gain (W/m^2)**
House cleaning	150
Seated, quiet	58
Standing, relaxed	70
Cooking	100
Sleeping	41
Reclining	46
Bathing[1]	81

1) For bathing, the heat gain was assumed to be the same as filing standing

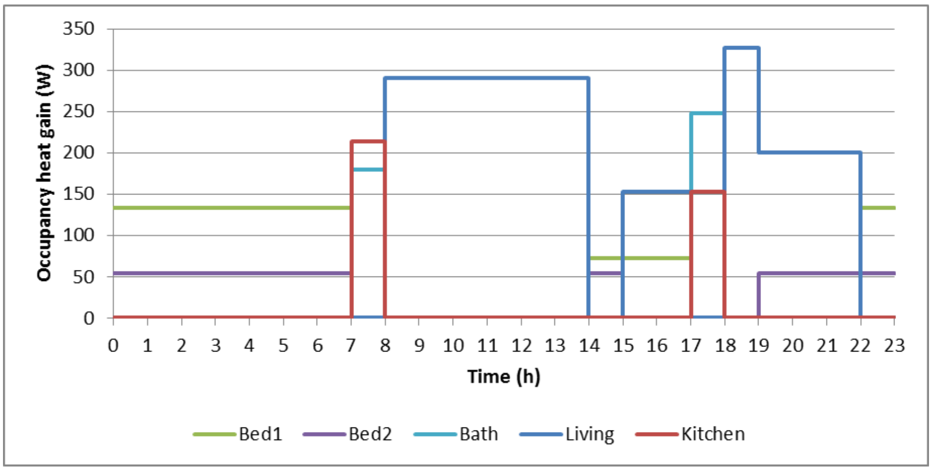

Figure 6.1: Total heat generation by occupants during weekdays

To include the occupancy gains in ESP-r, it is necessary to specify the sensible and latent parts of this heat generation. These have been calculated using the proportion of sensible and latent gains from Table 6.1 of CIBSE Guide A, *Benchmark values for internal heat gains for offices (at 24 °C. 50% RH)* (Chartered Institution of Building Services Engineers, 2015).

The sensible heat gain due to the use of the lights and appliances, and the latent heat gain due to evaporation and drying clothes have been calculated using the IHG sheet from PHPP (Passive House Institute, 2012), and the latent heat gain due to cooking activities has been estimated using the moisture load assumed by Markopoulos et al. (2013). The schedule of cooking and laundry activities have been derived from Richardson's Domestic Electricity Demand Model (Richardson et al., 2010). The lighting has been defined as 1.1 W/m^2 for all the rooms in the house when they are occupied and occupants are not sleeping. The sensible and latent IHG due to appliances are shown in Table 6.2.

Table 6.2: Appliances IHG assumed in this study

Location	Application	Sensible Heat Gain (W)	Latent Heat Gain (W)	Schedule
Living room	Consumer electronics and household appliances	75.0	-	Continuously
Kitchen	Dishwasher	313.7	-	19:00-21:00 daily
	Fridge/Freezer	70.0	-	Continuously
	Cooking	1,100.0	122.7	17:00-18:00 daily
Utility room	Washing machine	275.3	-	18:00-20:00 daily
	Drying clothes	-65.2	65.2	Continuously
Whole house[1]	Evaporation	-80.0	80.0	Continuously

1) This gain is distributed to the different rooms based on floor area

6.2. IEQ Criteria

In order to compare the results from the scenarios, different IEQ categories were defined for each parameter using the recommendations in CIBSE Guide A (Chartered Institution of Building Services Engineers, 2015), LEED v4 (U.S. Green Building Council, 2016) and World Health Organization (WHO Regional Office for Europe, 2010; World Health Organization, 2006). These categories are shown in Table 6.3.

Table 6.3: Categories for the indoor environmental parameters in this study

Temperature (°C)	**Winter**			**Summer**		
	Living	**Kitchen**	**Bedrooms**	**living**	**Kitchen**	**Bedrooms**
Cold	< 18	< 16	< 16	< 18	< 18	< 16
Cool	18-22	16-17	16-17	18-23	18-21	16-19
Comfortable	22-23	17-19	17-19	23-25	21-23	19-23
Warm	23-25	19-25	19-24	25-26	23-25	23-25
Hot	25-28	25-28	24-26	26-28	25-28	25-26
Overheating	> 28	> 28	> 26	> 28	> 28	> 26

CO_2 Concentration (ppmv)		**Relative Humidity (%)**		**Formaldehyde Conc. (mg/m^3)**	
Ambient	< 400[1]			Ambient	< 0.0025[2]
Comfortable	400-1000	Dry	< 40	Comfortable	0.0025-0.034
Poor	1000-1500	Comfortable	40-60	Poor	0.034-0.1
Very poor	> 1500	Humid	> 60	Very poor	> 0.1

$PM_{2.5}$ Conc. ($\mu g/m^3$)		**PM_{10} Conc. ($\mu g/m^3$)**		**NO_2 Conc. ($\mu g/m^3$)**	
Ambient	< 2.8[3]	Ambient	< 7.3[3]	Ambient	< 30.9[3]
Comfortable	2.8-25	Comfortable	7.3-50	Comfortable	30.9-200
Poor	> 25	Poor	> 50	Poor	> 200

[1] (ProOxygen, 2016)

[2] (WHO Regional Office for Europe, 2010)

[3] (Department for Environment Food & Rural Affairs, n.d.)

Regarding the temperature categories in Table 6.3, the "hot" limit of 25 ºC has been chosen as it is the limit set by CIBSE for air-conditioned buildings and it is also the overheating limit of the PH standard. The CIBSE benchmark for summer overheating is 26 and 28 ºC for bedrooms and living rooms respectively, and thus, these limits have been selected for the "overheating" category. The minimum limit for the "cold" range is selected based on the WHO guideline, which recommends a minimum temperature of 18 ºC inside buildings. Since the comfort temperature in bedrooms is usually lower than in the other rooms, the cold limit selected is 16 ºC for the bedrooms, since below this temperature *"resistance to respiratory infections may be diminished"* (Collins, 1986) in the elderly.

On the other hand, it should be noted that even though the guideline value of 0.1 mg/m^3 of formaldehyde is for short-term (30-minute), it will also prevent long-term health effects (WHO Regional Office for Europe, 2010). The limits shown for PM and NO_2 are the 24-hour and 1-hour mean guidelines respectively, but the annual mean guidelines mentioned in Chapter 2 will be also considered in the analysis of results.

The ambient concentrations of $PM_{2.5}$, PM_{10} and NO_2 shown in Table 6.3 correspond to the annual average concentrations for Dumfries in 2016 (Department for Environment Food & Rural Affairs, n.d.). However, to take into account hourly variations, in the Dormont PH model, one average day was selected (see Figure 6.2).

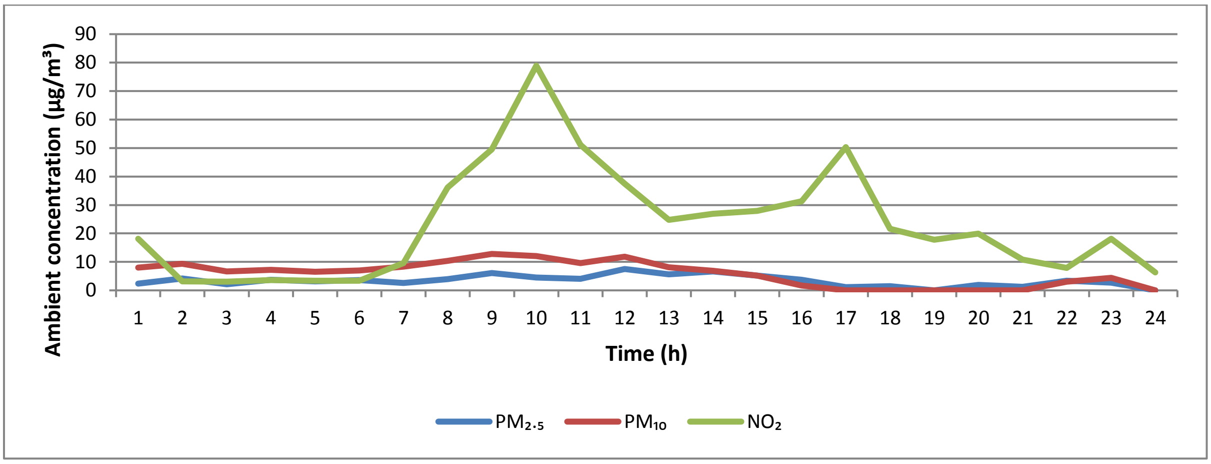

Figure 6.2: $PM_{2.5}$, PM_{10} and NO_2 ambient concentrations for the Dormont PH

6.3. Questions investigated

Scenarios were defined to answer several questions regarding the impact that different ventilation strategies and common ventilation issues have on the indoor environment. These questions were derived from common problems reported in previous studies, selected from the literature review. The questions explored and the ventilation scenarios defined to analyse them are shown in Table 6.7. It should be noted that even though this list is not comprehensive, these examples can show how detailed integrated modelling and simulation can predict IEQ issues and help to design appropriate ventilation strategies in low energy houses.

6.3.1. Question 1- Does an MVHR system without summer bypass lead to overheating periods? How does its impact on indoor temperature compare with a MVHR system with summer bypass?

MVHR systems may have some drawbacks compared to other ventilation systems. For instance, there are some concerns that MVHR without summer bypass can lead to overheating issues. One example can be found in the Dormont PH Development, where no summer bypass was provided in the 2-bedroom houses and overheating was recorded even during winter periods (MEARU, 2015). This is not a special case. Several studies have found that lack of summer bypass is a common shortcoming of MVHR systems in new buildings (Balvers et al., 2012; Sharpe et al., 2016).

This question investigates whether MVHR without summer bypass can lead to significant overheating risk in mild climates and whether providing boost control to the system and assuming window opening can solve the overheating issue. Finally, this question compares the performance of this system against the use of summer bypass.

The results that will be gathered are the operative temperature, RH and pollutants' concentration in the living room, kitchen and bedrooms. Analysis of these results against the IEQ criteria defined in Table 6.3, should highlight if the use of summer bypass is necessary to provide a satisfactory indoor environment in low-energy houses.

It is assumed that occupants will open the windows of a room when the indoor temperature rises over the comfort temperature as defined in Table 6.3. Window opening has been assumed as 10 % of the total window area.

6.3.2. Question 2 - What is the impact of a failure of the MVHR system? What are the peak concentrations of pollutants that could arise? How long after the fault is the acceptable IAQ threshold surpassed? Could window opening solve the IAQ issue?

As mentioned in Question 1, MVHR systems might have some shortcomings. In addition of summer bypass absence, one incident that may occur is a fault of the system, loss of power due to power cuts or the system being intentionally switched off by the inhabitants to avoid noise or running costs (Derbez et al., 2014; Sharpe et al., 2016).

This question investigates the consequences of a fault of the MVHR system and whether occupants opening windows could counteract them. The results that will be gathered are the operative temperature, RH and pollutants' concentration in the living room, kitchen and bedrooms. Analysis of these results against the IEQ criteria defined in Table 6.3, should highlight if window opening is able to provide a satisfactory indoor environment in low-energy houses despite a fault of an MVHR system.

In this case, window opening is modelled based on the adaptive comfort model (BSI, 2007) and using the Humphreys algorithm developed by (Rijal et al., 2007; Tuohy et al., 2007). According to this criterion, the comfort temperature (T_{comf}) is given by Equation (2.2):

$$T_{comf} = \begin{cases} 0.33\, T_{rm} + 18.8 & T_{rm} > 10\ °C \\ 0.09\, T_{rm} + 22.6 & T_{rm} \leq 10\ °C \end{cases} \qquad (6.1)$$

where T_{rm} is the running mean temperature and it is given by the next expression:

$$T_{rm} = (1-\alpha)\{T_{ed-1} + \alpha T_{ed-2} + \alpha^2 T_{ed-3} \ldots\} \quad (6.2)$$

where, α is the response factor, which is a constant value between 0 and 1, but it is usually assumed as 0.8. T_{ed-1} is the daily mean temperature for the previous day; T_{ed-2} is the mean external temperature for the day before and so on. The temperature of a room is considered acceptable if it is within two degrees above or below T_{comf}, and inhabitants would not take any action, opening or closing the windows. If the temperature is outside this band, then there is a probability that occupants will open or close the windows. This probability is calculated by the function derived from survey data (Rijal et al., 2007).

6.3.3. Question 3 - What is the impact on IAQ of a kitchen hood? What is the energy penalty of the unbalanced ventilation system?

Cooking is one of the main activities that contribute to particle generation in domestic buildings (Wallace, 1996). To mitigate this, Building Standards require an extract ventilation rate of 30 l/s if located above the hob (HM Government, 2010; Scottish Government, 2015). However, the use of the kitchen hood would lead to an unbalanced ventilation system, having therefore, an energy penalty. In addition, the use of cooking appliances may contribute to a significant increase in the indoor temperature (Bocanegra-Yanez et al., 2015).

This question investigates the impact that the use of the kitchen hood while cooking has on IAQ and thermal comfort levels. The consequent energy increase is also investigated. The results that will be gathered are the operative temperature, RH, pollutants' concentration in the living room, kitchen and bedrooms, and the heating demand in the whole house. Analysis of these results against the IEQ criteria defined in Table 6.3, should highlight the positive and negative impacts of using the kitchen hood on the indoor environment and heating demand. This information could be used to educate occupants on the importance of the proper use of the ventilation system.

Although the actual airflow through the kitchen hood will depend on the performance curve of the fan and flow resistance through the ventilation system (ASHRAE, 2012; Delp and Singer, 2012), a constant ventilation rate of 30 l/s is been assumed during cooking activities to investigate the energy penalty. Finally, to assess the impact on IAQ, a typical capture efficiency of 60 % is been assumed according to literature (Delp and Singer, 2012; Seppänen and Fisk, 2004).

6.3.4. Question 4 - Do trickle vents with Mechanical Extract Ventilation (MEV) supply enough ventilation for good IAQ? How does its performance compare with a MVHR system?

MEV with trickle vents is by far the most common ventilation strategy in the UK (Adam-Smith, 2014). Trickle vents should be always open to provide background ventilation for good IAQ. However, some studies have found that occupants do not usually know the purpose of these openings and keep them closed. In addition, curtains or blinds can prevent this ventilation system from providing enough ventilation (T. Sharpe et al., 2015; Sharpe et al., 2014).

This question investigates whether trickle vents in the living room, bedrooms and wet rooms (kitchen, utility room, bathroom and cloakroom), and continuous mechanical extract fans in the wet rooms, can assure good IAQ and thermal comfort. The impact of providing boost control to the system and assuming window opening based on adaptive comfort is also explored. Finally, this question compares the performance of this system against the use of an MVHR system.

The results that will be gathered are the operative temperature, RH, pollutants' concentration in the living room, kitchen and bedrooms, and heating demand in the whole house. Analysis of these results against the IEQ criteria defined in Table 6.3, should highlight the benefits and drawbacks of natural ventilation and MEV compared to MVHR regarding the indoor environment and heating demand. Understanding of the impacts of these systems should provide support to designers and could be used to update Building Standards requirements.

Building Standards in Scotland (Scottish Government, 2015) require a minimum of 10,000 mm^2 Equivalent Area (EA) of trickle vents in wet rooms and 12,000 mm^2 EA in habitable rooms. The EA of the trickle ventilators is determined by manufacturers and is available on their websites. Figure 6.3 and Table 6.4 show the dimensions of the trickle vents chosen in this study.

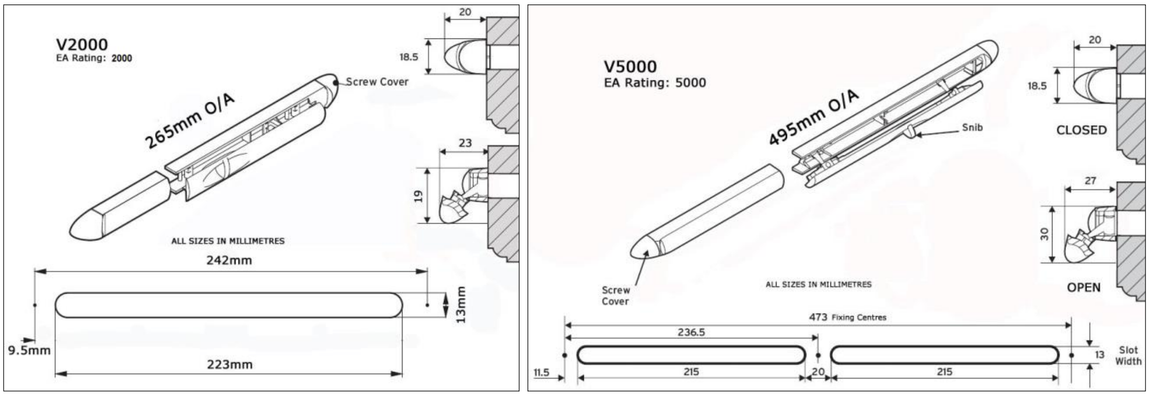

Figure 6.3: Trickle vents used in this study (Handlestore Ltd, 2017)

Table 6.4: Trickle vents dimensions

	Trickle ventilation provision (mm^2 EA)	**Number of trickle vents x (dimensions in mm)**
Kitchen, utility room, cloak room and bathroom	10,000	2 x (215x13)
Living room and bedrooms	12,000	2 x (215x13) 1 x (223x13)

Regarding continuous mechanical extract fans in the wet rooms, the minimum ventilation rates required by the Scottish Building Standards are shown in Table 6.5. Finally, window opening has been assumed as 10 % of the total window area.

Table 6.5: Continuous and boost extract rates of mechanical extract ventilation (MEV) (The Scottish Government, 2015)

Ventilation rate (m^3/h)	**Minimum continuous extract**	**Minimum boost extract**
Kitchen	22	47
Utility room	14	29
Cloak room	11	22
Bathroom	14	29
Total	61	127

6.3.5. Question 5 - How does a constant ventilation rate compare with the use of different types of ventilation control?

In the last decades, building standards have required more insulated and air-tight buildings to reduce the energy demand and associated carbon emissions. The ventilation rate specified by the standards is meant to be the minimum necessary to provide comfort and good IAQ based on a designed occupancy. However, in reality, occupancy profiles will differ from one dwelling to another and therefore, this fixed rate may not be sufficient to provide good IAQ or be outsized leading to an extra energy loss.

Previous studies have found that Demand-Controlled Ventilation (DCV) may have a significant impact on heating demand reduction while maintaining good levels of IAQ, since the ventilation rate is adapted to the specific needs at all times. Although it has been argued that DCV is only appropriated for buildings with large occupancy variability, such as offices or commercial buildings (Chenari et al., 2016), there have been several experimental and simulation studies that have found that DCV strategies in domestic buildings may have positive effects (Mortensen, 2011; Nielsen and Drivsholm, 2010; Pollet et al., 2013).

Usually, boost control in domestic buildings is based on manual switches or RH sensors that activate the boost mode when the indoor air is too humid (RH above 60 %) in wet rooms such as kitchens, bathrooms or utility rooms (HM Government, 2010; Scottish Government, 2015). Although this boost control may not be enough to provide good IAQ (Fisk and De Almeida, 1998; Laverge et al., 2011; Pavlovas, 2004), the use of other controls in dwellings, like CO_2-based DCV, is not common practice due to the higher costs involved (Bocanegra-Yanez et al., 2017).

This question investigates the performance of a constant ventilation rate system compared with DCV control strategies based on RH or CO_2. Finally, this question also explores the impact of window opening based on adaptive comfort.

The results that will be gathered are the operative temperature, RH, pollutants' concentrations in the living room, kitchen and bedrooms, and heating demand in the whole building. Analysis of these results against the IEQ criteria defined in Table 6.3, should highlight the benefits and drawbacks of different DCV strategies regarding the indoor environment and heating demand. Understanding of the impacts of these control systems should help the development of guidelines to help designers, educate occupants on the importance of the proper use of the ventilation system and update Building Standards requirements.

For the DCV strategies, the ventilation rate is assumed to be the minimum defined by PHPP and it is increased to the standard ventilation rate when occupants are present. Additionally, the ventilation rate is boosted by 30 % based on RH or CO_2. Table 6.6 shows the ventilation rates for all these modes (minimum, standard and boost) for the different rooms within the house.

Table 6.6: PH standard ventilation rates

Ventilation rate (m^3/h)	Boost	Standard	Minimum
Extract			
Kitchen	60.1	46.2	24
Utility room	20.0	15.4	8
Cloak room	20.0	15.4	8
Bathroom	40.0	30.8	16
Total	140.1	107.8	56.0
Supply			
Living room	61.7	47.5	24.7
Main bedroom (Bed1)	44.7	34.4	17.9
Rear bedroom (Bed 2)	33.7	25.9	13.5
Total	140.1	107.8	56.0

Table 6.7: Ventilation scenarios and questions analysed in this study

Questions	**Ventilation scenarios**
Question 1 - Does an MVHR system without summer bypass lead to overheating periods? How does its impact on indoor temperature compare with a MVHR system with summer bypass?	Scenario 1A – MVHR with constant ventilation rate: Heating is supplied by a post-air heating unit as part of the MVHR system. This unit senses the temperature in the living room and supplies warm air when the temperature drops below the set-point. In addition, there is a radiator in the bathroom. Ventilation is provided using the MVHR system only with a constant standard ventilation rate as defined in the Passive House Planning Package (PHPP) (Passive House Institute, 2012) (see). The PH standard requires the use of heat recovery units with a minimum efficiency of 75 %. Units that are more efficient are available in the market and efficiencies around 90 % are common practice. In this case, the efficiency is 91 % according to the manufacturer specifications (PAUL Wärmerückgewinnung GmbH, 2017).
	Scenario 1B - MVHR with summer bypass
	Scenario 1C - MVHR with boost control based on RH and indoor temperature: A control based on RH and indoor temperature is applied to the system to increase the ventilation rate of the fans by 30 % when RH is above 60 % or the indoor temperature rises over the comfort temperature as defined in CIBSE Guide A (Chartered Institution of Building Services Engineers, 2015) (see).
	Scenario 1D - MVHR with boost control and window opening available: It is assumed that occupants will open the windows of a room when the indoor temperature rises over the comfort temperature. Window opening has been assumed as 10 % of the total window area and the boost option is switched off when windows are open.
	Scenario 1E – Same situation as Scenario 1D but incorporating summer bypass
Question 2 - What is the impact of a	Scenario 2A – MVHR system failure or turned off

failure of the MVHR system? What are the peak concentrations of pollutants that could arise? How long after the fault is the acceptable IAQ threshold surpassed? Could window opening solve the IAQ issue?	Scenario 2B – MVHR system failure with window opening depending on adaptive thermal comfort
Question 3 - What is the impact on IAQ of a kitchen hood? What is the energy penalty of the unbalanced ventilation system?	Scenario 3A – MVHR with constant ventilation rate (Scenario 1A)
	Scenario 3B - MVHR with kitchen hood: Same situation as Scenario 3A but, in this case, it is assumed that occupants will use the extract ventilation hood in the kitchen while cooking. The extract ventilation rate is 30 l/s to comply with Building Standards (Scottish Government 2015).
Question 4 - Do trickle vents with Mechanical Extract Ventilation (MEV) supply enough ventilation for good IAQ? How does its performance compare with a MVHR system?	Scenario 4A - Trickle vents with continuous MEV: Trickle vents and mechanical extract fans were defined according to the Building Standards (Scottish Government 2015) (see Table 6.4 and). Since the heating was originally supplied by a post-air heating unit in the MVHR system, this scenario requires another heating system to keep the temperature within comfort limits, for example, radiators in the different rooms.
	Scenario 4B - Trickle vents with boost MEV control: A control based on RH is applied to the system to increase the ventilation rate of the fans by 30 % when RH is above 60 %.
	Scenario 4C - Trickle vents with boost MEV control and window opening: It is assumed that beside the fans working in boost mode when the air is humid, occupants will open the windows of a room when the indoor temperature rises over the comfort temperature, based on adaptive thermal comfort.
	Scenario 4D – MVHR with constant ventilation rate (Scenario 1A)
Question 5 - How does a constant	Scenario 5A – MVHR with constant ventilation rate (Scenario 1A)

ventilation rate compare with the use of different types of ventilation control?	Scenario 5B - MVHR with boost control based on RH: The ventilation rate is assumed to be the minimum defined by PHPP (see) and a control based on occupancy and RH is applied to the system to increase the ventilation rate of the fans to the standard ventilation rate when occupants are present and boost by 30 % when the house is occupied and RH is above 60 %.
	Scenario 5C - MVHR with boost control based on CO_2 concentration: Same situation as Scenario 5B but, in this case, a control based on CO_2 is applied to the system to increase the ventilation rate of the fans by 30 % when CO_2 is above 1000 ppmv.
	Scenario 5D - MVHR with boost control based on RH with window opening based on adaptive thermal comfort.
	Scenario 5E - MVHR with boost control based on CO_2 with window opening based on adaptive thermal comfort.

6.4. Pollutant cases

Four pollutant cases have been defined using the emission models described in Chapter 5:

- Time-dependent formaldehyde sources
- Temperature and RH dependent formaldehyde sources
- PM and NO_2 sources
- Formaldehyde, PM and NO_2 sources

In addition, some of these cases were divided further into a low and high emission case. Once the cases are defined, one pollutant case is assigned to each of the questions to be investigated according to the main focus of each question.

According to the literature review of Chapter 2, the target pollutants were: formaldehyde, NO_2, PM_{10}, $PM_{2.5}$, radon and mould. However, as explained in Chapter 4, measurements of radon and mould were not included in the monitoring as the risk of high radon concentrations were negligible and risk of mould growth can be estimated from RH levels. Therefore, radon and mould have not been included in the cases. In addition to the pollutants identified in the literature review, CO_2 was included in the model as it is extensively used as IAQ proxy. All the cases consider CO_2 emissions are due only to occupants.

6.4.1. Time-dependent formaldehyde sources

As previously mentioned in Chapter 2, in the last decades, there have been many studies on emission rates of specific pollutants. However, there is no comprehensive database that compiles all this information. In this case, the formaldehyde sources assumed have been taken from the PANDORA database (Abadie and Blondeau, 2011), which includes emission data from many previous studies regarding constant emission rates or emission rates depending on time. The pollutant sources chosen are shown in Table 6.8.

Table 6.8: Time-dependent formaldehyde sources considered in this study

Formaldehyde Source and Location	Pollutant model
Nylon carpet (Won and Shaw, 2004) in living room, bedrooms, stairs and halls	Gas transient power law model a_1=0.0455363 mg/m^{2}h a_2=0.3634 t_p=36.235 h
Kitchen cabinet (countertop) - Melamine particleboard (Won and Shaw, 2004)	Gas transient power law model a_1=0.0059902 mg/m^{2}h a_2=0.103 t_p =36.035 h
Gypsum wallboard (vinyl-faced) (Won and Shaw, 2004) in all rooms	Gas transient power law model a_1=0.0023535 mg/m^{2}h a_2=0.1793 t_p =36.485 h
Kitchen cleaner - Carrefour éco-planète brand (Meme et al., 2013)	Gas transient discrete emission data model a_1=25.8 µg/gh, t_1=0.5 h a_2=4.5 µg/gh, t_2=1 h
Bleach – low cost (Meme et al., 2013) in the bathroom	Gas transient discrete emission data model a_1=218.9 µg/gh, t_1=0.5 h a_2=196.1, t_2=1 h
Television PDP (Plasma Display Panel) (Kurosawa et al., 2008) in the living room	Gas transient discrete emission data model a_1=38 µg/h, t_1=0 a_2=30 µg/h, t_2=1 h a_3=38 µg/h, t_3=3 h a_4=30 µg/h, t_4=6 h a_5=38 µg/h, t_5=8 h a_6=30 µg/h, t_6=24 h
Desktop with CRT monitor (Nakagawa et al., 2003) in the living room	Gas steady state emission rate S=0.0128 mg/h
New laptop – switched off (Funaki et al., 2003) in the main bedroom	Gas steady state emission rate S=0.001 mg/h
Wooden chair (Roux, 2013) in the living room	Gas transient discrete emission data model a_1=128.8 µg/m^{2}h, t_1=24 h a_2=96.6 µg/m^{2}h, t_2=72 h a_3=50.6 µg/m^{2}h, t_3=672 h
Wooden table (Roux, 2013) in the living room and kitchen	Gas transient discrete emission data model a_1=19.1 µg/m^{2}h, t_1=24 h a_2=20.8 µg/m^{2}h, t_2=72 h a_3=14.9 µg/m^{2}h, t_3=672 h
Wooden wardrobe (Roux, 2013) in the living room and bedrooms	Gas transient discrete emission data model a_1=21.9 µg/m^{2}h, t_1=24 h a_2=18.1 µg/m^{2}h, t_2=72 h a_3=13.4 µg/m^{2}h, t_3=672 h
Kitchen cabinet - Melamine particleboard (Won and Shaw, 2004)	Gas steady state emission rate S=0.0362158 mg/m^{2}h

Two different formaldehyde emission cases were considered: a low emission rate case and a high emission rate one. These cases were defined to represent actual formaldehyde levels measured in several houses in Scotland (Farren, 2016). These houses were built after 2010 and the ventilation system consisted of trickle vents. Measurements were undertaken for 48 hours in the main bedrooms.

The low emission rate case is defined assuming materials are five years old. However, the model available for wooden furniture is a gas transient discrete emission data model and there is no information on the emission rate after 5 years. Hence, it has been assumed that the emission rate comes to steady state after the last emission data available (672 hours after the start of the emission). On the other hand, the high emission rate case assumes new materials. For both cases, it is assumed that cleaning products are used on Saturdays and the TV is used every evening when occupants are in the living room. Table 6.9 shows the minimum, average and maximum formaldehyde levels for the low and high emission rate cases.

Table 6.9: Monitored and simulated results for formaldehyde for the low and high emission rate cases

Case		**Formaldehyde concentration in the bedrooms (ppb)**		
		Minimum	**Average**	**Maximum**
Low emission	Simulated	10	14	25
	Measured	10	15	21
High emission	Simulated	10	24	68
	Measured	10	55	72

6.4.2. Temperature and RH dependent formaldehyde sources

The formaldehyde source considered has been taken from the study by Liang et al. (2016) which gives information for all the parameters needed to model formaldehyde emissions from a typical medium density fibreboard (MDF) (see Table 6.10). Once the model was calibrated, as mentioned in Chapter 4, the amount of MDF was adjusted so the formaldehyde concentrations obtained are in good agreement with those measured in the actual building (see Table 6.11). Thus, it is assumed that all formaldehyde sources in the house would behave in a similar way as the MDF studied by Liang et al. Measurements were undertaken for three days in the main bedroom and seven days in the living-room. The resulting source area is 14.9 m^2 in the living room and 7.4 m^2 in the main bedroom. As there is a lack of formaldehyde measurements in the kitchen and rear bedroom, sources were adjusted assuming the same average concentration in the living room and the kitchen, and the main and rear bedroom. The resulting source area is 2.3 m^2 in the kitchen and 5 m^2 in the rear bedroom.

Table 6.10: Formaldehyde emission parameters for MDF (Liang et al. 2016)

Correlation	**Constant**	**Value**
k (T)	A1	0.12
	A2	2376
D_m (T)	B1	5.18×10^{-17}
	B2	-194
C_0 (T,RH)	C1	0.0035
	C2	5.4×10^{18}
	C3	7700

Table 6.11: Monitored and simulated results for formaldehyde

Room		**Formaldehyde concentration (ppb)**		
		Minimum	**Average**	**Maximum**
Living-room	Simulated	12	16	19
	Measured	11	16	18
Main bedroom	Simulated	15	16	18
	Measured	11	15	27

Looking at the results in Table 6.11, it can be seen that the simulated results are mainly in good agreement with measured data in terms of minimum, average and maximum formaldehyde concentrations in the living room and main bedroom. However, the maximum concentration measured in the main bedroom is significantly above the prediction. This reading corresponds to the start of the monitoring but after four hours, concentrations decrease and stay around 15 ppb (see Figure 6.4). The initial formaldehyde levels could be due to a singular source of formaldehyde before the start of the monitoring. Therefore, it can be assumed that the formaldehyde concentrations in the building is fairly constant and that simulated results are enough accurate for the purpose of this study.

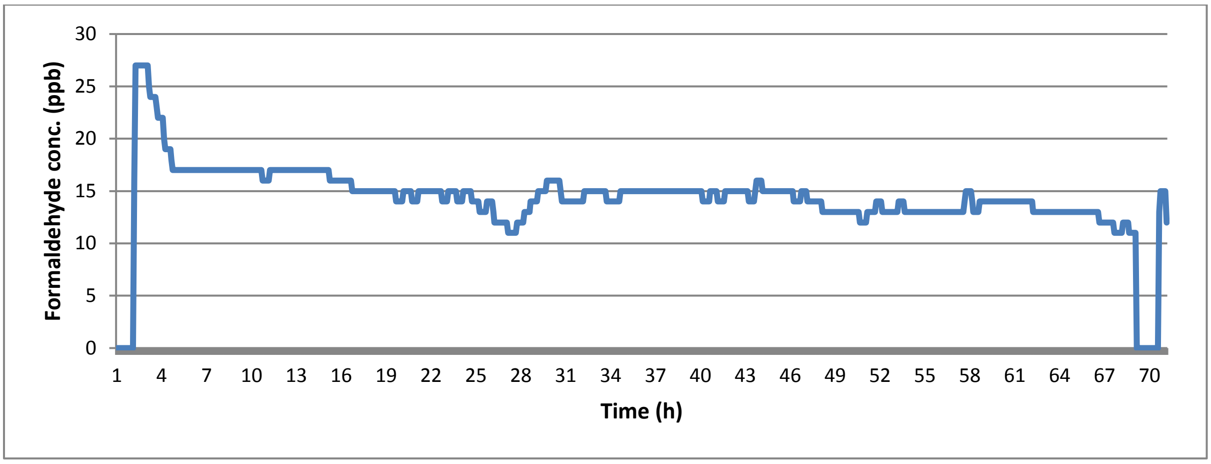

Figure 6.4: Formaldehyde measurements in the main bedroom

6.4.3. PM and NO_2 sources

In this case, two different emission cases were considered: a low emission rate case and a high emission rate one. For the low emission case, PM and NO_2 sources and sinks were defined to obtain pollutant concentrations in good agreement with those measured in the actual building and be consistent with emission data from the literature. As in the case of formaldehyde, measurements were undertaken for three days in the main bedroom and seven days in the living-room, but no measurements were undertaken in the kitchen or rear bedroom. Pollutant sources associated with cooking activities were located in the kitchen according to the occupants' diary. As ambient concentrations were not measured, hourly concentrations for an average day in Dumfries (Figure 6.2) have been used in the model, as previously explained. Therefore, exact match of simulated and measured data is not possible and the comparison between simulated and measured data has been done in terms of average concentrations as shown in Table 6.12. Since guidelines recommend limits for daily concentrations, average values are sufficient to assess IAQ.

Table 6.12: Monitored and simulated results for $PM_{2.5}$, PM_{10} and NO_2

Room		**$PM_{2.5}$ conc. (μg/m^3)**	**PM_{10} conc. (μg/m^3)**	**NO_2 conc. (ppm)**
Living-room	Simulated	7.3	19.6	0.02
	Measured	8.3	20.5	0.01
Main bedroom	Simulated	7.7	17.2	0.02
	Measured	4.9	14.9	0.01

Looking at the results in Table 6.12, it can be seen that measured NO_2 concentrations were very low. Therefore, no indoor sources were considered for the low emission rate case.

To estimate the $PM_{2.5}$ and PM_{10} emission and deposition rates data from the Particle TEAM (PTEAM) study (Ozkaynak et al., 1997) were used. In that study, the deposition rates and source strengths were estimated using nonlinear least squares to solve the model by Koutrakis et al. (1992). The only identified source from the occupants' diary at the Dormont PH was the cooking activity. In addition to this source, results from the PTEAM study showed that there were emissions from sources different from cooking or smoking. To include these emissions in the model, they were calculated for the whole building and they have been divided according to floor area to take into account their contribution to the PM concentration in the main habitable rooms (living room, kitchen and main bedroom). Then, the cooking emission rate and deposition rate were adjusted to match the average concentrations measured in the building. This led to cooking emission rates below the minimum range calculated by the PTEAM study. To avoid this, another possibility would have been to reduce the cooking time. However, since cooking emissions are highly variable (Shrubsole et al., 2012), the information gathered from the occupants' diary was prioritised, adjusting therefore, the cooking emission rate.

The resuspension rates have been retrieved from the study by Thatcher & Layton (1995), which calculated the resuspension rates according to particle size under "normal" activities such as walking or sitting. The deposition rate for NO_2 was assumed to be 0.99 h^{-1} as in Yamanaka (1984).

For the high emission rate case, a gas cooker, cigarette smoking and candles were added to the model. Smoking in homes is of great concern, especially after the smoking ban in public places (Watson, 2014). Although cigarette smoking would lead to a number of pollutant emissions, the focus in this case was on $PM_{2.5}$, PM_{10} and NO_2. The emission rates were selected from the PANDORA database (Abadie and Blondeau, 2011). The sources and sinks considered for $PM_{2.5}$, PM_{10} and NO_2 are shown in Table 6.13, Table 6.14 and Table 6.15 respectively.

Table 6.13: $PM_{2.5}$ sources/sinks considered in this study

$PM_{2.5}$ Source/Sink and Location	**Pollutant model**	**Schedule**
Low emission rate case		
Cooking in the kitchen	Particles steady state emission rate S=0.85 mg/min	17:00-18:00 daily
Sources other than cooking and smoking (Ozkaynak et al. 1997) in living room, main bedroom and kitchen	Particles steady state emission rate S=0.0096 mg/min (living room) S=0.0048 mg/min (kitchen) S=0.0072 mg/min (main bedroom)	Continuously
Deposition (Ozkaynak et al. 1997) and resuspension (Thatcher & Layton 1995) in the whole building	Deposition and resuspension model kd=0.55 h^{-1} r=1.8x10^{-5} h^{-1}	Deposition – continuously Resuspension – same as occupancy schedule
High emission rate case		
Smoking (Ozkaynak et al. 1997) in the living room	Particles steady state emission rate S=14 mg/cigarette x 4 cigarettes	19:00-20:00 daily
Gas stove (He et al., 2004) in the kitchen	Particles steady state emission rate S=0.24 mg/min	17:00-18:00 daily
Candle (He et al., 2004) in the main bedroom	Particles steady state emission rate S=0.91 mg/min	22:00-22:30 daily
Deposition (Ozkaynak et al. 1997) and resuspension (Thatcher & Layton 1995) in the whole building	Deposition and resuspension model kd=0.55 h^{-1} r=1.8x10^{-5} h^{-1}	Deposition – continuously Resuspension - same as occupancy schedule

Table 6.14: PM_{10} sources considered in this study

PM_{10} Source/Sink and Location	Pollutant model	Schedule
Low emission rate case		
Cooking in the kitchen	Particles steady state emission rate S=1.4 mg/min	17:00-18:00 daily
Sources other than cooking and smoking (Ozkaynak et al. 1997) in living room, main bedroom and kitchen	Particles steady state emission rate S=0.0312 mg/min (living room) S=0.0156 mg/min (kitchen) S=0.0228 mg/min (main bedroom)	Continuously
Deposition (Ozkaynak et al. 1997) and resuspension (Thatcher & Layton 1995) in the whole building	Deposition and resuspension model kd=0.93 h^{-1} r=8.3x10^{-5} h^{-1}	Deposition – continuously Resuspension - same as occupancy schedule
High emission rate case		
Smoking (Ozkaynak et al. 1997) in the living room	Particles steady state emission rate S=22 mg/cigarette x 4 cigarettes	19:00-20:00 daily
Candle (Zai et al., 2006) in the main bedroom	Particles steady state emission rate S=0.127 mg/min	22:00-22:30 daily
Deposition (Ozkaynak et al. 1997) and resuspension (Thatcher & Layton 1995) in the whole building	Deposition and resuspension model kd=0.93 h^{-1} r=8.3x10^{-5} h^{-1}	Deposition – continuously Resuspension - same as occupancy schedule

Table 6.15: NO_2 sources considered in this study

NO_2 Source/Sink and Location	Pollutant model	Schedule
Low emission rate case		
Deposition (Yamanaka 1984) in the whole building	Deposition model kd=0.99 h^{-1}	Continuously
High emission rate case		
Smoking (Health Canada, 2004) in the living room	Steady state emission rate S=1.5 mg/cigarette x 4 cigarettes	19:00-20:00 daily
Gas stove (Girman et al., 1982) in the kitchen	Steady state emission rate S=2.27 mg/min	17:00-18:00 daily
Deposition (Yamanaka 1984) in the whole building	Deposition model kd=0.99 h^{-1}	Continuously

Finally, filters were also included in the model according to the manufacturer specifications (PAUL Wärmerückgewinnung GmbH 2017). The filter efficiencies are 96 % for $PM_{2.5}$ and 99 % for PM_{10}.

6.4.4. Formaldehyde, PM and NO_2 sources

For this pollution case, five pollutants were included in the model: CO_2, formaldehyde, $PM_{2.5}$, PM_{10} and NO_2. As in the previous cases, the CO_2 emissions are assumed to be only from occupants. The formaldehyde source considered is the MDF from Liang et al. (2016) and the PM and NO_2 sources are according the low emission rate case explained previously.

6.4.5. Selection of pollutant cases

Finally, one pollutant case was selected for each of the questions described in Section 6.2 and they are shown in Table 6.16. Question 1 focuses on the overheating and thermal comfort issue and therefore, the simplified time-dependent emission sources were selected, not to add complexity to the model. For Question 2, the more detailed temperature and RH dependent source was selected to obtain more accurate results of the impact that a fault of the MVHR system has on IAQ levels. The PM and NO_2 sources were selected for Question 3 as these are the main pollutants related to cooking activities and the ones that could be mostly influenced by the use of a kitchen hood. Lastly, Questions 4 and 5 are analysed using the formaldehyde, PM and NO_2 sources to serve as examples on how detailed simulation, taking into account several pollutants in different parts of the building at different times, can help the design and comparison of ventilation strategies.

Table 6.16: Pollutant cases and questions analysed in this study

Questions	Pollutant cases
Question 1 - Does an MVHR system without summer bypass lead to overheating periods? How does its impact on indoor temperature compare with a MVHR system with summer bypass?	Time-dependent formaldehyde sources
Question 2 - What is the impact of a failure of the MVHR system? What are the peak concentrations of pollutants that could arise? How long after the fault is the acceptable IAQ threshold surpassed? Could window opening solve the IAQ issue?	Temperature and RH dependent formaldehyde sources
Question 3 - What is the impact on IAQ of a kitchen hood? What is the energy penalty of the unbalanced ventilation system?	PM and NO_2 sources
Question 4 - Do trickle vents with Mechanical Extract Ventilation (MEV) supply enough ventilation for good IAQ? How does its performance compare with an MVHR system?	Formaldehyde, PM and NO_2 sources
Question 5 - How does a constant ventilation rate compare with the use of different types of ventilation controls?	Formaldehyde, PM and NO_2 sources

6.5. Summary

Questions to investigate and analyse common IAQ and comfort issues in low energy buildings and help the design of different ventilation strategies have been described, explaining in detail the assumptions made to define the different ventilation scenarios and pollutant cases associated with them.

Question 1 investigates whether MVHR without summer bypass can lead to significant overheating risk in mild climates and whether providing boost control to the system and assuming window opening can solve the overheating issue. This question also compares the performance of this system against the use of summer bypass. Question 2 investigates the consequences of a fault of the MVHR system and whether occupants opening windows could counteract them. Question 3 investigates the impact that the use of the kitchen hood while cooking has on IAQ and thermal comfort levels. The consequent energy increase is also investigated. Question 4 investigates whether trickle vents in the living room, bedrooms and wet rooms, and continuous mechanical extract fans in the wet rooms, can assure good IAQ and thermal comfort. The impact of providing boost control to the system and assuming window opening based on adaptive comfort is also explored. In addition, this question compares the performance of this system against the use of an MVHR system. Finally, question 5 investigates the performance of a constant ventilation rate system compared with DCV control strategies based on RH or CO_2, and assuming window opening based on adaptive comfort.

The results that will be gathered are the operative temperature, RH and pollutant concentrations (CO_2, formaldehyde, $PM_{2.5}$, PM_{10} and NO_2) in the living room, kitchen and bedrooms. In addition, the heating demand in the whole building was retrieved for some cases. Analysis of these results against the IEQ criteria should highlight the benefits and drawbacks of different ventilation strategies regarding the indoor environment and heating demand. Understanding of the impacts of different parameters and control systems should help the development of guidelines to help designers, educate occupants on the importance of the proper use of the ventilation system and update Building Standards requirements. The simulation results from these scenarios are presented and discussed in the following chapter.

Chapter 7. Results and Discussion

This chapter analyses the simulation results obtained for the different scenarios described in the previous chapter. Question 1 investigates whether MVHR without summer bypass can lead to significant overheating risk in mild climates and whether providing boost control to the system and assuming window opening can solve the overheating issue. This question also compares the performance of this system against the use of summer bypass. Question 2 investigates the consequences of a fault of the MVHR system and whether occupants opening windows could counteract them. Question 3 investigates the impact that the use of the kitchen hood while cooking has on IAQ and thermal comfort levels. The consequent energy increase is also investigated. Question 4 investigates whether trickle vents in the living room, bedrooms and wet rooms, and continuous mechanical extract fans in the wet rooms, can assure good IAQ and thermal comfort. This question also explores the impact of providing boost control to the system and assuming window opening based on adaptive comfort, and it compares the performance of this system against the use of an MVHR system. Finally, question 5 investigates the performance of a constant ventilation rate system compared with DCV control strategies based on RH or CO_2, and assuming window opening based on adaptive comfort.

The results gathered are the operative temperature, RH and pollutant concentrations (CO_2, formaldehyde, $PM_{2.5}$, PM_{10} and NO_2) in the living room, kitchen and bedrooms. In addition, the heating demand in the whole building was retrieved for some cases. The simulation results are assessed using the IEQ criteria defined in the previous chapter (Table 6.3) using the recommendations in CIBSE Guide A (Chartered Institution of Building Services Engineers, 2015), LEED v4 (U.S. Green Building Council, 2016) and World Health Organization (WHO Regional Office for Europe, 2010; World Health Organization, 2006). Analysis of these results should highlight the benefits and drawbacks of different ventilation strategies regarding the indoor environment and heating demand. Understanding of the impacts of different parameters and control systems should help the development of guidelines to help designers, educate occupants on the importance of the proper use of the ventilation system and update Building Standards requirements.

Finally, the IAQ indices proposed by Cony Renaud Salis et al. (2017) are used in one of the scenarios to show a different approach for assessing IAQ results.

7.1. Question 1 - Does an MVHR system without summer bypass lead to overheating periods? How does its impact on indoor temperature compare with a MVHR system with summer bypass?

Question 1 investigates whether MVHR without summer bypass can lead to significant overheating risk in mild climates and whether providing boost control to the system and assuming window opening can solve the overheating issue. This question also compares the performance of this system against the use of summer bypass. Simulations of Scenarios 1A to 1E were run in order to analyse Question 1 as shown in Table 6.7. These simulations were run for a summer period (June 1st to August 31st) using a time step of 10 minutes. The results gathered are the operative temperature, CO_2 concentration, RH and formaldehyde concentration in the living room, kitchen and bedrooms. The formaldehyde sources considered in this case are the time-dependent sources described in the previous chapter.

7.1.1. Results

Results show that MVHR without summer bypass and no window opening (Scenario 1A) can lead to overheating and hot periods for 40 % of the occupied time in the bedrooms and living room, and almost 90 % of the occupied time in the kitchen; with a maximum temperature of 33 °C (see Figure 7.1). Selecting boost ventilation when temperature rises over the comfort threshold does not make a significant difference. The use of summer bypass eliminates the overheating and reduces the hot periods to around 10 % of the time in the living room but the overheating and hot periods persist in the kitchen for 65 % of the time. MVHR combined with window opening (Scenario 1D) keeps the temperatures within the comfort range in the living room and bedrooms when doors remain open. However, hot periods remain in the kitchen for 27 % of the time. When internal doors are shut, the situation worsens, leading to hot and overheating periods for around 30 %, 40 % and 65 % of the time in the living room, bedrooms and kitchen, respectively. In this case, increased air velocity could improve thermal comfort as naturally ventilated buildings may have higher air velocities due to window opening. Indicative air velocities were calculated using the ach and it was found that the maximum velocity was 1 m/s. Nevertheless, the air velocity was around 0.02 m/s for more than 84 % of the time. Therefore, for Scenario 1D with internal doors shut, air velocity is negligible and will not have an impact on thermal comfort levels. The overheating problem is solved in the living room and the bedrooms when MVHR with bypass is combined with window opening, with internal doors open or shut. However, hot and overheating periods are still found in the kitchen 60 % of the occupied time.

Figure 7.2 shows a comparison of the overheating results for Scenario 1A with indoor doors open (worst case) and Scenario 1E with indoor doors open (best case).

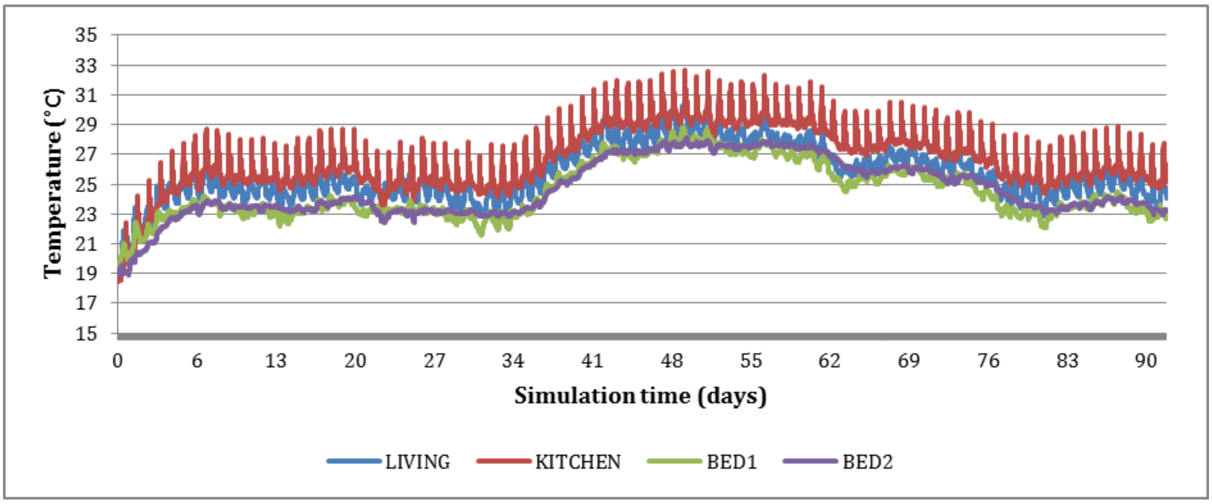

Figure 7.1: Temperature results for Scenario 1A with indoor doors open

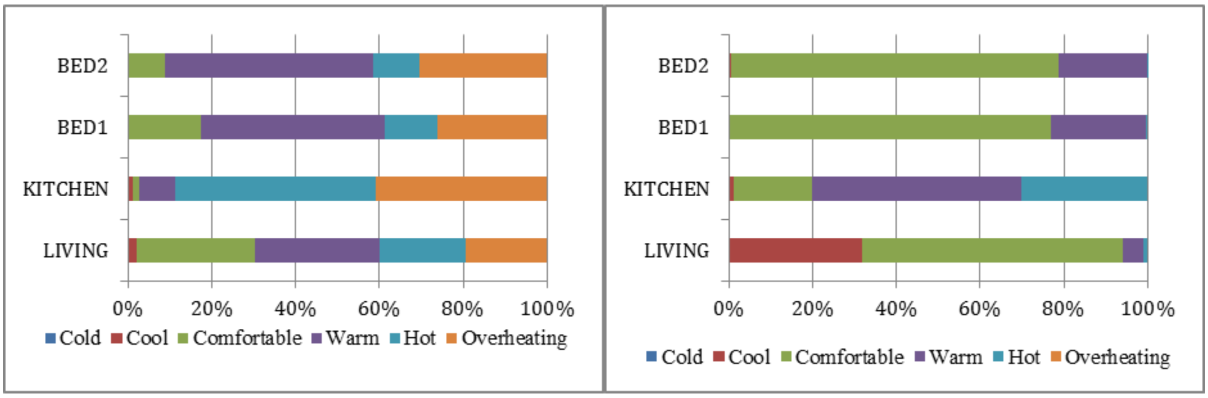

Figure 7.2: Comparison of overheating results for Scenario 1A with indoor doors open (left) and Scenario 1E with indoor doors open (right)

Regarding IAQ, formaldehyde concentration remained below 0.1 mg/m^3 for all the scenarios. CO_2 concentration in the living room is over 1000 ppmv around 42 % of the occupied time when there is no boost control for the MVHR and the doors are shut. This improves with the use of boost control and window opening but the CO_2 level still remains over 1000 ppmv around 18 % of the time in the living room if the internal doors are closed. This is solved by opening the doors to let the air flow from the polluted rooms to the ambient through the extract fans.

Finally, RH stays within comfortable levels around 90 % of the time when MVHR is used. Conversely, the use of summer bypass with or without window and door opening (Scenario 1B and 1E) leads to RH levels above 60 % (humid air) between 30 % and 40 % of the time. To check the mould growth risk, CIBSE Guide A (Chartered Institution of Building Services Engineers, 2015) states that if the RH is above 80 % for less than two hours a day, and it does not stay above 70 % for long periods, there is no risk of mould growth. Analysis of the results shows that RH is never above 80 % for more than 2 hours a day and it is above 70 % around 15 non-consecutive hours in the living room and the kitchen, and less than 5 days in the bedrooms. Therefore, the use of summer bypass does not imply a risk for mould growth in this case. Figure 7.3 shows the RH results obtained for the living room, kitchen and bedrooms for Scenario 1E.

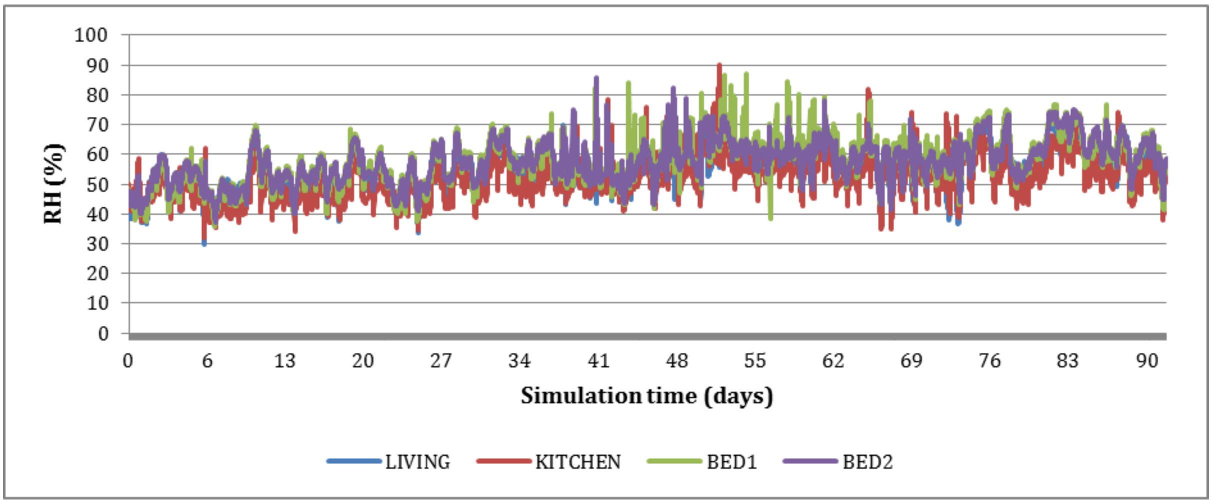

Figure 7.3: RH results for Scenario 1E with indoor doors open

It should be noted that although humidity buffering has not been taken into account in the modelling, these results are believed to be fairly accurate for the purpose of this study as no hygroscopic materials are used in the walls. Furthermore, the vapour control layer located inside the wall would decrease the impact of the hygrothermal properties of the materials used.

7.1.2. Discussion

From the scenarios analysed, it can be concluded that the use of the heat recovery unit during summer may lead to unacceptable levels of overheating throughout the house, even in temperate climates like Scotland. Apart from the overheating in the kitchen, which was predictable due to cooking activities, results showed overheating conditions in the bedrooms for 25 consecutive days, with a maximum temperature above 28 °C. Therefore, there is definitely a noteworthy overheating risk if summer bypass is not permitted in this type of houses, with great insulation and airtightness levels, light thermal mass and no external shading. This situation would impair sleep and have a direct impact on occupant's health and comfort.

The use of summer bypass solves the overheating in the bedrooms in this case. However, a maximum temperature of 25 °C was predicted, which is below but very close to the limit established by CIBSE during night time. Thus, if conditions differ from the present study, i.e. different climate or IHG, there could be some overheating in the bedrooms despite the use of summer bypass. In that case, combining the use of bypass with window opening could alleviate the overheating issue.

Despite results not being absolute values due to the inherent uncertainties of the modelling, these findings suggest that summer bypass should be mandatory to minimise the risk of overheating even in mild climates.

7.2. Question 2 - What is the impact of a failure of the MVHR system? What are the peak concentrations of pollutants that could arise? How long after the fault is the acceptable IAQ threshold surpassed? Could window opening solve the IAQ issue?

Question 2 investigates the consequences of a fault of the MVHR system and whether occupants opening windows could counteract them. Simulations of Scenario 2A and 2B were run in order to analyse Question 2 as shown in Table 6.7. These simulations were run for a summer period (June 1st to August 31st) using a time step of 20 minutes and assuming 100 grid points inside the material. The results gathered are the operative temperature, CO_2 concentration, RH and formaldehyde concentration in the living room, kitchen and bedrooms. The formaldehyde source considered is the temperature and RH dependent source described in the Chapter 6.

7.2.1. Results

Results show that, when there is a failure of the MVHR system or it is intentionally switched off (Scenario 2A), the IAQ becomes very poor. CO_2 concentrations are over 1000 ppmv over 90 % of the occupied time in the living room and bedrooms. This situation gets slightly worse if the internal doors remain closed. Figure 7.4 shows the variation of CO_2 concentration during the summer period for this scenario (worst case). It can be seen that the maximum CO_2

concentration in the main bedroom (Bed1), where two occupants were assumed, is almost eight times above the comfortable level described in Table 6.3. In terms of the time scale, only 24 hours after the failure occurs, the threshold is already surpassed with CO_2 concentrations around 1700 ppmv in the bedrooms and 1300 ppmv in the living room and the kitchen when internal doors are open, and concentrations of 2500 ppmv in the main bedroom and 3100 ppmv in the living room when internal doors are shut.

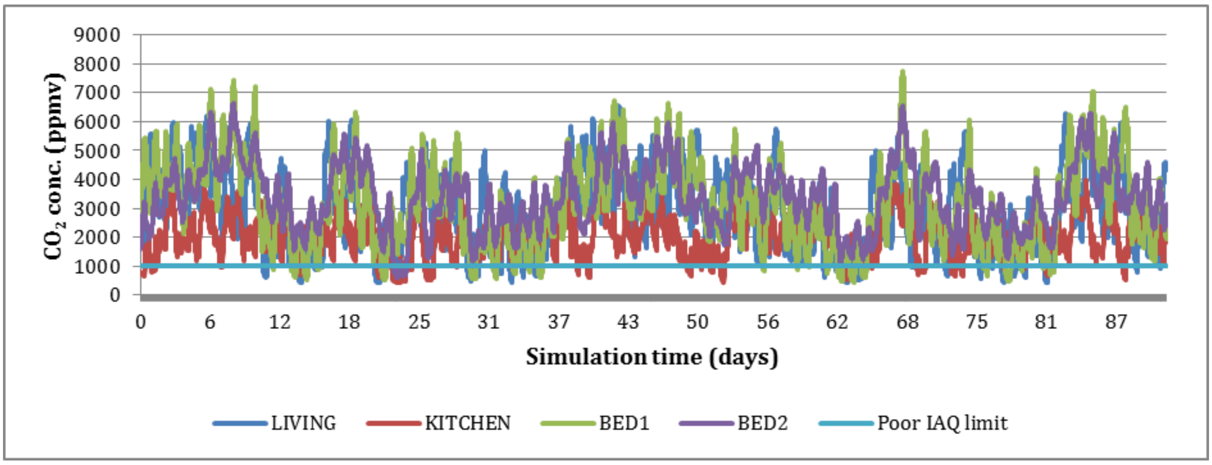

Figure 7.4. CO_2 concentration results for Scenario 2A with indoor doors shut (worst case)

Regarding formaldehyde concentration, the same behaviour shown in Chapter 5 is found. The emission rates are very high at the beginning of the emission and they decrease rapidly with time as shown in Figure 7.5. The formaldehyde concentrations remained above the 0.034 mg/m^3 recommended limit (U.S. Green Building Council, 2016) practically all the time. When doors are closed, the formaldehyde concentration decreases at the beginning of the emission due to lower ach, which are in the order of 6 % of those obtained when doors are open, leading to lower mass transfer coefficients and emission rates, in the order of 20 % of those obtained when doors are open. This reduction in the air infiltration when internal doors are closed has been reported previously in the literature. For instance, Miller and Nazaroff (2001) carried out experiments using a two-story test site and measured the airflow between two rooms finding that the airflow rate when doors remained closed was 10 % of the airflow rate when doors were open.

Two weeks after the emission starts, concentrations are higher when internal doors are shut due to higher formaldehyde concentration in the material surface. Figure 7.6 shows the variation of formaldehyde concentration for this scenario. In terms of the time scale, the threshold is surpassed after one hour in all the rooms independently of internal doors being open or shut.

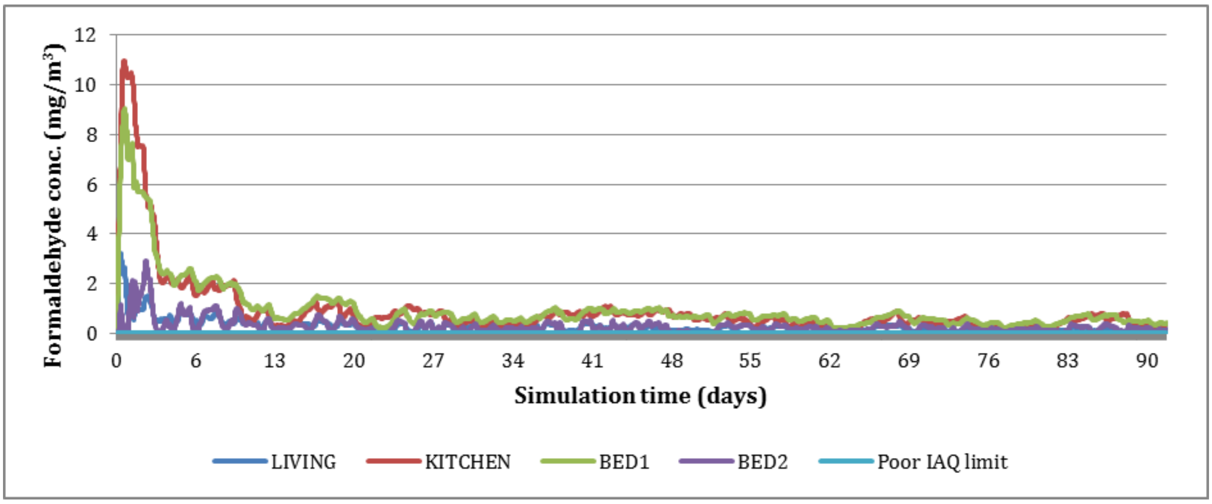

Figure 7.5. Formaldehyde concentration results for Scenario 2A with indoor doors shut

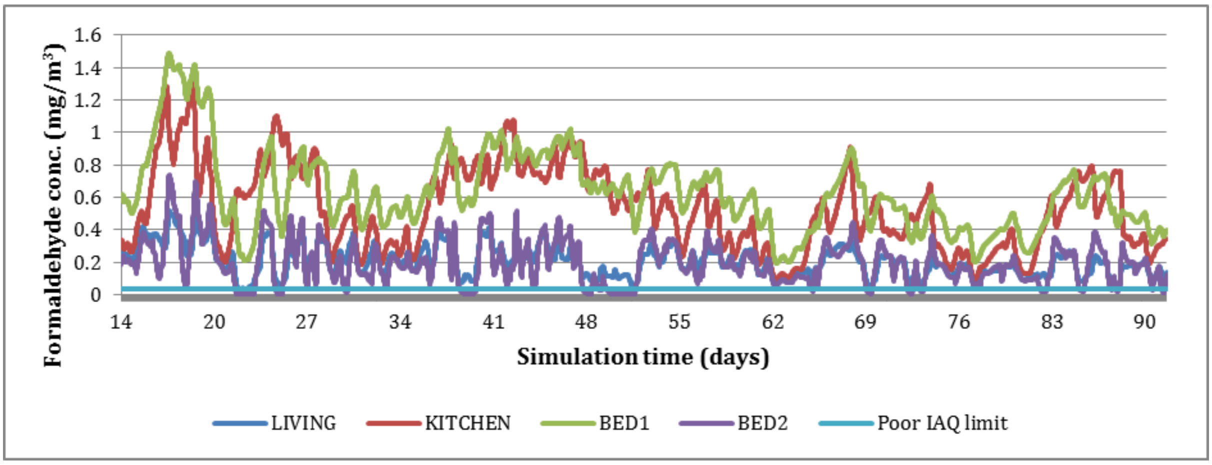

Figure 7.6: Formaldehyde concentration results for Scenario 2A with indoor doors shut two weeks after the start of the emission

In addition to poor IAQ, a failure of the MVHR system would also lead to discomfort due to elevated temperatures and high humidity levels, with a maximum temperature of 37.1 °C in the kitchen when cooking appliances are used, and RH over 60 % in the bedrooms for 86 % of the occupied time.

These results correspond to a worst-case scenario, which assumes that the MVHR system fails or is switched off and windows remain closed for three months. In a more realistic scenario, occupants would be able to open the windows when they feel discomfort (Scenario 2B). In this case, a window opening of 10 % of the total window area is assumed. The results show that IAQ improves but CO_2 concentration remains over 1000 ppmv for around 50 % of the occupied time in the living room and around 76 % in the bedrooms, while formaldehyde is above 0.034 mg/m^3 for around 67 % of the time in the living room, and 90 % of the time in the bedrooms and the kitchen. Therefore, opening windows mitigates the IAQ issue but cannot solve it completely in this case. Figure 7.7 and Figure 7.8 show the comparison of the CO_2 and formaldehyde concentration results for Scenarios 2A and 2B with indoor doors shut.

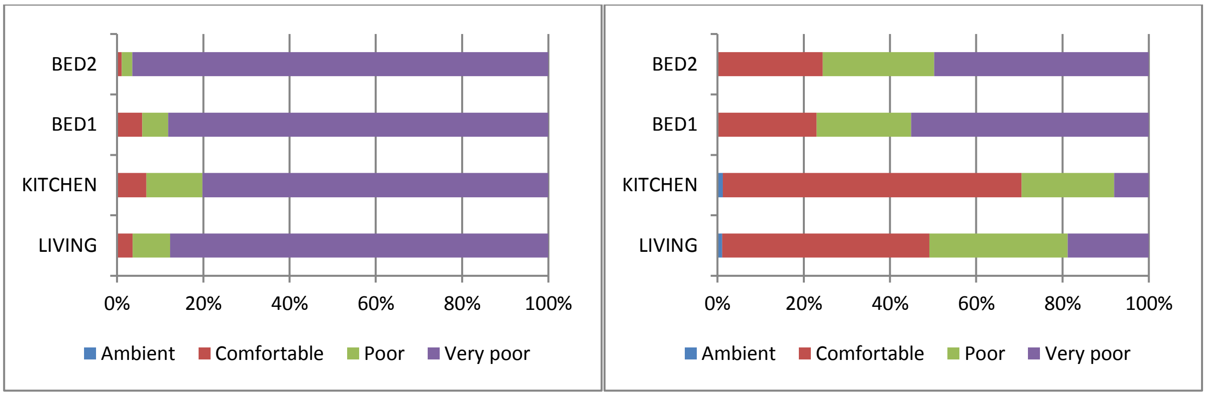

Figure 7.7: Comparison of CO_2 results for Scenario 2A (left) and Scenario 2B (right) with indoor doors shut

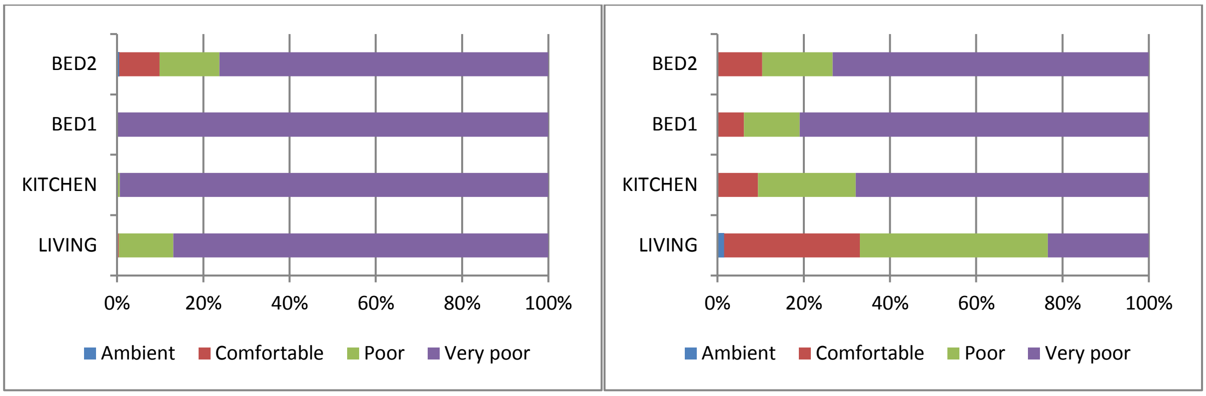

Figure 7.8: Comparison of formaldehyde results for Scenario 2A (left) and Scenario 2B (right) with indoor doors shut

Finally, it should also be noted that, despite its IAQ benefits, window opening in the winter period could have the drawback of leading to a heating energy increase. In this case, heating energy demand was not investigated as this scenario assumes a fault of the MVHR system, which also included the heating system.

7.2.2. Discussion

Results showed that a fault of the MVHR system may lead to high formaldehyde levels which rise above the threshold only one hour after the fault occurs. Window opening based on adaptive comfort mitigates the IAQ issue but cannot solve it completely in the case simulated, as occupants would operate the windows based on outside and indoor temperatures and not pollutant concentrations. Resulted concentrations of CO_2 and formaldehyde were above the threshold around 76 % and 90 % of the occupied time in the bedrooms, and peak concentrations were 4.5 and 6 times above the recommended limit for CO_2 and formaldehyde respectively, highlighting the magnitude of the IAQ issue. These results could be improved in a different climate that requires occupants to open windows more frequently. However, people in hot and humid environments would tolerate high indoor temperatures better (Fabi et al., 2012), and therefore, high levels of CO_2 and formaldehyde would still be expected.

These results emphasise that a good design, commission, operation and maintenance of the MVHR system is necessary to achieve good indoor conditions. In addition, they highlight the importance of designing the building to enable natural ventilation when necessary, to alleviate overheating and IAQ issues. This is key in the case of an unintentional fault of the system since it can lead to severe IAQ and comfort problems. Finally, these results could help occupants to understand the importance of operating the ventilation system properly, as switching off the MVHR system to avoid costs or noise could impact their health seriously.

7.3. Question 3 - What is the impact on IAQ of a kitchen hood? What is the energy penalty of the unbalanced ventilation system?

Question 3 investigates the impact that the use of the kitchen hood while cooking has on IAQ and thermal comfort levels. The consequent energy increase is also investigated. Simulations of Scenario 3A and 3B were run in order to analyse Question 3 as shown in Table 6.7. These simulations were run for a winter period (January 2nd to March 31st) using a time step of 20 minutes. The results gathered are the operative temperature, RH, concentrations of $PM_{2.5}$, PM_{10}, NO_2 and CO_2 in the living room, kitchen and bedrooms, and the heating demand in the whole house.

7.3.1. Results

Results show that cooking activities without the use of a kitchen hood (Scenario 3A) can lead to poor IAQ when indoor doors are closed with 24-hour mean levels of $PM_{2.5}$ above 25 µg/m^3 (WHO Guidelines 2006) all the time in the kitchen even for the low emission scenario. This worsens for the high emission scenario, with high levels of $PM_{2.5}$ also in the living room and main bedroom for 100 % of the time due to cigarette smoking and candle lighting. The use of the kitchen hood (Scenario 3B) helps removing pollutants associated with cooking activities improving, therefore, the IAQ. When the kitchen hood is used, 24-hour mean levels of $PM_{2.5}$ remain below the threshold for the low emission scenario. However, the hood capture efficiency assumed is not enough to keep good IAQ for the high emission scenario with 24-hour mean levels of $PM_{2.5}$ above 25 μg/m^3 practically every day if internal doors remain closed. When doors are open, the 24-hour mean levels of $PM_{2.5}$ are below the threshold without the need of the kitchen hood for the low emission scenario, leading to a median concentration of 7.1 μg/m^3 in the kitchen and living room, which is slightly below but in good agreement with the median concentration measured in seven newly built, energy-efficient houses in France (Derbez et al., 2014). Nevertheless, for the high emission scenario, the average concentration in the living room, main bedroom and the kitchen are 42 μg/m^3, 23 μg/m^3 and 49 μg/m^3 respectively, which are above the annual mean guideline of 10 μg/m^3 (WHO Guidelines 2006). The use of the kitchen hood when doors are open decreases the average concentration in the kitchen and living-room but they still stay slightly above the annual mean guideline.

Figure 7.9 shows the daily mean concentration for $PM_{2.5}$ for the living room and the kitchen for the low emission scenario with doors open, and Figure 7.10 shows the daily mean concentration for $PM_{2.5}$ for the living room and the kitchen for the high emission scenario with doors shut. Both figures compare the results obtained when using the kitchen hood and without using it. It can be seen that when doors are shut, the use of the kitchen hood does not make a significant difference on the $PM_{2.5}$ concentration in the living room as expected. Consequently, concentrations are higher in the living room than the kitchen when the doors are shut and the hood is switched on since the kitchen hood removes the particles from cooking but not those emitted from cigarette smoking.

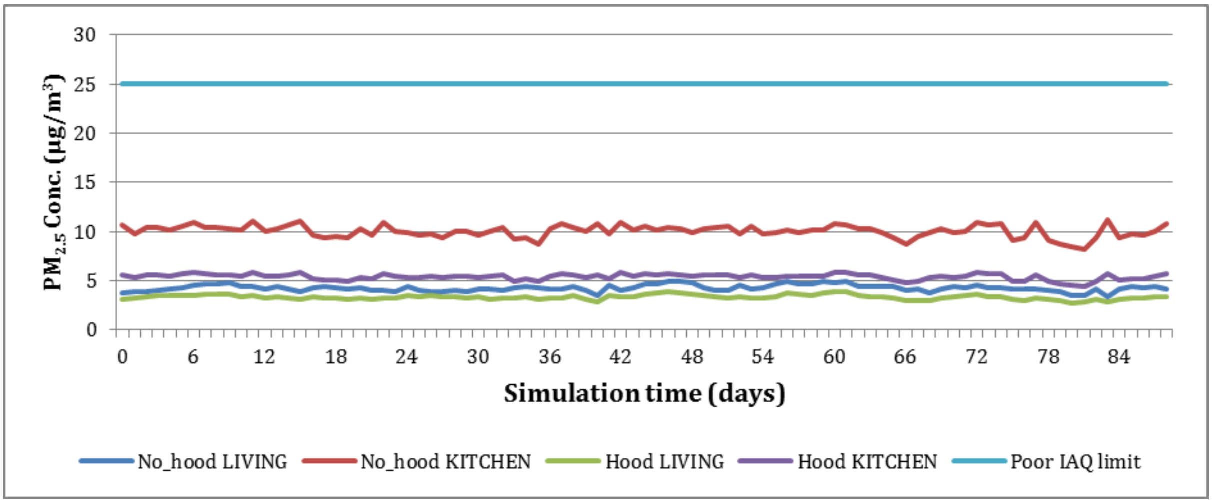

Figure 7.9: Comparison of 24-hour mean results for $PM_{2.5}$ for Scenario 3A and 3B with indoor doors open – Low emission scenario in the living room and the kitchen

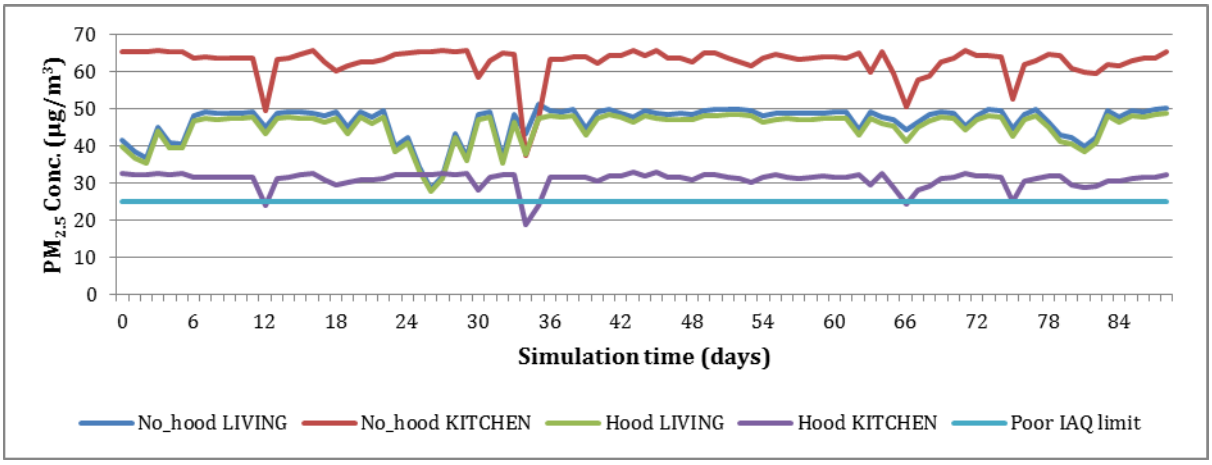

Figure 7.10: Comparison of 24-hour mean results for $PM_{2.5}$ for Scenario 3A and 3B with indoor doors shut – High emission scenario in the living room and the kitchen

A similar situation occurs for PM_{10} where 24-hour mean levels above 50 μg/m^3 (WHO Guidelines 2006) can be found almost all the time in the kitchen for the low emission scenario when doors are shut and the kitchen hood is not used, with an average concentration of 66 μg/m^3. For the high emission scenario, high levels of PM_{10} are also found in the living room for 100 % of the time. The use of the kitchen hood provides good IAQ in the kitchen with an average concentration of 37 μg/m^3. However, it does not remove the particles in the living room for the high emission scenario, leading to 24-hour mean levels above 50 µg/m^3 all the time when internal doors are shut. If the doors remain open, the daily mean concentrations are below the threshold for all the scenarios and the average concentration in the living room for the high emission scenario is 20 µg/m^3 which is the annual limit recommended (WHO Guidelines 2006).

Regarding NO_2, 1-hour mean levels remain below 200 µg/m^3 (WHO Guidelines 2006) for the low emission scenario. On the contrary, they are above the threshold 50 % of the occupied time in the kitchen for the high emission scenario despite the use of the kitchen hood. Nevertheless, the use of the kitchen hood helps decreasing the average concentration in the kitchen from 94 µg/m^3 when doors are closed and the hood is not used, to 29 µg/m^3 when doors are open and the hood is used. Figure 7.11 and Figure 7.12 show the hourly average values for NO_2 for the kitchen for the high emission scenario with doors open and shut, using the kitchen hood and without using it.

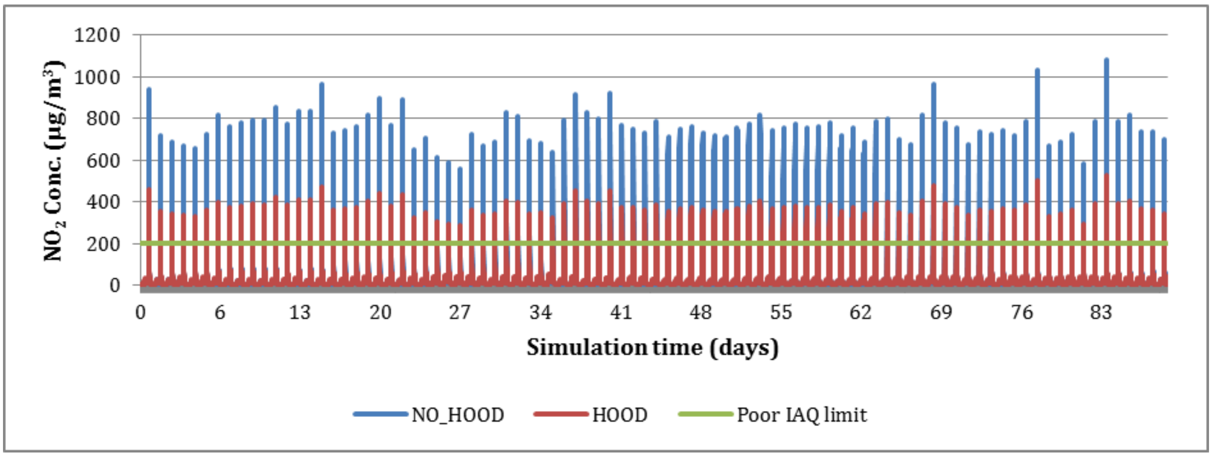

Figure 7.11: Comparison of 1-hour mean results for NO_2 in the kitchen for Scenario 3A and 3B with indoor doors open – High emission scenario

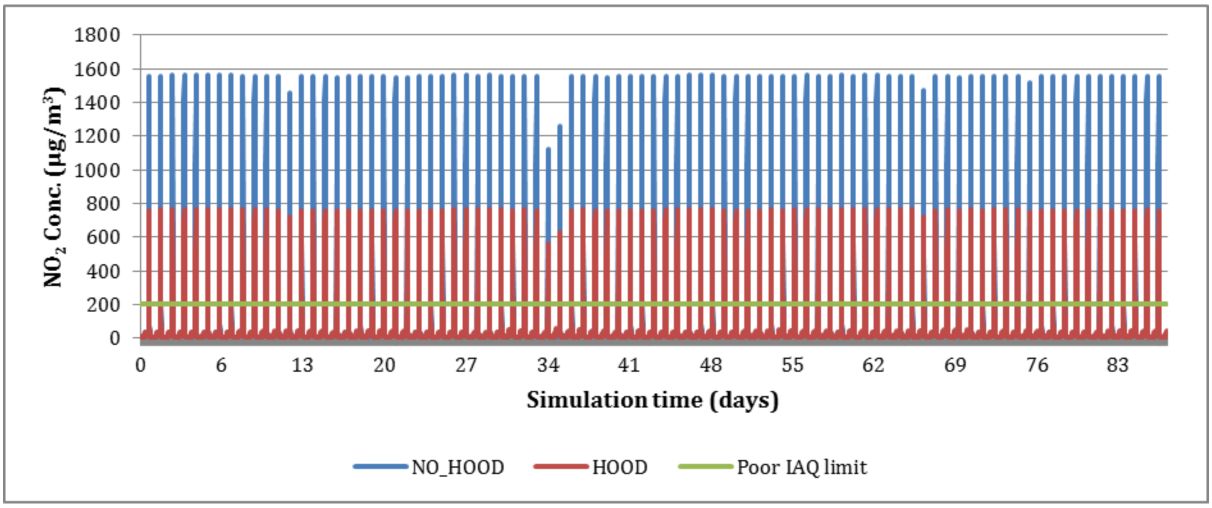

Figure 7.12: Comparison of 1-hour mean results for NO_2 in the kitchen for Scenario 3A and 3B with indoor doors shut – High emission scenario

Looking at the CO_2 concentrations, IAQ is poor (CO_2 concentration over 1000 ppm) for almost 55 % of the occupied time in the living room when internal doors are shut as it was assumed that all the occupants stay in the room in the evening. The use of the kitchen hood does not solve this problem, as it does not make any difference on pollutant concentrations in the living room if internal doors remain shut.

Regarding thermal comfort, there are no overheating issues. On the contrary, the temperature is cold in the kitchen for 28 % of the time when internal doors are shut despite the use of cooking appliances. This is due to the heating system supplying warm air to the living room and bedrooms, which is common practice in PH buildings (BRE, n.d.). When the kitchen hood is used, the cold period increases to 38 % of the time since peak temperatures during cooking are reduced as shown in Figure 7.13. Figure 7.14 and Figure 7.15 show the temperatures for the Scenario 3B with internal doors open and shut. Looking at these results, it is clear that closing the internal doors makes it difficult for the air to flow and mix within the building even when door undercuts are in place.

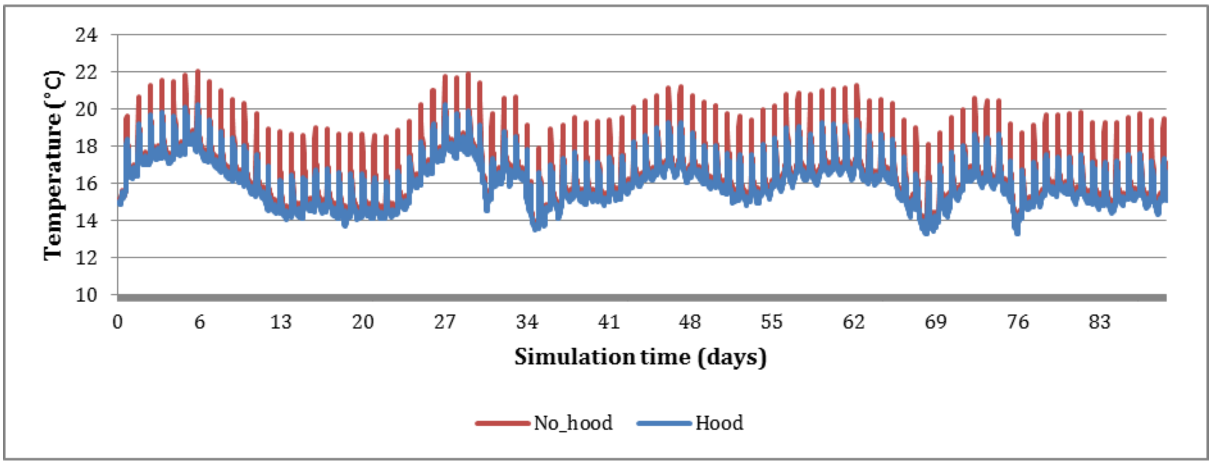

Figure 7.13: Temperature results in the kitchen for Scenario 3A and 3B with indoor doors shut

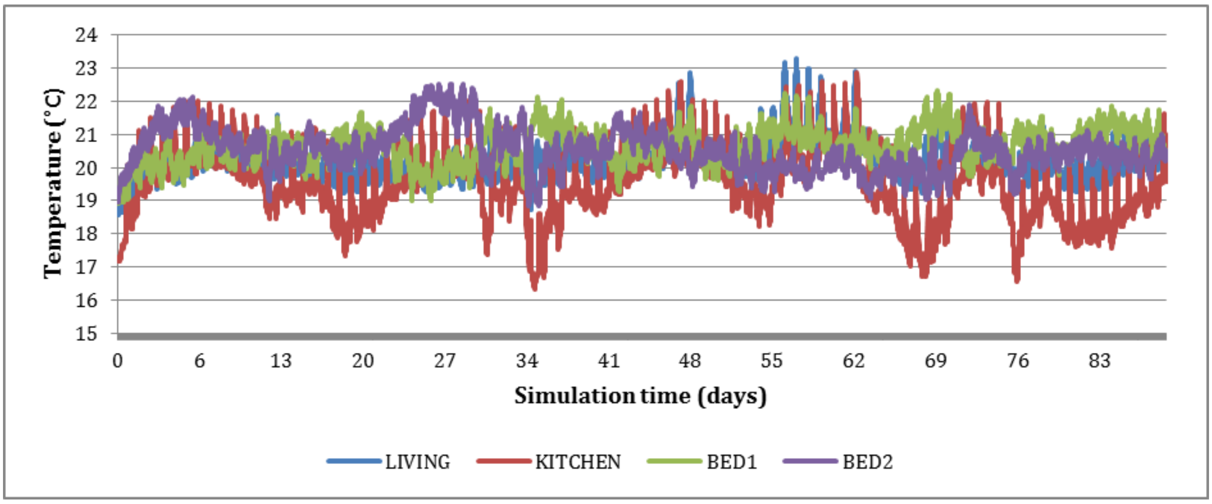

Figure 7.14: Temperature results for Scenario 3B with indoor doors open

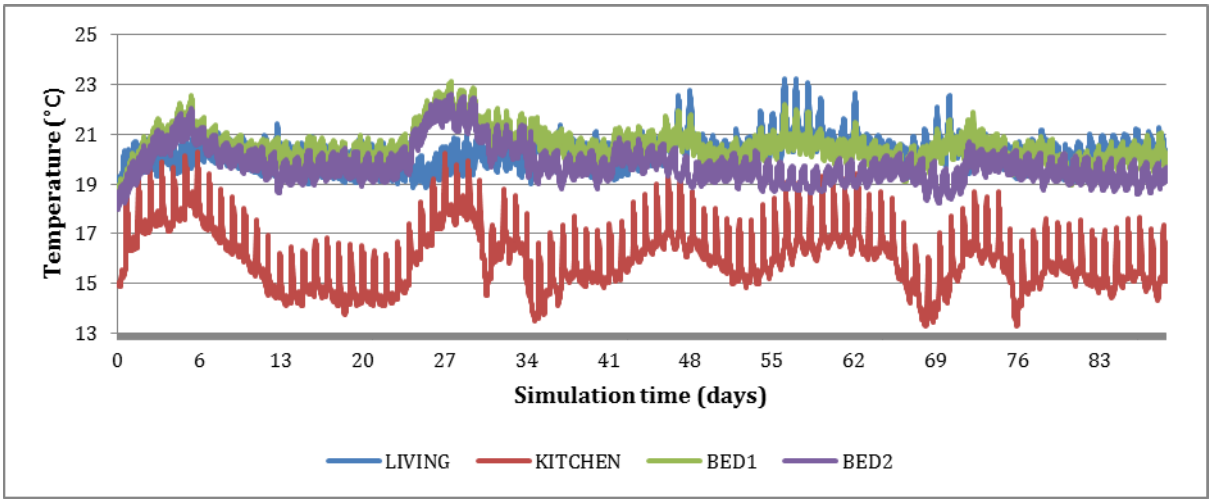

Figure 7.15: Temperature results for Scenario 3B with indoor doors shut

Regarding the heating energy demand for the 3-month simulation period, it is about 1463 kWh when doors are open and it increases to 1503 kWh when doors are closed since the radiator in the bathroom needs to provide more heat to keep a comfortable temperature. The use of the kitchen hood increases the heating demand by 2 %. Therefore, the increase in heating demand due to the use of the kitchen hood is insignificant.

Finally, RH levels are mainly low, leading to dry periods for around 60 % of the time in the living room, 45 % in the kitchen and around 80 % of the time in the bedrooms when internal doors are open. When doors are shut, the dry periods decrease to 47 % in the living room, 8 % in the kitchen, 66 % in the main bedroom and 76 % in the rear bedroom. The use of the kitchen hood does not have a major impact on the humidity levels. Figure 7.16 shows the RH of the supply air for Scenario 3A with internal doors open and shut. These results show that the supply air is slightly drier when internal doors are open, as the heating system is used more often, 2008 hours, compared to 1672 hours when indoor doors remain closed.

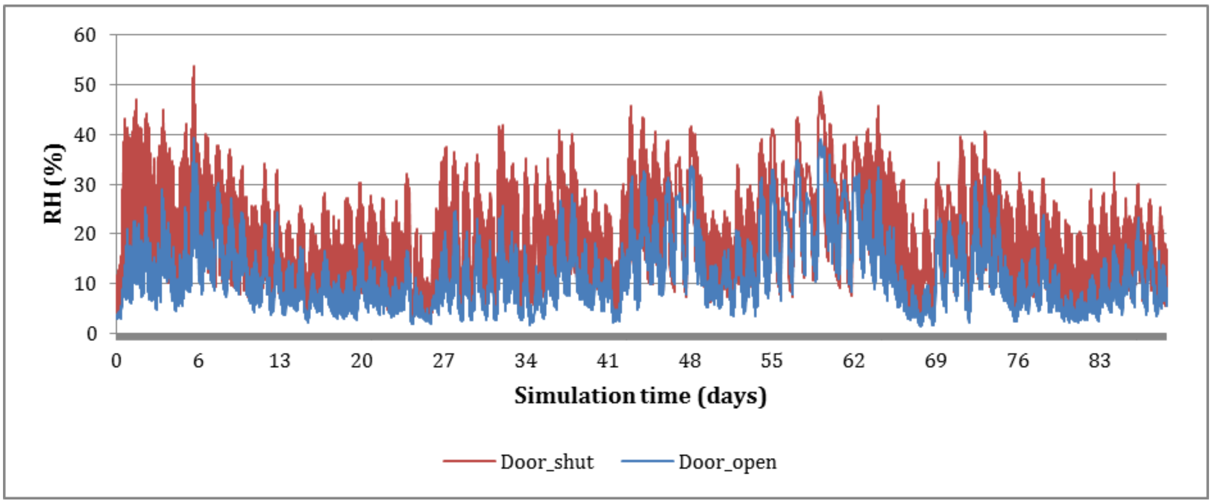

Figure 7.16: RH of the supply air for Scenario 3A with indoor doors open and shut

7.3.2. Discussion

Results showed that the use of the kitchen hood can significantly decrease the average pollutant concentrations in the kitchen by around 50 %, with a minor increase of the heating energy demand, which was only 2 %. A typical hood capture efficiency of 60 % was assumed in this study. Different capture efficiencies and pollutant emission rates from cooking activities would lead to different PM and NO_2 concentrations but the positive impact of the kitchen hood would still be valid. This highlights the importance of the correct operation and maintenance of the kitchen hood.

7.4. Question 4 - Do trickle vents with Mechanical Extract Ventilation (MEV) supply enough ventilation for good IAQ? How does its performance compare with a MVHR system?

Question 4 investigates whether trickle vents in the living room, bedrooms and wet rooms, and continuous mechanical extract fans in the wet rooms, can assure good IAQ and thermal comfort. The impact of providing boost control to the system and assuming window opening based on adaptive comfort is also explored. This question also compares the performance of this system against the use of an MVHR system. Simulations of Scenario 4A to 4D were run in order to analyse Question 4 as shown in Table 6.7. These simulations were run for a winter period (January 2^{nd} to March 31^{st}) using a time step of 20 minutes and assuming 100 grid points inside the material. The results gathered are the operative temperature, RH, and concentrations of formaldehyde, $PM_{2.5}$, PM_{10}, NO_2 and CO_2 in the living room, kitchen and bedrooms, and the heating demand in the whole house.

7.4.1. Results

Results show that, when trickle vents and MEV are used (Scenario 4A), CO_2 concentration is over 1000 ppmv for around 40 % of the occupied time in the living room and main bedroom (Bed1) and 26 % in the rear bedroom (Bed2). This situation gets clearly worse when the internal doors remain shut, with CO_2 levels exceeding 1000 ppmv around 80 % of the time in the living room and main bedroom and 70 % in the rear bedroom. Figure 7.17 shows the variation of CO_2 concentration during the winter period for this scenario (worst case). It can be seen that the maximum CO_2 concentration in the main bedroom, where two occupants were assumed, is almost six times above the comfortable level. The calculated average concentration during the sleeping hours is 1900 ppmv, which is slightly higher but in good agreement with the CO_2 concentration measured in natural ventilated bedrooms with closed windows and trickle vents open in 40 new houses in Scotland (T. Sharpe et al., 2015). Also, peak CO_2 concentration of 3425 ppmv for one occupant in a bedroom with closed windows and trickle vents open has been measured in a monitoring study of several new built houses in Scotland (Farren, 2016) so these predictions are not unreasonable. Figure 7.18 shows a comparison of the CO_2 concentration results for the Scenario 4A with doors open and shut. The use of boost control based on RH reduces the CO_2 concentrations but they still rise above the threshold 30 % of the time in the living room and main bedroom, and 21 % of the time in the rear bedroom when internal doors are open. Window opening based on adaptive thermal comfort does not make any difference as the simulations were run during a winter period. Finally, the use of a MVHR system increases the ventilation rate (see Figure 7.19) and decreases the CO_2 to acceptable levels if indoor doors are open. However, they still rise over the threshold 55 % of the occupied time in the living room when doors are shut. Therefore, for this case study, MVHR can provide adequate ventilation, regarding CO_2 concentration, only when internal doors remain open.

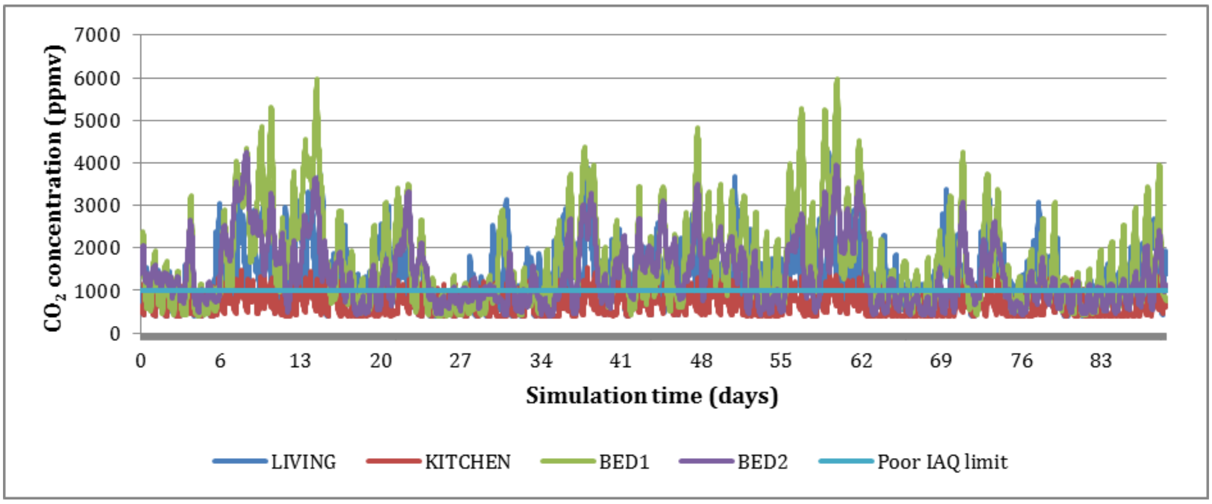

Figure 7.17: CO_2 results for Scenario 4A with indoor doors shut (worst case)

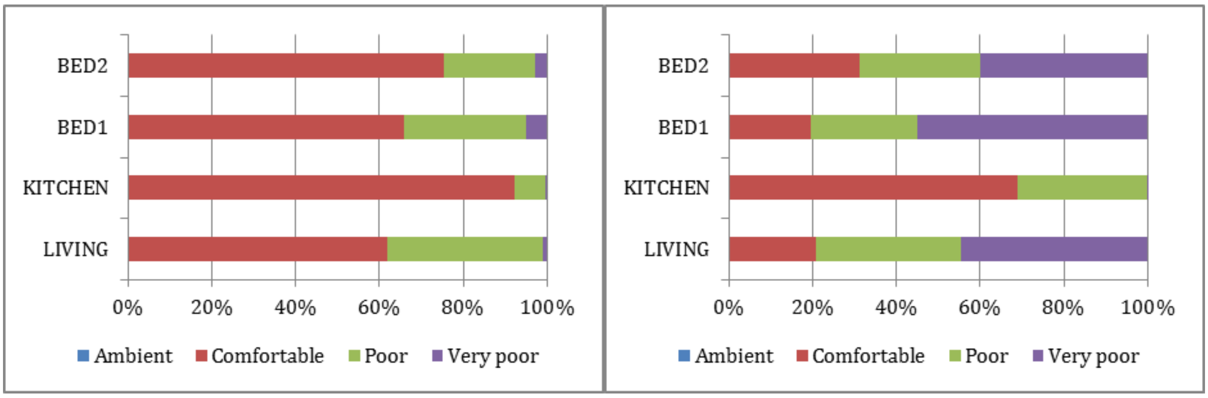

Figure 7.18: Comparison of CO_2 results for Scenario 4A with indoor doors open (left) and shut (right)

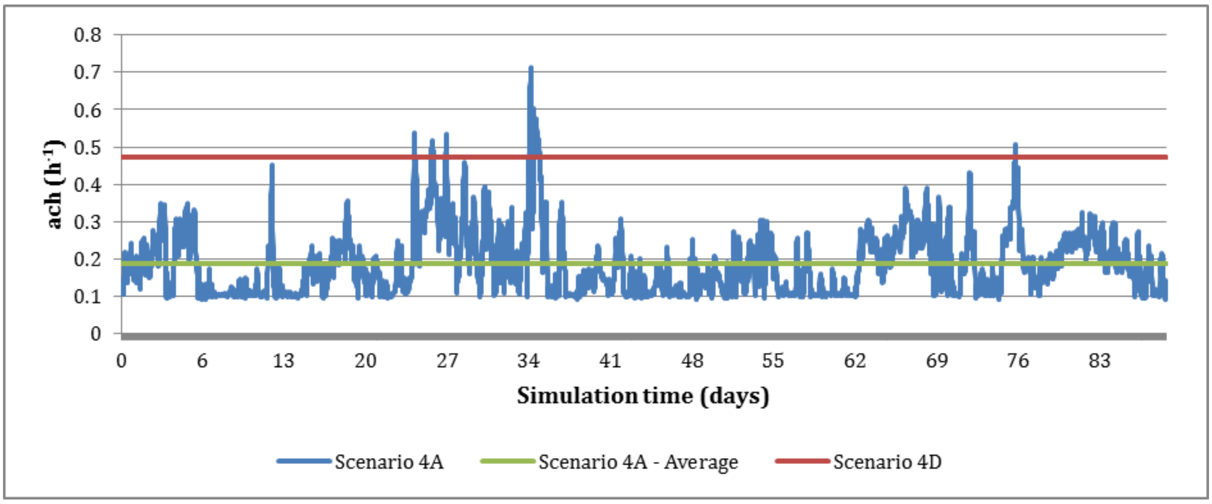

Figure 7.19: Comparison of ach for Scenario 4A and 4D with indoor doors open

Regarding formaldehyde concentrations, focus was placed on two weeks after the start of the emission in order to avoid focusing on the high initial emission levels. Results show that formaldehyde concentrations exceed the recommended limit of 0.034 mg/m^3 (U.S. Green Building Council, 2016) 60 % of the occupied time in the living room and the kitchen, and 80 % of the time in the bedrooms, when trickle vents and MEV were used (Scenario 4A). The concentrations are higher and they remain above the threshold practically all the time when the indoor doors remain shut. Figure 7.20 shows the variation of formaldehyde concentrations within the building for this scenario (worst case). The use of boost control based on RH reduces the formaldehyde concentrations slightly but does not make a significant difference on the results. When MVHR is used, formaldehyde concentrations decrease but they remain above the threshold 90 % of the occupied time in the bedrooms and 60 % of the time in the living room if internal doors remain shut. In that case, the median concentration in the main bedroom for the first and last week simulated are 68.4 µg/m^3 and 31.6 µg/m^3 respectively, which are in good agreement with the median concentration measured in seven newly built, energy-efficient houses in France (Derbez et al., 2014). Figure 7.21 shows a comparison of the formaldehyde concentration results for the Scenario 4A and Scenario 4D with indoor doors open.

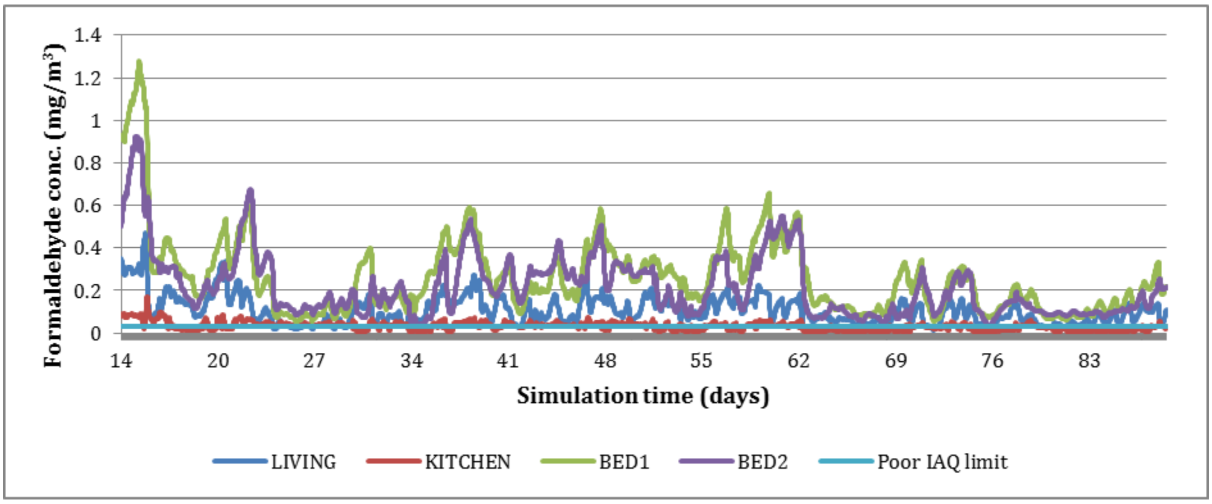

Figure 7.20: Formaldehyde results for Scenario 4A with indoor doors shut two weeks after the start of the emission

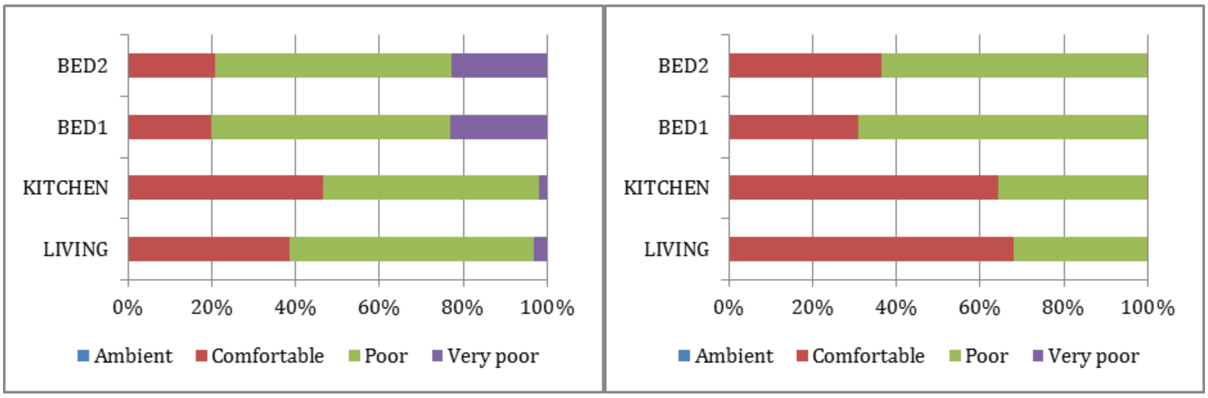

Figure 7.21: Comparison of formaldehyde results for Scenario 4A (left) and Scenario 4D (right) with indoor doors open

Regarding $PM_{2.5}$, results show that, when trickle vents and MEV are used (Scenario 4A), 24-hour mean levels of $PM_{2.5}$ are over 25 μg/m^3 around 50 % of the time in the living room and 85 % of the time in the kitchen when internal doors are open. The average levels for the simulation period are 24 and 31 μg/m^3 in the living room and the kitchen respectively. When internal doors are shut, the average concentration of $PM_{2.5}$ decreases to 15 μg/m^3 in the living room and it increases to 64 μg/m^3 in the kitchen, since the air is less mixed. The use of boost control based on RH decreases the concentration of $PM_{2.5}$ but it still rises over 25 μg/m^3 around 26 % of the time in the living room and 83 % of the time in the kitchen when internal doors are open. When MVHR is used, the IAQ issue is solved if internal doors remain open. However, the 24-hour mean levels of $PM_{2.5}$ remain over the threshold at all times in the kitchen if internal doors are shut, with an average concentration of 43 μg/m^3. Figure 7.22 and Figure 7.23 show the $PM_{2.5}$ daily mean concentration for the living room and the kitchen for trickle vents and MEV (Scenario 4A) and MVHR (Scenario 4D), with internal doors open and shut.

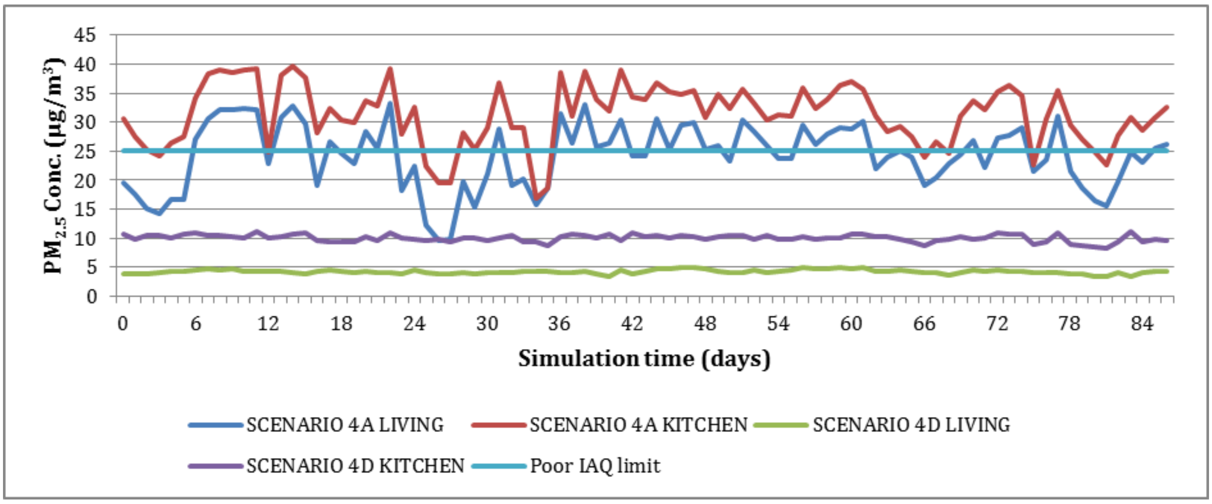

Figure 7.22: Comparison of 24-hour mean results for $PM_{2.5}$ for Scenario 4A and 4D with indoor doors open

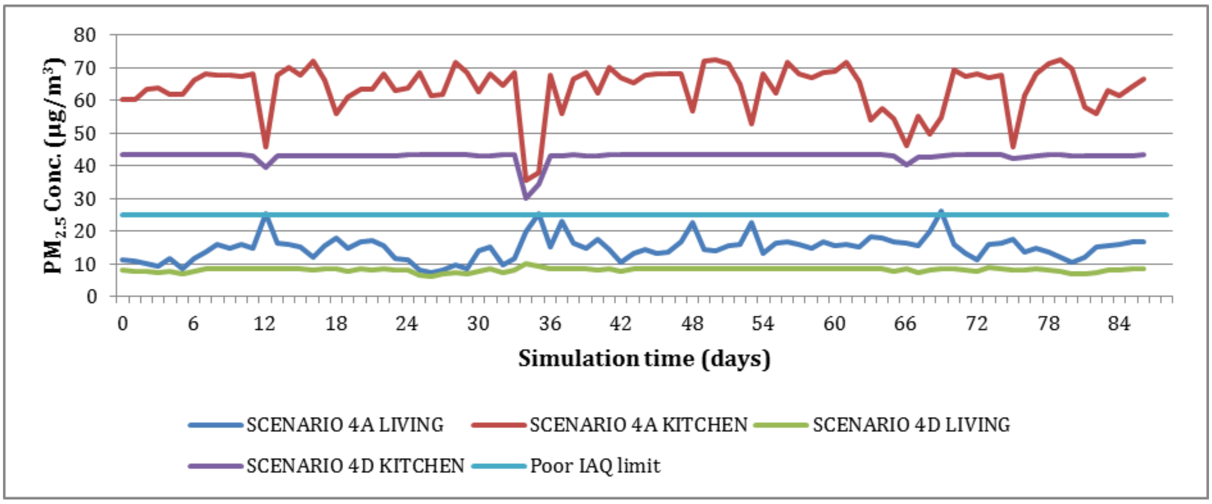

Figure 7.23: Comparison of 24-hour mean results for $PM_{2.5}$ for Scenario 4A and 4D with indoor doors shut

A similar situation occurs for PM_{10}. When the ventilation system involves trickle vents with MEV and internal doors are open, the 24-hour mean levels of PM_{10} are above 50 μg/m^3 for 3 % of the time in the living room and 55 % of the time in the kitchen, and the average concentrations are 40 and 51 μg/m^3 for the living room and the kitchen respectively. When internal doors are shut, the 24-hour mean levels are acceptable for the living room but rise over the threshold 100 % of the time in the kitchen, with an average concentration of 95 μg/m^3. The use of boost control based on RH decreases the concentration of PM_{10} but cannot solve the IAQ issue in the kitchen, where it still rises over 50 $\mu g/m^3$ for 45 % of the time if the internal doors are open and all the time if they are shut. Finally, the use of an MVHR system can guarantee good IAQ if internal doors remain open but it still leads to high levels of PM_{10} for 100 % of the time in the kitchen if internal doors are closed.

Regarding NO_2, 1-hour mean concentrations remained below 200 $\mu g/m^3$ (WHO Guidelines 2006) for all the scenarios investigated. The maximum concentration is around 60 $\mu g/m^3$ in all the rooms when internal doors are shut and around 40 $\mu g/m^3$ in the bedrooms if the doors are open. When internal doors are open, average levels are around 10 $\mu g/m^3$ when trickle vents and MEV are used and slightly higher for the MVHR. This is due to pollutant from the ambient air, which is the sole source of NO_2 assumed.

Regarding RH, opening or closing the indoor doors makes a significant difference on the results in the case of trickle vents and MEV system (Scenario 4A). When doors are open the air is humid around 20 % of the occupied time in the living room and main bedroom and 15 % of the time in the kitchen and rear bedroom; while it is humid 50 % of the time in the living room, 26 % in the kitchen and 75 % in the bedrooms when doors are closed (see Figure 7.24). Thus, in the latter case, it is crucial to check the risk of mould growth. Analysis of the results shows that RH is above 80 % for more than 2 hours a day for 25 days in the living room, 63 days in the main bedroom (Bed1) and 45 days in the rear bedroom (Bed2). Additionally, RH is above 70 % for around 50 % of the time in the bedrooms. Hence, mould growth is very likely when trickle vents and MEV are used and internal doors remain closed. Figure 7.25 shows the distribution of RH results within the building for that scenario.

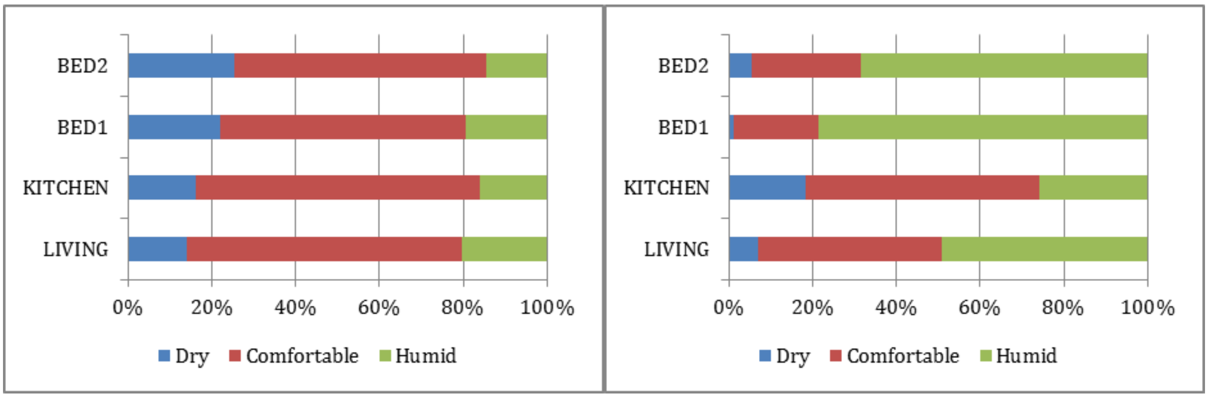

Figure 7.24: Comparison of RH results for Scenario 4A with indoor doors open (left) and shut (right)

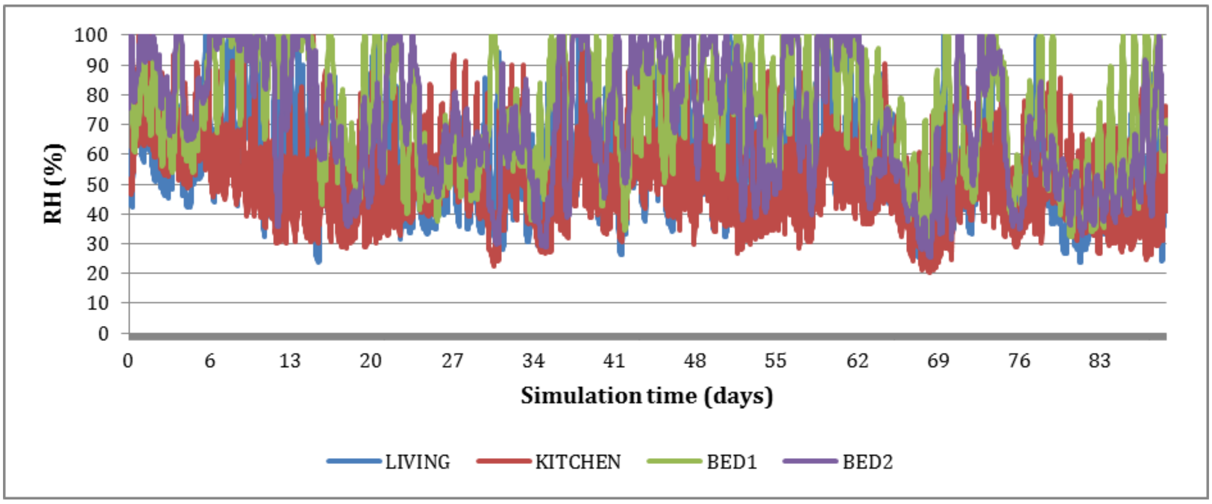

Figure 7.25: RH results for Scenario 4A with indoor doors shut

For the other scenarios, air becomes drier when applying boost control, being comfortable for around 80 % of the time in all rooms when internal doors remain open. Scenario 4D is the case with drier air, with RH levels below 30 % for around 45 to 60 % of the time in the living room and the kitchen, and more than 80 % of the time in the bedrooms. This agrees with previous studies that found that the air is perceived drier when MVHR is used compared to natural ventilation or MEV (Balvers et al., 2012; Mlecnik et al., 2012). Figure 7.26 shows a comparison of the RH results for Scenario 4B and Scenario 4D.

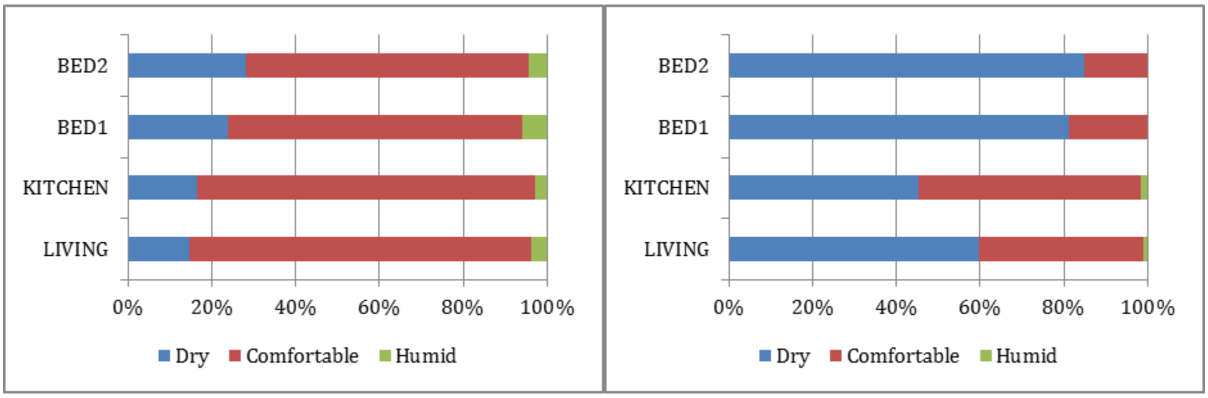

Figure 7.26: Comparison of RH results for Scenario 4B (left) and Scenario 4D (right) with indoor doors open

Overheating is not an issue for any of the scenarios simulated in this case.

Finally, heating demand results show that the use of MVHR leads to a significant reduction (up to 28 %) of the energy demand, varying from 2020 kWh when trickle vents and MEV with boost control are used (Scenario 4B), to 1463 kWh for an MVHR system (Scenario 4D), when internal doors are open.

7.4.2. Discussion

A comparison of the performance of trickle vents with continuous MEV against MVHR was undertaken showing that MVHR increases the ventilation rate 2.5 times on average. This value would vary for a different climate or building type but nevertheless, it shows a significant increase and emphasises one of the problems of natural ventilation, as the minimum required ventilation rate cannot be guaranteed at all times due to the intrinsic variability of climate conditions.

The impact that the mechanical increased ventilation rate has on the indoor environment is also very noteworthy, decreasing the peak CO_2 concentration in the main bedroom from almost 6000 ppmv when trickle vents and MEV is used and indoor doors remain shut, to slightly above 1000 ppmv when MVHR is used. Regarding formaldehyde, results showed that the average formaldehyde concentration decreases from 0.264 mg/m^3, almost eight times the recommended limit by the WELL Standard, when trickle vents and MEV is used and indoor doors remain shut, to 0.04 mg/m^3, which is slightly above the recommended limit when MVHR is used and doors are open. This situation is similar in the case of $PM_{2.5}$ and PM_{10}, with average concentrations decreasing more than 30 % when MVHR is used. In contrast, in the case of NO_2, higher ventilation rates would increase the indoor concentration as the ambient air was the only NO_2 source considered in this case. However, this increase is not significant as NO_2 concentrations remain well below the threshold in all the scenarios simulated.

These concentrations will differ in other houses, with different material loading factors. In addition, the current case study is located in a rural area where ambient pollution of $PM_{2.5}$ and PM_{10}, for example, are low. In urban areas, a higher ambient pollution is expected and, therefore, an increase of the ventilation rate could become detrimental. However, in that case, the use of filter in the MVHR system would help to minimise the introduction of pollutants from the ambient air, which is not possible when using natural ventilation. Thus, it can be concluded that the use of MVHR could improve the overall IAQ in the building if it is operated and maintained properly. However, the optimum ventilation rates would be case specific. Finally, it should be mentioned that despite these benefits, the MVHR system has the drawback of dry air during winter periods, agreeing with previous studies in the literature (Balvers et al., 2012; Mlecnik et al., 2012).

7.5. Question 5 - How does a constant ventilation rate compare with the use of different types of ventilation control?

Question 5 investigates the performance of a constant ventilation rate system compared with DCV control strategies based on RH or CO_2, and assuming window opening based on adaptive comfort. Simulations of Scenario 5A to 5E were run in order to analyse Question 5 as shown in Table 6.7. These simulations were run for a winter period (January 2nd to March 31st) using a time step of 20 minutes and assuming 100 grid points inside the material. The results gathered are the operative temperature, RH, and concentrations of formaldehyde, $PM_{2.5}$, PM_{10}, NO_2 and CO_2 in the living room, kitchen and bedrooms, and the heating demand in the whole house.

7.5.1. Results

Results show that CO_2 concentrations remain below 1000 ppm independent of the control strategy used if internal doors are open. However, when internal doors are shut, the CO_2 concentration is above the threshold for 55 % of the occupied time in the living room when MVHR with constant ventilation rate is used (Scenario 5A). Figure 7.27 shows the variation of CO_2 concentrations within the building for this scenario (worst case). This problem is mitigated by the use of RH or CO_2 boost control (Scenarios 5B and 5C) with poor IAQ for 26 % and 38 % of the time, respectively. In this case, the RH boost control results in higher ventilation rates due to the high moisture load due to drying clothes assumed in the utility room (see Table 6.2). Finally, window opening based on adaptive comfort (Scenarios 5F and 5G) does not help to reduce the CO_2 concentrations in this case as the simulation were run for a winter period.

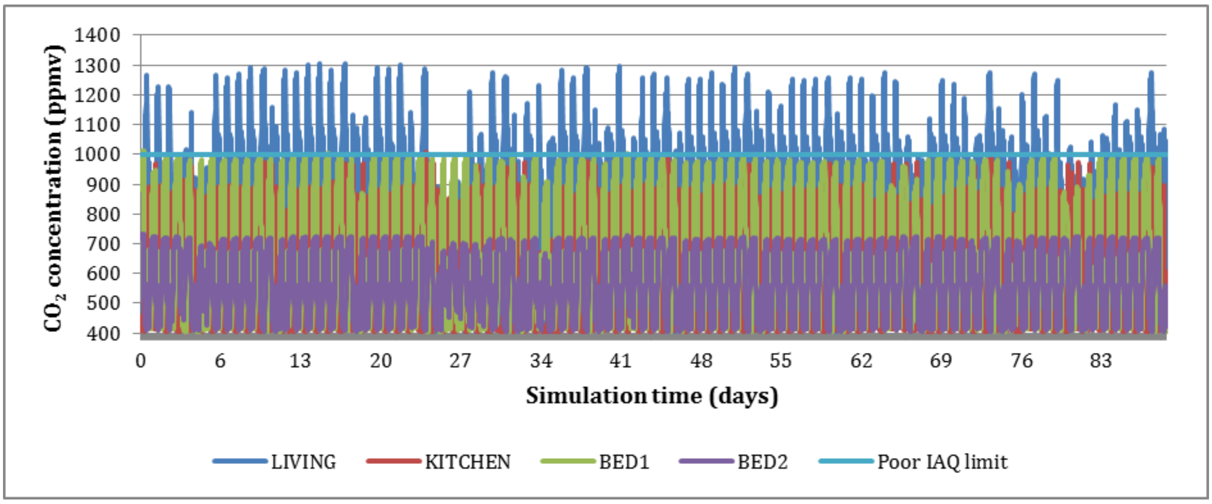

Figure 7.27: CO_2 results for Scenario 5A with indoor doors shut (worst case)

Regarding formaldehyde concentrations, they stay above the threshold around 65 % of the occupied time in the bedrooms and around 35 % of the time in the living room and the kitchen if internal doors are open and a constant ventilation rate is used (Scenario 5A). When doors are shut, formaldehyde concentrations rise above the threshold 95 % of the time in the bedrooms and 60 % of the time in the living room (see Figure 7.28). Boost control based on RH does not mitigate the problem significantly when internal doors are open but it has a positive effect when they are shut, reducing the periods of poor IAQ to 22 % in the living room, 68 % in the main bedroom and 44 % in the rear bedroom. Boost control based on CO_2 has also a positive effect but results in higher formaldehyde concentrations compared to the use of boost control based on RH, as seen before in the case of CO_2 concentrations. Figure 7.29 shows the comparison of formaldehyde concentrations for Scenario 5A and Scenario 5B with internal doors shut.

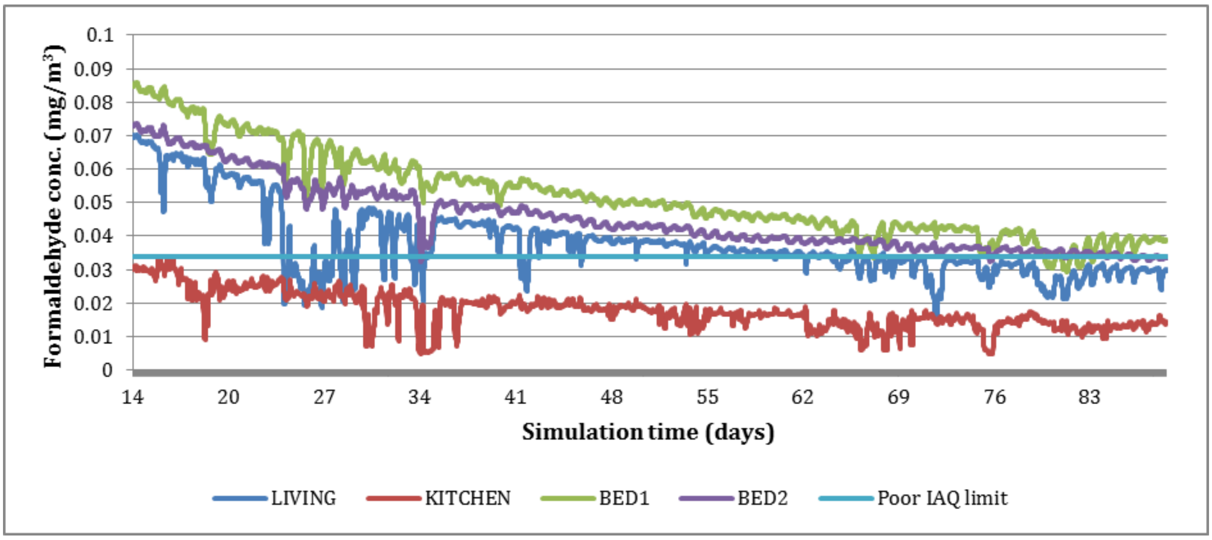

Figure 7.28: Formaldehyde results for Scenario 5A with indoor doors shut (worst case)

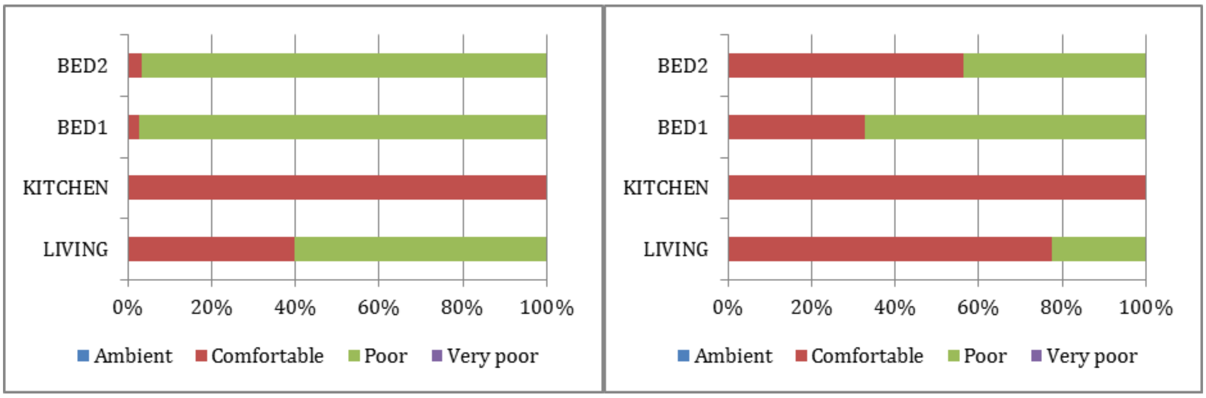

Figure 7.29: Comparison of formaldehyde results for Scenario 5A (left) and Scenario 5B (right) with indoor doors shut

$PM_{2.5}$ results show that the recommended 24-hour mean concentration (25 µg/m^3) is not exceeded if internal doors are open in any of the scenarios investigated. However, when indoor doors remain closed, the 24-hour mean level of 25 µg/m^3 is exceeded all the time in the kitchen. The RH/CO_2 boost control improves the mean concentration slightly but does not make a significant difference.

Looking at PM_{10} concentrations, an analogous situation is found. The recommended 24-hour mean concentration (50 µg/m^3) is not exceeded if internal doors are open. When indoor doors remain closed, the 24-hour mean level of 50 µg/m^3 is exceeded almost all the time in the kitchen. The RH/CO_2 boost control improves the mean concentration slightly but does not make a significant difference. Figure 7.30 compares the PM_{10} results obtained for MVHR with constant ventilation rate (Scenario 5A) in the living room and the kitchen with internal doors open and shut. Looking at these results, it can be seen how opening or closing the internal doors in the building influences the distribution of indoor particles. When doors are open, the PM_{10} concentration in the living room is acceptable and very similar to the ambient concentration (7.3 µg/m^3), and the concentration in the kitchen is slightly higher but remains below the threshold. However, when doors are shut, the PM_{10} concentration in the kitchen becomes much higher since the main sources, in this case, were due to cooking activities.

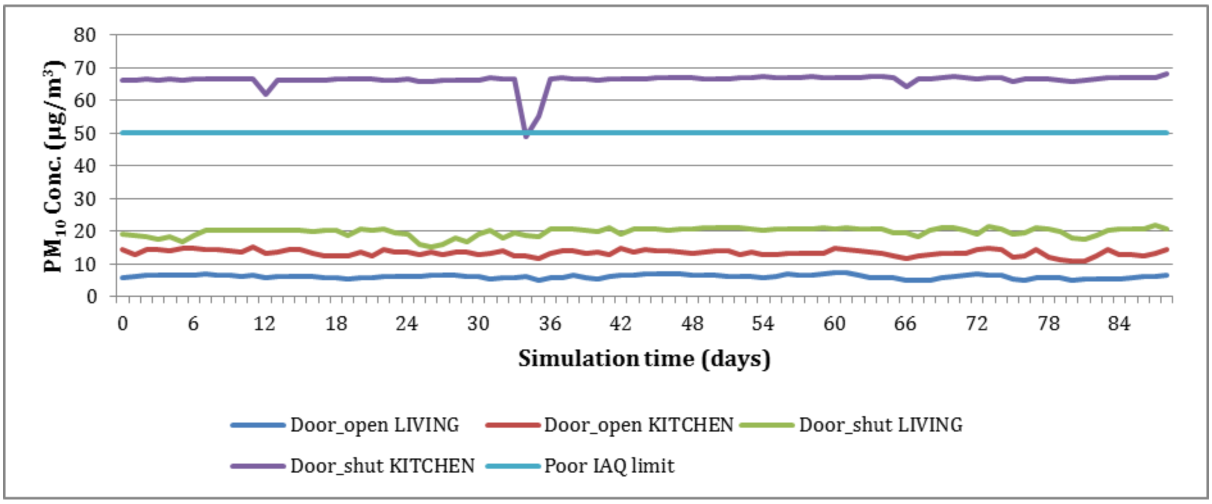

Figure 7.30: Comparison of 24-hour mean results for PM_{10} for Scenario 5A with indoor doors open and shut

Regarding NO_2, 1-hour mean concentrations remained below 200 µg/m^3 (WHO Guidelines 2006) for all the scenarios investigated. The maximum concentration is around 60 µg/m^3 in all the rooms when internal doors are shut and around 40 µg/m^3 in the bedrooms if the doors are open. When internal doors are open, average levels are around 12 µg/m^3 when no control is used and slightly higher when boost ventilation is available due to the NO_2 from the ambient air, which was assumed to be the only source of NO_2.

Regarding RH, the air is mainly dry in all rooms when doors are open, with RH below 30 % for around 60 % of the occupied time in the living room, and more than 80 % of the time in the bedrooms. The use of boost control provides similar results. This situation improves if indoors doors are closed, leading to comfortable periods for 50 % of the time in the living room. However, the air remains dry in the bedrooms for around 70 % of the time.

Overheating is not an issue for any of the scenarios simulated in this case.

Finally, regarding heating demand, its minimum level is achieved by the use of RH control (Scenario 5B) with indoor doors open, and its maximum level is achieved when indoor doors are shut. Figure 7.31 shows the heating demand results obtained for all the scenarios simulated in Question 5. Looking at these results, it can be seen that, in this case, the DCV strategies analysed do not suppose a significant energy saving, since the house was occupied most of time. In addition, it can be seen that the heating demand increases an average of 16 % when internal doors are shut since the warm air is not able to flow easily within the building and the radiator in the bathroom would need to provide more heat in order to keep a comfortable temperature. Finally, it is also worth noting that the heating demand of Scenarios 5B and 5C is the same as the heating demand of scenarios 5D and 5E, meaning that no window opening was necessary based on adaptive comfort behaviour.

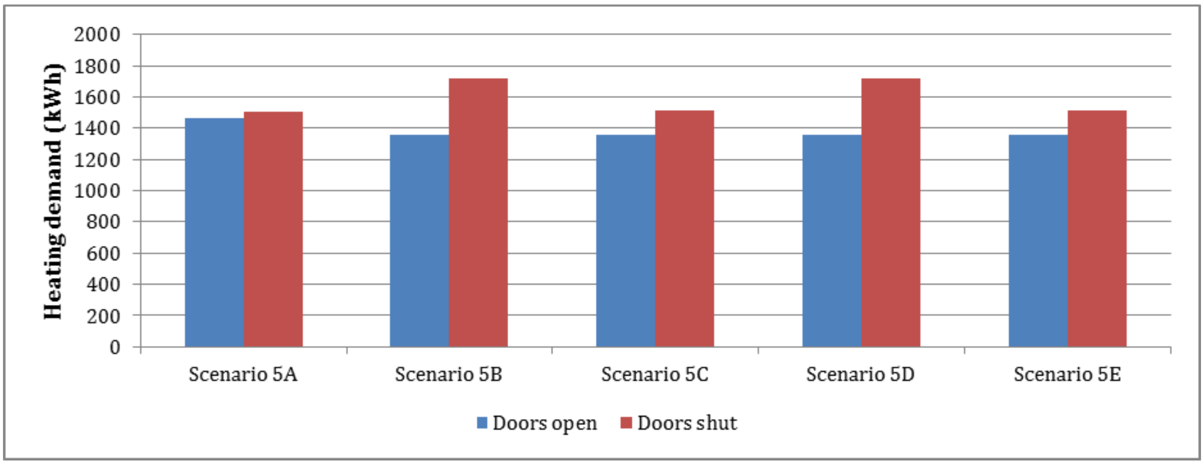

Figure 7.31: Heating demand for the different scenarios to analyse Question 5

7.5.2. Discussion

The use of DCV has been investigated, showing how boost control can improve IAQ, reducing peak concentrations 15 % for CO_2 and PM, and 25 % for formaldehyde when indoor doors remain shut. In addition, the use of DCV reduces the percentage of time of poor IAQ due to high levels of CO_2 by 50 %, and 30 % in the case of formaldehyde. However, in the case simulated, the DCV strategies did not result in a significant energy saving since the ventilation rate was reduced when the house was unoccupied and it was assumed that the house was occupied most of the time.

Different conditions from the current case study, like other occupancy profiles and pollutant loads inside the building, would lead to different results and DCV should be assessed assuming a wide range of scenarios to get an understanding of the impacts that different control strategies have in different situations. Despite this, results show the potential benefits of DCV for the indoor environment and the energy consumption in buildings, and demonstrates how detailed simulation could help the design of ventilation strategies.

Finally, it is also worth noting that indoor door opening improves thermal comfort and IAQ while reducing the heating demand. However, this may not be a practical solution due to privacy reasons.

7.6. Use of Annex 68 IAQ indices

As part of the IEA-EBC Annex 68 research project entitled "Indoor Air Quality Design and Control in Low Energy Residential Buildings", three different IAQ indices have been proposed to assess the risk to short and long-term exposures (Salis et al., 2017). In this section, an example of the use of these indices is presented for the living room and main bedroom for the case of MVHR system with constant ventilation and internal doors shut.

The first index is the Short-Term Exposure Limit (IAQ-STEL) based on the exposure limit values (ELV) shown in Table 7.1. In this case, all the pollutants simulated (CO_2, formaldehyde, NO_2, $PM_{2.5}$ and PM_{10}) have concentrations below the short-term ELV. To assess the risk to long term exposure, two indices are proposed: the Long-Term Exposure Limit (IAQ-LTEL) and the IAQ-DALY. Table 7.2 and Table 7.3 show the parameters used in these methods, and Figure 7.32 and Figure 7.33 show the results of these indices for the living room and main bedroom respectively.

Table 7.1: Short-term ELV method parameters

	ELV	Unit	Averaging period	Source
Carbon dioxide	1000	ppm	8 h	Hong-Kong (HKEPD, 2003), Korea (Korea ministry of Environment, 2011)
Formaldehyde	123	µg/m³	1 h	Canada (Government of Canada, 2016)
Nitrogen dioxide	470	µg/m³	1 h	USA-California (Office of Environmental Health Hazard Assessment, 2016)
PM_{10}	50	µg/m³	24 h	WHO (World Health Organization, 2006)
$PM_{2.5}$	25	µg/m³	24 h	WHO (World Health Organization, 2006)

Table 7.2: Long-term ELV method parameters

	ELV	Unit	Averaging period	Source
Carbon dioxide	-	ppm	-	-
Formaldehyde	9	µg/m³	1 year	USA-California (Office of Environmental Health Hazard Assessment, 2016)
Nitrogen dioxide	20	µg/m³	1 year	France (ANSES, 2016)
PM_{10}	20	µg/m³	1 year	WHO (World Health Organization, 2006)
$PM_{2.5}$	10	µg/m³	1 year	WHO (World Health Organization, 2006)

Table 7.3: DALY method parameters

Age (years)	% of population	Cancer ADAF	% of day spent at home	Air intake (m³/day)
<= 2	3	10	75	7
2-16	19	3	75	13
>=16	78	1	69	15

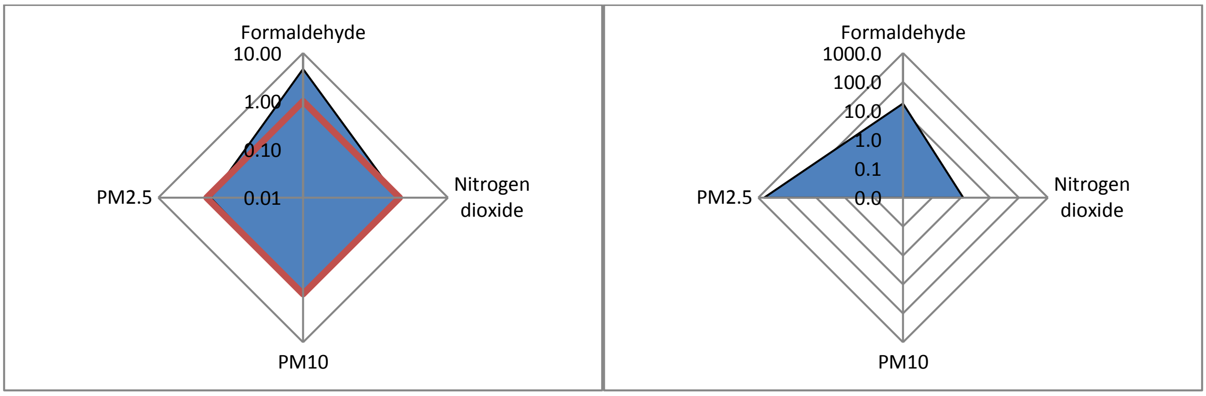

Figure 7.32: IAQ-LTEL (left) and IAQ-DALY (right) values for the living room for Scenario 5A with indoor doors shut

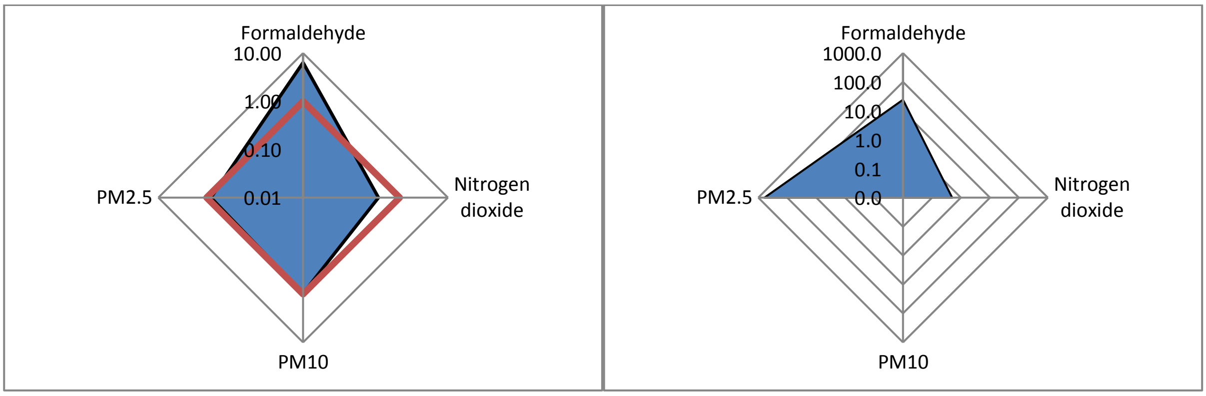

Figure 7.33: IAQ-LTEL (left) and IAQ-DALY (right) values for the main bedroom for Scenario 5A with indoor doors shut

Looking at these results, it can be seen that formaldehyde is the only pollutant that surpasses the Long-term EVL with a concentration around 5 times higher than the recommended limit in both living room and main bedroom due to the high emission rate at the start of the emission. On the other hand, the DALY method gives a total of 646 and 641 DALYs lost/(year.100,000 persons) in the living room and main bedroom respectively, mainly due to the exposure to $PM_{2.5}$. These results are in good agreement with findings from previous studies. Logue et al. (2012) used data from 77 studies in residential buildings in the U.S. and similar countries, finding a range of 400 to 1,100 DALYs lost, and the main pollutants that caused these DALY losses were $PM_{2.5}$, acrolein and formaldehyde.

7.7. Summary

IEQ results have been presented and analysed to answer five different questions presented in the previous chapter. The results gathered are the operative temperature, RH and pollutant concentrations (CO_2, formaldehyde, $PM_{2.5}$, PM_{10} and NO_2) in the living room, kitchen and bedrooms. In addition, the heating demand in the whole building was retrieved for some cases.

Question 1 investigated whether MVHR without summer bypass can lead to significant overheating risk in mild climates and whether providing boost control to the system and assuming window opening could solve the overheating issue. This question also compared the performance of this system against the use of summer bypass. The simulation results highlighted that the use of MVHR without summer bypass can definitely lead to overheating periods that would impair sleep and have a direct impact on occupant's health and comfort, even in temperate climates like Scotland. These findings suggest that summer bypass should be mandatory to minimise the risk of overheating even in mild climates.

Question 2 investigated the consequences of a fault of the MVHR system and whether occupants opening windows could counteract them. Results showed that formaldehyde levels would rise above the threshold only an hour after the fault occurs. Window opening based on adaptive comfort mitigated the IAQ issue but could not solve it completely in the case simulated, as occupants would operate the windows based on outside and indoor temperatures and not pollutant concentrations. These results emphasise that a good design, commission, operation and maintenance of the MVHR system is necessary to achieve good indoor conditions. In addition, they stress the importance of designing the building to enable natural ventilation when necessary, to alleviate overheating and IAQ issues. This is key in the case of an unintentional fault of the system since it can lead to severe IAQ and comfort problems. Additionally, these results could help occupants to understand the importance of operating the ventilation system properly, as switching off the MVHR system to avoid costs or noise could impact their health seriously.

Question 3 investigated the impact that the use of the kitchen hood while cooking has on IAQ and thermal comfort levels. The consequent energy increase was also investigated. Results proved that the use of the kitchen hood can significantly decrease the pollutant concentrations in the kitchen with a minor increase of the heating energy demand. This highlights the importance of the correct operation and maintenance of the kitchen hood.

Question 4 investigated whether trickle vents in the living room, bedrooms and wet rooms, and continuous mechanical extract fans in the wet rooms, could guarantee good IAQ and thermal comfort. The impact of providing boost control to the system and assuming window opening based on adaptive comfort was also explored. In addition, this question compared the performance of this system against the use of an MVHR system. Results showed that MVHR increases the ventilation rate 2.5 times on average, showing the benefits of MVHR versus MEV and trickle vents. Thus, it can be concluded that the use of MVHR can improve the overall IAQ in the building if it is operated and maintained properly. However, the optimum ventilation rates would be case specific. On the other hand, the MVHR system has the drawback of dry air during winter periods.

Question 5 investigated the performance of a constant ventilation rate system compared with DCV control strategies based on RH or CO_2, and assuming window opening based on adaptive comfort. Results showed that boost control can improve IAQ. However, in the case simulated, the DCV strategies did not result in a significant energy saving since the ventilation rate was reduced when the house was unoccupied and it was assumed that the house was occupied most of the time. Despite this, results show the potential benefits of DCV for the indoor environment and the energy consumption in buildings. It was also worth noting the increase in the heating demand when indoor doors remained shut.

These examples show how detailed integrated modelling and simulation can predict IAQ and overheating issues and help to design appropriate ventilation strategies in low energy houses.

Finally, assessment of IAQ using the three indices proposed by the IEA-EBC Annex 68 research project have been carried out for one scenario. Results showed that formaldehyde is the only pollutant that surpasses the Long-term EVL due to the high emission rate at the start of the emission. On the other hand, the DALY method gives a total of 646 and 641 DALYs lost/(year.100,000 persons) in the living room and main bedroom respectively, mainly due to the exposure to $PM_{2.5}$. These results are in good agreement with findings from previous studies and show how the use of several indices can lead to information that is more complete and useful.

Chapter 8. Conclusions and Future Work

This chapter reviews the aim and work carried out in this thesis. Then, the main research outcomes, conclusions and the original contribution are highlighted. Finally, recommendations for further work to take this research forward are listed followed by the final remarks.

8.1. Review

New buildings are increasingly becoming more insulated and airtight in order to meet Building Standards. Despite its beneficial outcomes, like reducing the energy demand which tackles fuel poverty and reduces the carbon emissions to the environment, this new way of construction may lead to a poor quality indoor environment if the ventilation provision is not designed appropriately. Some examples can be found in the Dormont Park Passivhaus (PH) Development in Scotland, where significant overheating was recorded, even during winter periods (MEARU, 2015; Morgan et al., 2017), and in Coventry where 18 out of 25 flats built to the PH standard failed the overheating criteria of the standard (Sameni et al., 2015). Also, Indoor Air Quality (IAQ) problems were found is the three PH dwellings monitored by McGill et al. (2014) in England, which had operation and maintenance issues of the Mechanical Ventilation with Heat Recovery (MVHR) system.

The aim of this project was to assess the impact that different ventilation strategies, occupant's behaviour and pollutant sources have on thermal comfort levels and IAQ in low energy houses. To address this aim, detailed modelling, including thermal and airflow modelling, contaminant source and sink models, definition of global ventilation controls based on different indoor parameters, such as CO_2 or relative humidity (RH), was required. ESP-r was used as it provided much of the necessary functionality and it was upgraded by implementing emission, deposition and resuspension models. Finally, a multi-zone approach, assuming the air is mixed within a zone, presenting uniform temperature, RH and pollutant concentrations was chosen over a Computational Fluid Dynamics (CFD) approach as it can provide reasonably accurate results when zones are not very large, like in standard dwellings (Wang and Zhai, 2016), saving time and computational capacity.

A detailed model of a low energy house was developed. The model was described and the assumptions made explained in Chapter 4. Once the base model was built, it was calibrated using monitored data to confirm that the modelling results were in acceptable agreement with the measured data in terms of the indoor environment (temperature and pollutant distribution) within various rooms within the house.

For this, a calibration methodology based on previous methodologies was defined and explained in Chapter 3. A review of common metrics was carried to select the most appropriate metrics for the sensitivity analysis (SA) and calibration criteria in this study. The calibration results showed acceptable agreement between simulated and measured data regarding the indoor environment. Hence, predictions can be considered accurate enough to predict overheating and indoor air quality issues within this specific low-energy dwelling. Several assumptions regarding IHG, occupancy profile, MVHR ventilation rates, etc. were made in Chapter 6 to adapt this model and generalise the analysis to other low-energy houses in mild climates.

A review of target pollutants usually found in domestic buildings, including their health effects, sources and current guidelines was conducted in Chapter 2. In addition, the main source and sink mechanisms that affect indoor pollution were summarised. Commonly used building modelling and simulation tools for early building design were also analysed, discerning the advantages and disadvantages of each of them.

After this review, five different emission models and the deposition and resuspension model from CONTAM were implemented in ESP-r. These models were described in detail in Chapter 5 together with the assumptions made for their implementation. The correct implementation was checked using Excel spreadsheets and running simulations replicating the results from Huang & Haghighat (2002). The comparison of the results from ESP-r simulations and Huang and Haghighat's study were done regarding pollutant concentration in the material at different depths, pollutant surface concentration for different air velocities and pollutant emission rate for different air velocities, showing that the model was implemented correctly.

Main indoor environmental issues, specifically overheating and poor IAQ were reviewed in Chapter 2, highlighting their importance, common causes and possible solutions, especially ventilative cooling and the relation between ventilation and IAQ. Questions to investigate and analyse these issues were defined in Chapter 6, explaining the assumptions made to define the different ventilation scenarios and pollutant cases associated with them. These questions were derived from common problems reported in previous studies, selected from the literature review. Questions 1 and 2 related to possible shortcomings of MVHR systems, while Questions 3, 4 and 5 compared the performance and impact on the indoor environment of different ventilation strategies. The simulation results from these scenarios were presented and discussed in Chapter 7.

8.2. Research Outcomes

The research outcomes of this work can be used to predict Indoor Environmental Quality (IEQ) issues and help the design of appropriate ventilation strategies in buildings. The research outcomes are:

- A calibration methodology and criteria to assess model predictions based on the indoor environment have been defined addressing the current absence of specific guidelines for model calibration based on the indoor environment. The metrics chosen were the 50, 75 and 90 percentiles. Maximum differences between the simulated and the measured percentiles of 150 ppmv and 2 °C were considered acceptable for CO_2 and temperature calibration respectively.

These criteria were defined using the British Standard BS EN 15251:2007 (BSI, 2007) recommendations and comfort data from previous monitoring studies.

- Implementation of five different emission models in ESP-r: the gas steady state model, the gas transient power law model, the gas transient discrete emission data model, the gas transient peak model and Huang and Haghighat's model. In addition, the deposition and resuspension model from CONTAM was implemented.

- A SA for several parameters in Huang and Haghighat's model was undertaken. This analysis found that the air velocity has little influence on IAQ in the long term. The grid size has a great impact on the emission rate and concentration in the material and air during the entire simulation period due to the slow diffusion of formaldehyde through the material. However, this effect decreases with increasing number of grid points, and for 50 grid points and above the differences are negligible after three months. Choosing different time steps for the simulation do not significantly change the results.

- The relevance of detailed modelling of formaldehyde emission rates depending on prevailing temperature and RH was demonstrated by comparing the simulation results assuming a constant indoor temperature, a constant RH and variable values for temperature and RH. It was found that the emission rate and the emittable formaldehyde concentration at the material surface increase greatly with temperature. The impact of RH on IAQ is less evident but it still causes changes in the indoor concentration of formaldehyde. From the comparison of the simplified models against Huang and Haghighat's model, it was found that, in the current case study, the use of the simplified models underestimates the formaldehyde concentration in the indoor air at the beginning of the emission, when the concentration in the material is very high and it overestimates the concentration one month after the start of the emission. Hence, detailed modelling and simulation of formaldehyde emission is important in order to assess the IAQ accurately and therefore, to assess different ventilation strategies if best practices are to be developed for future design of buildings. This is of great importance as a good understanding on how different factors interact and impact the indoor environment can be gained through the use of modelling and simulation, instead of learning by experience after construction, which is costly and more importantly, affects the health and life quality of the occupants.

- The relevance of including deposition and resuspension mechanisms in the model was also checked. It was concluded that it is important to include deposition and resuspension processes in the model in order to increase the accuracy of the results.

8.3. Conclusions

The main conclusion arising from the study is that, contrary to the usual assumption of even distribution of the indoor environmental conditions, there can be significant variations in the internal distribution. Therefore, a simple one-zone model simulation could provide misleading results as it could predict acceptable average indoor conditions for the whole building. Important factors are the use of appliances in different rooms within the building at different times, distribution of pollutant sources, indoor door opening and the ventilation strategy used.

From the scenarios analysed, it can be concluded that the use of the heat recovery unit during summer may lead to unacceptable levels of overheating throughout the house, even in temperate climates like Scotland. Apart from the overheating in the kitchen, which was predictable due to cooking activities, results showed overheating conditions in the bedrooms that impair sleep and have a direct impact on occupant’s health and comfort. Therefore, there is a noteworthy overheating risk if summer bypass is not permitted in low-energy houses, which have great insulation and airtightness levels, light thermal mass and no external shading.

The use of summer bypass solves the overheating in the bedrooms in this case. However, a maximum temperature of 25 °C was predicted, which is below but very close to the limit established by CIBSE during night time. Thus, if conditions differ from the present study, i.e. different climate or IHG, there could be overheating in the bedrooms despite the use of summer bypass. In that case, combining the use of bypass with window opening could alleviate the overheating issue. Despite results not being absolute values due to the inherent uncertainties of the modelling, these findings suggest that summer bypass should be mandatory to minimise the risk of overheating even in mild climates.

The second question showed that a fault of the MVHR system may lead to high formaldehyde levels which rise above the threshold only one hour after the fault occurs. Window opening based on adaptive comfort mitigates the IAQ issue but cannot solve it completely in the case simulated, as occupants would operate the windows based on outside and indoor temperatures and not pollutant concentrations. These results could be improved in a different climate that requires occupants to open windows more frequently. However, people in hot and humid environments would handle high indoor temperatures better (Fabi et al., 2012), and therefore, high levels of CO_2 and formaldehyde would still be expected. These findings emphasise that a good design, commission, operation and maintenance of the MVHR system is necessary to achieve good indoor conditions. In addition, they highlight the importance of designing the building to enable natural ventilation when necessary, to alleviate overheating and IAQ issues. This is key in the case of an unintentional fault of the system since it can lead to severe IAQ and comfort problems. Finally, these results could help occupants to understand the importance of operating the ventilation system properly, as switching off the MVHR system to avoid costs or noise could impact their health severely.

Question 3 showed that the use of the kitchen hood can significantly decrease the average pollutant concentrations in the kitchen by around 50 %, with a minor increase of the heating energy demand, which was only 2 %. A typical hood capture efficiency of 60 % was assumed in this study. Different capture efficiencies and pollutant emission rates from cooking activities would lead to different PM and NO_2 concentrations but the positive impact of the kitchen hood would still be valid. This highlights the importance of the correct operation and maintenance of the kitchen hood.

A comparison of the performance of trickle vents with continuous Mechanical Extract Ventilation (MEV) against MVHR was undertaken in Question 4, showing that MVHR increases the ventilation rate 2.5 times on average. This would vary for a different climate or building type but nevertheless, it shows a substantial increase and emphasises one of the problems of natural ventilation, as the minimum required ventilation rate cannot be guaranteed at all times due to the intrinsic variability of climate conditions. The impact that the mechanical increased ventilation rate has on the indoor environment was also very noteworthy. Concentrations in other houses, with different material loading factors, for example, will differ from the ones obtained in this study but they show the clear benefits of MVHR versus MEV and trickle vents, if it is operated and maintained properly. However, MVHR has the drawback of dry air during winter periods.

Finally, the use of Demand-Controlled Ventilation (DCV) was investigated, showing how boost control can improve IAQ, reducing peak concentrations 15 % for CO_2 and PM, and 25 % for formaldehyde when indoor doors remain shut. In addition, the use of DCV reduces the percentage of time of poor IAQ due to high levels of CO_2 by 50 %, and 30 % in the case of formaldehyde. However, in the case simulated, the DCV strategies did not result in a significant energy saving since the house was occupied most of the time. Despite this, results prove that DCV has a beneficial impact on the indoor environment.

It was also worth noting that indoor door opening improves thermal comfort and IAQ while reducing the heating demand. However, this may not be a practical solution due to privacy reasons.

To conclude, it should be noted that there is not an optimum ventilation strategy for all the indoor parameters considered. A compromise should be made between them in order to decide the most appropriate strategy.

8.4. New Contribution of the Research

The novel contribution of this research is the general capability of investigating a whole range of IAQ, thermal comfort and energy issues in buildings using a single tool, which can take into account the interactions of a number of parameters (temperature, humidity, air velocity, emission rates, etc.), simplifying the modelling and reducing the time and resources needed.

8.5. Future Work

The work undertaken to complete this study could be expanded in the future taking into consideration additional scenarios, contaminant emission information from experimental data, enhancing the accuracy of the model, developing a calibration standard or evaluating additional aspects of IEQ.

8.5.1. Additional scenarios

Additional scenarios could be simulated to investigate the impact of:

- Occupancy profiles, for example: inhabitants holding a party, children playing in a bedroom or intensive use of appliances like electronic devices throughout the house. In addition, CIBSE has developed a new methodology to assess overheating in homes using thermal simulation (CIBSE, 2017). This methodology includes internal gain profiles. It would be interesting to see if these profiles lead to different results from the ones shown in this study.
- Climates such as hot and humid climates.
- Building typologies such as flats, offices, commercial buildings, etc.
- Ventilation strategies such as the use of a humidity recovery device as part of the MVHR system or different hybrid ventilation configurations.
- Different percentages of window opening area.

- Filter blockage as result of lack of maintenance or efficiency change during filter life.

Results from these scenarios should lead to recommendations of good practices to help the design of ventilation systems and a better understanding of variations in the indoor environment. Furthermore, these results could help the development of guidelines to educate end users (occupants) as their behaviour and way they operate the building impact intensely the indoor environment. Finally, this analysis could be used to revise Building Standards which should address the IAQ issue.

8.5.2. Contaminant information

A comprehensive database that compiles correlations between emission parameters (C_0, D_m and k) and indoor conditions (temperature and RH) is needed in order to model the emission of formaldehyde and other pollutants from different materials.

Particulate Matter - $PM_{2.5}$ and PM_{10}- and nitrogen dioxide predictions are limited by lack of data on deposition and resuspension rates. Therefore, correlations to estimate deposition and resuspension rates based on particle size, air velocity and other environmental factors should be developed. In addition, data to estimate the deposition and resuspension areas in different building configurations is needed.

Filters were modelled using a constant efficiency, which do not change according to filter age, contaminant residing on the filter, etc. Hence, an algorithm to calculate filter efficiency based on these conditions would be needed.

8.5.3. Modelling accuracy

This study has demonstrated that it is possible to include detailed thermal and IAQ capabilities in a single tool, simplifying the modelling and reducing the time and resources needed. However, work is needed to improve the accuracy of the results further. Some limitations of the present modelling are:

- Humidity modelling is limited as absorption was not considered, and therefore, moisture buffering effects are ignored. This could be improved by coupling ESP-r and NPI as illustrated by the IEA ECBCS Annex 41 project (Woloszyn and Rode, 2008).
- The heat recovery efficiency was assumed to be constant. However, the efficiency specified by the manufacturer corresponds to specific conditions for the flow rate and pressure. Mardiana and Riffat (2013) reviewed the performance of heat recovery systems in buildings, highlighting that increasing airflow rates decrease the heat recovery efficiency. In addition, heat recovery efficiency varies with the temperature difference between supply and return air.
- Pollutant exposure calculation is not integrated into the tool so pollutant exposure is not automatically calculated using the occupants' profile and the pollutant concentrations.
- As air velocity at the material surface has a significant impact on emission results at the beginning of the emission, CFD modelling could be used to improve the accuracy of the results during this period despite the large resources needed by this approach. However, many uncertainties will still influence the accuracy of the results, like furniture layout, movement of occupants within the room, etc.
- Currently, ESP-r pollutant ambient concentration is defined for a typical day. However, defining concentrations for a whole year could help to model PM and NO_2 concentration in a more realistic manner.
- The model by Huang and Haghighat assumes that formaldehyde is completely mixed in the room air and the initial concentration inside the material is homogenous. In addition, it is assumed that no formaldehyde is passing through the bottom surface of the material. If more accurate predictions are needed for cases where, for example, there are many localised sources in large rooms, a more complicated emission model would be required. In addition, this model needs to calculate the initial emittable concentration of the material, which is influenced by the temperature and RH at the start of the emission. Thus, the emission needs to start within the simulation period. This makes difficult the assessment of emission rates in the long term. Also, in practice, the initial concentration inside the material would not likely be homogeneous when it is installed in the house, as the

main emissions from the near surface will take place immediately after manufacture.

8.5.4. Calibration Standard

A standard is needed for building calibration based on indoor environment data rather than energy demand. The calibration methodology and criteria proposed give reasonable results and could help in the definition of the standard.

8.5.5. IEQ Evaluation

Noise and luminance assessment could be added to the model for a more complete evaluation of IEQ. In addition, lighting control according to natural light could impact the IHG and heating demand of the building.

8.6. Concluding remarks

This research examined the question of how important is the use of detailed modelling in predicting IEQ issues in low energy houses and whether this approach is recommended to help decision-making and the design of appropiate ventilation strategies, which focus not only on reducing energy consumption and costs, but also on occupants' comfort and health.

Barriers were identified in the calibration of models based on the indoor environment and software capabilities for detailed modelling of pollutant emissions based on prevailing temperature and RH. A calibration methodology and criteria have been proposed and used in a case study. ESP-r simulation tool has been enhanced to meet the needs of the current research. Finally, a scenario-based approach has been used to investigate several research questions regarding ventilation strategies and IEQ in dwellings. It was proved that detailed integrated modelling and simulation is useful to predict IEQ issues and can help the design of appropriate ventilation strategies in low energy houses.

The results obtained are specific to this particular case study, but it is believed that the comparison between different ventilation strategies should still be valid for other low energy houses where ventilation rates are calculated on a whole house basis rather than considering the different spaces within the house, each with different pollutant source emissions.

This study provides a base for future research: taking into consideration additional scenarios, contaminant emission information from experimental data, enhancing the accuracy of the model, developing a calibration standard or evaluating additional aspects of IEQ. This work should lead to:

- Recommendations of good practices to help the design of ventilation systems.
- Guidelines to educate end users.
- Revision of Building Standards which should address the IAQ issue.

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