Assessment of indoor air quality in energy efficient residential buildings in Ireland

By

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Declaration

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Niti Saini

Abstract

Over the last two decades, Europe has witnessed a drive towards building energy efficiency. The EU directive on energy performance of buildings, as implemented in 2002, targeted the improvement in energy efficiency of buildings, reduction of carbon emissions and mitigation of their impact on climate change. Thereafter, further initiatives were established by the Energy Efficiency Directive (2012), which called upon the European member states to set up energy-efficiency targets to be met by 2050. The recent versions of the standard established in the Irish Building Regulations imposed a requirement on new domestic buildings to be highly insulated using a sealed external fabric to secure a building energy A-rating. Consequently, an increase in energy efficiency and airtightness has brought about a change in humidity levels internally that has led to mould formation generated by human activities, which may result in an adverse impact on user wellbeing. In addition, indoor air quality issues have been reported in the literature for a variety of high-performance buildings across the world, including offices, schools, and residential buildings.

The prediction of human behaviour, be it active or passive, is a challenge for designers. There is a lack of research on the correlation between the actual indoor air quality and the interaction between users and the installed ventilation systems as designed, which this thesis seeks to address. Inhabitants often block vents and switch off their mechanical ventilation systems or change their settings inappropriately, leading to a higher risk of health issues in these airtight dwellings.

As part of this research, the indoor air quality of 56 newly constructed energy-efficient A-rated residential dwellings in Ireland was studied to gauge the relationship between different indoor air quality parameters and the occupants' behavioural aspects. Specifically, temperature, humidity and CO_2 levels were monitored for one calendar year in similar dwellings with different family profiles to establish the influence of user behaviour on these aspects of indoor air quality. For the purpose of the thesis, these three measured factors (temperature, humidity and CO_2) are referred collectively as IAQ, even though factors traditionally included in

IAQ are not going to be discussed such as VOCs, dust, radon, etc. as they were not measured nor considered to be a particular problem at these sites. This project seeks to assess impact of design-related factors such as house orientation, house zone, type of house, occupancy, and seasons on the different aspects of indoor air quality. Millions of data were gathered and utilised as a part of this research. Critical condition issues were analysed to determine the influence of occupant behaviour on the indoor environment through interpretation of gathered data from the installed sensors in 44 houses. Interim feedback was given to the occupants after analysing the data for six months to determine if the houses can be operated in a way to ensure adequate environmental quality throughout the seasons, whilst maintaining perceived adequate comfort levels. The impact of the advice given, and subsequent sustainability of their actions is assessed for another 6 months. Findings from this research show that many homeowners do not know how to behave in an efficient house. Results show that 40% of the houses have CO_2 exceedances for more than 20% of the time and 7% of the houses have exceedances for more than 40% of the time in a winter month. Worst performing houses showed much higher CO_2 levels ranging up to 5000 ppm. In winter season, 20 houses show the temperature exceedances of higher than 25 degrees, and all of them exceeded for about 1-2% of the total times. In Summers, 5 houses experienced RH exceedance to be lesser than 10%, and 13 houses reported RH exceedances to be less than 20%. 11 houses had exceedances for more than 40% of the times, and 3 houses reported RH exceedances for more than 80% while 23 houses out of 44 experienced RH exceedances for lesser than 10% of the times, and 14 houses reported RH exceedance to be more than 20%. Seven houses had exceedance for more than 50% of the times during winter.

The building type was modelled to establish its suitability in a real-life building environment using the Integrated Environmental Solutions (IESVE) software platform for modelling, including calibrating and simulating the results. Different simulations were run to resolve the issues faced by different families. The aim was to model the monitored houses with a view to predicting the consequences of family behaviour on the IAQ. It is found that different zones of the house, due to their design, suffer from poor IAQ. Recommendation of installing an extra extract in the landing area and inserting a vent grill above the door of the second bedroom in modelling showed much reduced CO_2 and humidity level. The robustness of the model was tested by predicting whether it has the ability to be applied to other housing schemes. Thus, another set of 12 houses was considered for evaluating the model in which important variables that impact the temperature, relative humidity and the CO_2 levels in different zones were assessed. The aim of these analyses was to substantiate the findings made under the first set of the houses, and to establish whether the impact of occupant behaviour in these houses was predictable using modelling. The findings were further synthesised to draw final recommendations for designers and occupants of A-rated homes, so that environmental quality and human behaviour trends can be integrated in enhancing the wellbeing in living spaces.

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List of Acronyms

AH	Absolute Humidity
BER	Building Energy Rating
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CV	Coefficient of Variance
DCV	Demand Controlled Ventilation
EED	Energy Efficiency Directive
EPBD	Energy Performance Building Directive
EPC	Energy Performance Certificates
EU	European Union
HVAC	Heating, Ventilation and Air-conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
IES	Integrated Environmental Solutions
IESVE	Integrated Environmental Solutions Virtual Environment
IOT	Internet of Things
MV	Mechanical Ventilation
NE	North-East
NW	North-West
NZEB	Nearly Zero-Energy Building
PEB	Positive Energy Buildings

PIR	Positive Infrared Sensor
RH	Relative Humidity
SD	Standard Deviation
SEAI	Sustainable Energy Authority of Ireland
SW	South-West
T	Temperature
TTN	The Things Network
TV	Trickle Vents
VOC	Volatile Organic Compound
WHO	World Health Organisation

1. Introduction

1.1. Background and Motivation

Over the past few decades, the annual consumption of energy has significantly increased globally. The building sector is equally responsible for attaining the energy and environmental goals in the European Union (EU). Collectively, buildings are responsible for generating 40% of the total energy consumption in the EU and contribute about 36% towards the green-house gas emissions (EU Commission, 2020). Controlling the emissions and improving energy efficiency in the building sector is, therefore, important for achieving the ambitious goal of carbon-neutrality by the year 2050, as proposed in the European Green Deal (EU Commission, 2021).

Thus, over the last two decades, Europe has witnessed a drive towards building energy-efficient operations. The EU Directive on energy performance of buildings was implemented in the 2002, with the aim of improving energy efficiency of buildings, reducing carbon emissions, and mitigating impact of climate change. Thereafter, further initiatives were established in December 2012 by the Energy Efficiency Directive, which called upon the European member states to set up energy-efficiency targets. For the buildings sector, the first Energy Performance of Buildings Directive was set up in 2010, which was further amended in 2018 (EU Directive, 2018), with the aim of ensuring the reduction in carbon emissions by 80-95% as compared to 1990 levels, as well as setting high energy-efficient and decarbonised building targets in all member States of the EU by 2050.

Furthermore, prior to the building regulations in 1970, domestic houses in Ireland experienced conditions of draughts and difficulty in heating (Clinch & Healy, 2000). The buildings developed before 1979, therefore, reflected poor performance, owing to poor thermal conditions (Sustainable Energy Authority of Ireland, 2020). The thermal performance of domestic buildings in Ireland began to improve only after the standards of regulations were raised, as stated under Part-L of the Building Regulations. The recent and most-updated versions of the standards and laws established in Part-L posed a requirement on the domestic buildings to be highly insulated using a sealed external fabric, to secure an A-rating in the Building Energy Rating (BER) system (McGill et al., 2015a). Thus, in the context of Ireland, Parts L and F of Building Control Amendment Regulations have been provided to ensure that the building sector becomes much more energy efficient. Part-L pertains to the Conservation of Fuel and Energy requirements, specifying the minimum performance levels in different elements and systems in buildings. Part-F covers aspects of ventilation, which specifies that adequate ventilation must be provided in the buildings (Department of the Environment, Community & Local Government, 2021; TGDL, 2017; TGDF, 2009). With the advent of the European Performance of Buildings Directives and the mandated increases in energy efficiency, the need to reduce the overall energy usage of buildings has become an imperative best encapsulated in the most recent Nearly Zero Energy Buildings (NZEB) Guidance (Ministry of Housing, 2021).

Currently, design of high-performance buildings is focussed on reduction of energy consumption with specific standards that require significant care in design, construction and operation to ensure user comfort. Following these regulations, buildings can be well-designed and insulated, but the balance between occupants' comfort levels and the need for appropriate amounts of air flow for good IAQ is not fully being covered by the current regulations (European Commission, 2017). Improved thermal insulation and resultant air tightness in buildings often leads to increased dampness that can cause problems of mould formation and poor IAQ (Adan & Samson, 2011).

In addition, a study by the World Health Organization pan-Europe claimed that the residential dwellings are at high health risks induced due to indoor mould exposure (Bonnefoy et al., 2004). The IAQ is affected by a multitude of factors including outdoor environment, activities and behaviour of occupants, and the use of systems such as construction materials, furniture, ventilation, heating, lighting etc. (Bluyssen, 1996; 2020). Thus, all these factors are considered vital in maintaining good IAQ within buildings.

An increase in energy efficiency and airtightness can bring about a rise in IAQ issues that can lead to health hazards such as mould formation due to high humidity levels or a rise in indoor air pollutants (such as VOCs and CO_2) that are generated by human activities and which result in an adverse impact on user wellbeing (Ortiz et al., 2020). Indoor air quality issues have been reported in the literature in a variety of high-performance buildings across the world, including offices, schools and residential buildings (Kaunelienė et al., 2016; McGill et al., 2015b; Rios et al., 2009). See for example, a study conducted by McGill on six newly constructed row houses suggest inadequate indoor air quality and perceived thermal comfort, insufficient use of purge ventilation, presence of fungal growth, significant variances in heating patterns, occurrence of Sick Building Syndrome (SBS) symptoms and issues with the mechanical ventilation and heat recovery (MVHR) system. Thus, with a known required air exchange rate for adequate ventilation, airtightness should be designed in conjunction with a proper ventilation strategy, to optimise both energy consumption and indoor air quality within the buildings.

To achieve a low air permeability rate in nearly zero energy buildings, it is most likely that mechanical ventilation will be required to maintain adequate indoor air quality conducive to an occupant's good health. Research in residential dwellings has shown that the air quality of mechanically ventilated homes is better than natural ventilated homes (Wallner et al., 2015) because the recommended air exchange rate is not fully controlled by occupants. However, mechanical ventilation systems are known to perform less efficiently than their design targets (Brown and Gorgolewski, 2015; Kamendere et al., 2015; Lipinski et al., 2020). Despite the advantages of forced ventilation, it is still not widely used or accepted, principally due to perceived problems with noise, actual air freshness achieved, costs of running/maintenance and a reluctance to take control of the system (Harvie-Clark & Siddall, 2014).

Consequently, these issues have often led occupants to operate the buildings in a way that improves their comfort, for example by opening windows and ventilation grids, but thereby decreasing the thermal efficiency of buildings. The prediction of human behaviour, be it active or passive, is a challenge for designers. Studies have shown that inhabitants often switch off their mechanical ventilation system or change its setting inappropriately leading to a risk of health issues in these airtight dwellings (Brown & Gorgolewski, 2015). User actions and ventilation design strategies are frequently contradictory (Saini et al., 2018; Lipinski et al., 2020). This has a direct impact on the energy performance of the buildings which are in turn worsened by unnecessarily increased air exchanges and related heating loads in Winter (Stazi, 2019). In these cases, the occupants are encouraged to use their buildings better but it tends to result in poor uptake, as the proposed measures do not address the root issue of comfort levels being lower than acceptable to the occupants (Zeiler and Boxem, 2013). Research shows that control of the indoor climate and the perceived effect of interventions have a significant impact on comfort and satisfaction (Fabbri and Tronchin, 2015). Therefore, the correlation between the actual IAQ, perceived comfort and installed ventilation systems needs to be studied in detail. This, thereby, exposes the research gap, and acts as the motivation for this research.

Thus, in the current research, the indoor air quality of 56 energy-efficient A-rated residential dwellings in Ireland are duly studied, to gauge the consequences on the different indoor air quality parameters and occupant's behavioural aspects in the energy efficient residential dwellings. The research utilises the Assessment Methodology Building Energy Ratings (AMBER) project as its vehicle, in which well-sealed, air-tight residential dwellings with similar house-designs in Ireland are studied. In the AMBER project, BER and sensor data from 80 domestic and 25 non-domestic A-rated buildings were collected, to analyse power loads and indoor environmental quality at 5-minute interval resolution for one year in each building, taking into account the differences in use and operation of the different building types. The data was collected by installing automatic temperature/humidity/CO_2 sensors in multiple rooms in multiple houses with different family profiles, but with the same fundamental house design. IAQ data was paired with post-occupancy surveying to carry out a set of in-depth analyses. With the help of LoRaWAN enabled Internet of Things (IoT) sensors, the data on selected different IAQ parameters (temperature, relative humidity and carbon dioxide levels) were collected, evaluated and modelled in this project to provide meaningful insights into the IAQ of energy-efficient residential buildings. For the purpose of the thesis, these three measured factors (temperature, humidity and CO_2) are referred collectively as IAQ, even though factors traditionally included in IAQ are not going to be discussed such as VOCs, dust, radon, etc. as they were not measured nor considered to be a particular problem at these sites.

1.2. Research Objectives

The overall aim of this research is to analyse the indoor environmental quality in thermally efficient housing (A-rated) in Ireland. To fulfil this objective, the following objectives are stated:

1) To study IAQ of energy efficient homes

- To study different parameters (temperature, relative humidity and carbon dioxide emissions) and observe the IAQ patterns in A-rated residential buildings during all 4 seasons.
- To assess the impact of design-related factors such as house orientation, house zone, type of house, occupancy and seasons on the different aspects of indoor air quality.

2) To understand occupant's behaviour in energy efficient homes

- To understand the impact of occupants' behaviour on indoor air quality parameters in residential dwellings.
- To establish patterns of usage for each home through simple occupant surveys, insofar as that is possible, and through interpretation of the gathered data.
- To determine if the houses can be operated in a way to ensure adequate IAQ throughout the year whilst maintaining perceived adequate comfort levels.

- To identify where occupant actions have likely improved or reduced IAQ levels and the consequences of these actions on maintaining perceived comfort levels.

3) To model family behaviour and provide recommendations for a better IAQ

- To model the monitored houses with a view to predicting the consequences of family behaviour on the IAQ.
- To develop a set of occupier guidelines for the promotion of more efficient operation of these houses to optimise both energy usage and occupant comfort.
- To develop a set of guidelines for the designers of such homes to improve the predictability of outcomes compared to actual energy and IAQ performance.

1.3. Structure of thesis

The thesis is written in eight-chapter format such that their inclusion may be summarised as follows:

Chapter 1 – Introduction

In this chapter, the background information of the subject area and the conflicts between energy-efficiency, IAQ and occupant's behaviour are discussed. The rationale for the research and the key objectives are clearly specified in this chapter.

Chapter 2 - Literature review

This chapter provides the background underpinning of the subject area. It contains a comprehensive literature review focusing on factors influencing IAQ and responsible for inadequate ventilation in dwellings. It also covers the impact of IAQ and indoor pollutants on the occupant's wellbeing in energy efficient buildings. It highlights gaps in the installed ventilation systems, as designed and acts as the motivation for this research.

Chapter 3 - Methodology

The research, in order to meet the pre-determined research objectives, is undertaken using primary quantitative data and its analysis. A sample size of 56 dwellings in the same locality with the same design are considered. The data collection was completed in five interdependent stages. In phase-1, the sensors were installed on the first set of 44 houses for a year. In phase-2, the same sensors were installed on the next set of 12 houses for one year. The IAQ data recordings were collected from the likely most occupied rooms in each of these houses. From the sensors installed in the houses, real-time data was gathered by a software analysis tool called iSCAN provided by project partners IES. Using iSCAN, results were generated by configurable rules using pre-packaged analyses or user-specific rules using Python scripts.

Chapter 4 - Results and Analysis: Variable analysis

In this chapter, the collected data is analysed to understand the impact of occupiers' decisions on the IAQ in different zones of the house, the influence on temperature, RH and CO_2, using regression analysis, in which each of these variables is taken as dependent, while a number of important independent variables such as orientation of the house, occupancy, an advice intervention by the researcher, type of the house etc. are assessed. The data is divided into four seasons, to investigate the effect on the different IAQ parameters of the season. The three key variables to monitor the house's IAQ are the levels of carbon dioxide (CO_2), relative humidity (RH) and temperature (T), as measured throughout the day.

Chapter 5 – Results and Analysis: Family profiles and impact on IAQ

In this chapter, first a sub-set of A-rated homes is investigated to assess the family profiles and understand their influence on the IAQ. One of the objectives of this study is to establish patterns of usage for each home with the help of the information gathered from different families, insofar as that is possible, and through feedback sessions with the occupants and interpretation of gathered data from the installed sensors. It is also determined if the houses can be operated in a way to ensure adequate IAQ throughout the seasons whilst maintaining perceived adequate comfort levels and where occupant actions have likely improved or reduced IAQ levels. The data analysis pertains to the overall evaluation of 44 houses, which are assessed using the data over 1 year.

Chapter 6: Data Modelling

In this chapter, the building environment is modelled, and the data tested to learn its suitability in real-life building environments. The researcher utilised a virtual environment modeller using software provided by Integrated Environmental Solutions for data modelling, including calibrating and simulating the results. Once the model is successfully constructed in the IESVE software, the simulations of the internal environment of the sample houses were performed, allowing for different human behaviour. Once the model is calibrated, then different simulations are run to solve the IAQ issues faced by the different families.

Chapter 7: Prediction

In this section, the robustness of the model is tested by predicting whether it has the ability to be applied to other similar houses located elsewhere. Thus, a sample of 12 other houses are considered for testing the derived model, in which it is important that the variables that impact the temperature, relative humidity and the CO_2 levels in different zones are assessed. The aim of this analyses is to substantiate the findings made from the first set of the houses, and whether the modelling of the impact of occupant behaviour in these houses is justified and follow similar patterns as recorded in the actual houses themselves.

Chapter 8: Conclusion and recommendations

In the concluding chapter of the thesis, based on the overall findings, the key conclusions of the research are derived. The findings are further synthesised to draw future recommendations for the designers and occupants of A-rated homes, so that energy efficiency and IAQ are integrated for enhancing the overall efficiency of living spaces.

2. Literature Review

2.1. Introduction

This chapter aims to provide an in-depth review of publications related to IAQ in modern airtight houses, ventilation, occupants' living behaviour and their effects on the IAQ of energy-efficient houses. After compiling different energy saving and efficiency models, the chapter discusses the national and international policies for optimising the energy consumption in buildings. The following section describes a brief background of the history of buildings and the importance of the quality of the indoor air environment. The next section constitutes an in-depth literature review of the various common indoor air pollutants and their contributory factors to occupant ill-health; It also includes a review of indoor environmental issues and the resultant health issues specifically in A-rated, energy-efficient domestic buildings. Moreover, the impact of the resultant IAQ on the health of the occupants is also studied using exploratory research. The findings of the literature review are discussed to establish the relationship between occupant's behaviour and indoor environmental quality.

2.2. Energy and buildings

Over the past few decades, the annual consumption of energy has significantly increased globally. The building/construction industry causes the largest consumption of energy at national and global levels, accounting for 36% of global final energy use in 2018 (UN Environment Programme, 2019). The report by Santamouris (2018) has revealed that the building and construction industry consumes energy ranging between 20–40% of total energy. Moreover, the consumption of energy by that industry varies across different countries. For instance, in the United Kingdom (UK), the building construction and operation industry consumes about 39% more energy than other European nations, which is much higher than the average global consumption (Spandagos and Ng, 2017). Jung et al. (2018) supports these findings and add that the residential and commercial building sector consumes about 41% of the total energy and electricity's share of the world's final consumption of energy has risen to 20% (IEA, 2021) and, therefore, contributes considerably towards climate change and this needs urgent attention worldwide. The consumption of energy in buildings is associated with different factors involving the thermo-physical properties of the building elements, construction-related factors like efficient buildings and appliances, characteristics of the climatic location, the quality and maintenance of any installed HVAC systems, and occupants' behaviour during energy utilisation (Chen et al., 2015a; Page et al., 2007).

2.2.1. Energy efficiency and saving measures

In energy efficient buildings, HVAC systems contribute considerably to energy consumption (Abdullah et al., 2021), which also entail the replacement of non-efficient lighting systems with energy-efficient alternatives. Although, this study was undertaken in a hot climate it gives useful background knowledge for this research and it is evident that energy efficiency is of paramount importance and an integral part of sustainable and green buildings (Fonseca et al., 2020). Due to the high energy costs and environmental concerns, there is a renewed interest by architects and engineers towards building energy efficiency (Jia et al., 2021).

There is a number of variables that influence the energy consumption and efficiency in buildings, for example, the design optimisation of the building construction. Design optimisation and design philosophy for energy efficiency is a practical technique, as proposed by architects and engineers (Shi et al., 2016). Shi's study further deduces that a building energy efficient design optimisation technique helps to achieve optimum energy use in buildings.

Different strategies have been proposed by a range of researchers for building energy efficiency. Sadineni et al. (2011) stated that building energy consumption in developing nations can be reduced significantly using strategies of energy efficiency, energy consumption optimisation and reducing energy costs in buildings. These include energy-saving methods, thermal mass application, holistic energy approaches that reduce the size of mechanical systems and effective building design. The study also highlighted that infiltration and airtightness play a major role in building energy consumption. Considering this fact, it can be found that improvements in building components entail energy savings and enhanced efficiency, known as passive energy strategies, which are meteorologically sensitive and require a deeper understanding of the climatic conditions (Sadineni et al., 2011).

Friess and Rakhshan (2017) proposed a measure for the reduction in building energy consumption under hot climatic conditions with high urban growth. Specific measures were taken during the planning phase, in the context of building a new envelope or as a retrofit that includes radiative, conductive and convective effects as transfers through windows, walls, roofs and techniques for natural ventilation. A study conducted by Shen et al. (2011) further shows that the use of reflective coatings influences the building's energy consumption and indoor environment (Shen, Tan and Tzempelikos, 2011). It further indicates that, depending on the season, location and orientation, the temperature of interior and exterior surfaces can be reduced below about 5°C and 20°C, respectively by using different types of coatings.

2.2.2. Energy policies and nZEB

There are national and international policies for optimising the energy consumption in buildings. For instance, the recasting of the Energy Performance of Buildings Directive (EPBD) in 2010 introduced the concept of and responsibilities for nearly zero energy buildings (nZEB). The Directive mainly evolved a general framework involving the member States for providing appropriate definitions. Therefore, nZEB has been known as the most flexible policy requirement, with a harmonised nZEB definition throughout the EU. D'agostino et al. (2017) revealed the differences between deep, major and nZEB renovation while involving the adoption of best practice policies and measures to target retrofit and investment related to non-residential buildings. Buildings have been considered as the major concern in European (EU) policies that majorly contribute to maintaining sustainable and competitive low-carbon economies by 2050. The Energy Efficiency Directive (EED) and the recasting of the EPBD aim to reduce the energy consumption within the existing building stock while achieving nZEB status. Hence, there is a need to comply with such requirements and adopt actions to exploit energy savings within the building sector. The study by D'agostino et al. (2017) helped in analysing nZEB levels for new and existing residential and non-residential buildings. Hence, the results of the study clearly indicate the successful implementation of nZEB policies. Magrini et al. (2020) have stated the most recent developments in nZEB. The development of European directives evolved the tools and practical application of the indications for the EU towards the resolution of environmental problems such as, air pollution, depletion of natural resources and climate change. These environmental problems have been considered a matter of concern. Hence, the study involved the contribution of the EU in offering tools to its Member States for integrating energy policies and action programs to finance nZEB and Positive Energy Buildings (PEB) projects towards energy building performance.

Several other guidelines and certification systems have highlighted the integration of practices for maintaining the IAQ and energy performance within buildings. A positive drive in Europe to ensure that both domestic and commercial buildings are constructed in a way that supports highly energy efficient operation has taken the form of European Directives (EPBD, 2002; EPBD, 2010). These have been implemented at national level by the member States, such as Ireland (Building Regulations, 2006), to legislate for the minimum requirements in building materials and plant to supply occupant comfort. The recast version of the European Performance of Buildings Directive (2010) announced the intention for member States to introduce the concept of Nearly Zero Energy Building (NZEB). This was implemented in Ireland for domestic buildings in 2017 as a requirement for all new homes (TGDL, 2011 amended 2017, from January 2019) and for commercial buildings (TGDL, 2017).

CIBSE Guide A involves the implementation of environmental design, acting as the premier Irish and UK technical reference source for designers and installers of HVAC services within the building industry. This guide aims to enable the design of comfortable, environmentally sustainable, energy-efficient buildings. Similarly, ASHRAE (2017) has stated the policies and practices for the health and comfort of occupants and to provide acceptable thermal comfort for the buildings' occupants. As part of this building energy policy effort in Ireland, the level to which a domestic building is insulated, made airtight and contains equipment or plant capable of delivering the required level of occupant comfort whilst ensuring adequate fresh air supply, have all been encapsulated in Irish statutes and building regulations in Parts L and F of the Building Control Amendment Regulations. *Part L - Conservation of Fuel and Energy* is one section of the Irish Building Regulations and, within its Technical Guidance Document (TGD), guidance is offered as to how compliant implementation should be achieved, along with the minimum performance levels of various building elements and plant or equipment. Part L seeks to ensure that the quality of the asset is sufficiently high to facilitate efficient operation. *Part F - Ventilation* covers the requirements for sufficient levels of ventilation for occupants in a domestic setting. Again, in its accompanying Technical Guidance Document (TGD Part F, 2009) guidance is offered to building designers to ensure adequate levels of ventilation are provided, at least according to the applicable regulations.

2.2.3. Building energy consumption modelling and prediction models

There are many studies focussed on the application of different models to study the consumption of energy in buildings. Most of these studies undertook a prediction analysis to estimate the future use of energy. The most popular model utilised by the majority of the studies is the urban building energy model (Ali et al., 2021; Nutkiewicz et al., 2021; Abbasabadi et al., 2019; Villa, 2021; Buckley et al., 2021). Urban building energy modelling offers a robust framework, which can be used for energy planning, retrofits, and city development to achieve optimal urban stock building performance (Ali et al., 2021). Other approaches and models utilised for analysing and predicting building energy consumption include rough set theory (Lei et al., 2021), the quasi-steady-state method (Negendahl et al., 2015), Microsoft Azure cloud-based machine learning platform (Shapi et al., 2021), Lagrangian relaxation method (Li Q et al., 2017), a data mining approach (Fan & Xiao, 2014; Khan et al., 2013), multiple linear programming (Howard et al., 2012) and a hybrid genetic algorithm-adaptive network-based fuzzy inference system (GA-ANFIS) (Li et al., 2011). The paper by Villa (2021) utilised Building Energy Modelling, meter data and climate projections to estimate the effects of heat waves on energy consumption and electric peak loads. The results of this research provided important information about heat waves and weather impacts, useful for institutional and national planners. It also provided the potential for undertaking resilience analyses involving probabilistic risk assessments. Another study by Nutkiewicz et al. (2021) developed a hybrid data-driven urban energy simulation model. It utilised simulation models for building energy along with deep learning models to predict the impact of building energy retrofits on multiple spatiotemporal scales. The study made important findings about the potential of the model in informing energy-related decisions for various stakeholders, including architects, engineers, urban planners and policymakers.

On the other hand, the results of the study conducted by Zhang et al. (2013) showed that building energy simulations of floor-heating systems, and personal ventilation and displacement ventilation that utilises a non-uniform indoor environment, help in studying thermal comfort and energy efficiency. The contribution ratio of indoor climate (CRI) or indoor environment coupled with computational fluid dynamics (CFD) simulations are efficient methods for achieving reduced energy demand (by 15%-20%). These intelligent building energy models can manage the indoor environment well (Yao & Zheng, 2010). As per the study, the interaction of the occupants and their behaviour greatly affects the indoor environment which in turn helps to achieve energy savings in buildings. Thus, the existing literature signifies the popularity which different building design planning models have for predicting energy consumption in different buildings. These findings facilitate informed decision-making for multiple stakeholders in the construction industry.

2.2.4. Building Compliance

The construction industry in European Union (EU) member States focuses on building towards a sustainable built-environment sector and is required to follow stringent energy-efficiency guidelines. As per the EPBD directive, all new building construction must adhere to these energy efficiency guidelines, in compliance with nZEB standards (EU Commission, 2011). These considerations are imposed to achieve the aim of the EU in building energy-efficient homes such that the greenhouse gas emissions are reduced by 80-95 percent by the year 2050 (Ciucci & Keravec, 2021). The new European Union regulation, Energy Performance of

Buildings Directive (EPBD) (Directive 2010/31/EU, 2019) imposes the nZEB standard on buildings constructed after 31st December 2020 (Ecofys, 2013). The energy consumption of buildings in the EU represented 41.0% of total final EU energy consumption, of which 26.3% was consumed by residential buildings in 2019 (Eurostat, 2021). However, different countries in Europe exhibited different energy-efficiency compliance and adhered to different regional compliance mechanisms and energy ratings. For instance, Ireland was listed among the least energy-efficient nations in Northern Europe in the housing sector (Ahern et al., 2013). Typical houses in Ireland were regarded as draughty and difficult to heat to an acceptable standard before Irish construction legislation was introduced in the late 1970s (Swinand and O'Mahoney, 2014).

The Sustainable Energy Authority of Ireland (SEAI) has provided software to help in the determination of compliance with various versions of Part L (selectable by the Assessor based on Part L enforcement dates) and the associated Building Energy Rating (BER) method which determines the final rank of a domestic or commercial building. The assessment method, known as the Domestic Energy Assessment Procedure (DEAP) is implemented using software known as DEAP for domestic buildings. It is important to note that it is designed to assess the asset or building fabric under certain standardised occupancy and use patterns. Building energy ratings (BER) certificates are based on the assessed houses' efficiency for energy, water, space, ventilation, heating, lighting, and insulation, denominated as A1 to G in ranking, where A1 is deemed the most efficient. To comply with the nZEB standard, a newly build house's ranking must be at least A3. Similarly, in the United Kingdom, Energy Performance Certificates (EPCs) summarise the energy efficiency of buildings and give ratings similar to the European Union: A (Very efficient) to G (Inefficient) ratings (Arcipowska et al., 2014).

Likewise, different member States provide their own building energy rating systems along with national regulations and directives, facilitating the achievement of high ratings for the energy efficiency of buildings.

2.3. Indoor air quality

IAQ for buildings is an important variable that impacts the health and comfort of the building occupants. Carbon Monoxide (CO) intoxication, allergic conditions such as rhinitis, asthma, and chemical sensitivity to indoor air pollutants can be caused by unhealthy and poor-quality indoor air (Fisk et al., 2007; Caillaud et al., 2018; Howard et al., 2021). More than 3.8 million people die prematurely from illness attributable to household air pollution every year (WHO, 2018; Ramya et al., 2021). Lung cancer is the leading cause of cancer death in Europe partly due to radon exposure in airtight homes (Yoon et al., 2016). One study found that the radon exposure in Irish homes was 77 Bq/m^3 compared to 39 Bq/m^3 on average worldwide, which becomes responsible for causing more than 300 lung cancer cases per year (Bahabin et al., 2021). Particulate matter (PM) is also high in improper ventilation conditions and is a significant factor in respiratory problems in occupants (Muleng and Siziya, 2019). Furthermore, one in four deaths from chronic obstructive pulmonary disease (COPD) in adults in low- and middle-income countries are due to exposure to household air pollution (WHO, 2018).

Furthermore, the quality of indoor air depends on several factors, including CO_2 concentration, toxicity levels, relative humidity and temperature (USEPA, 2017; Fang et al., 2004). Humans are also a major cause of poor indoor air quality through their daily activities, habits, lifestyles, use of household chemicals, furniture choice, and behaviour towards ventilation closing and opening. Human activity such as smoking, use of cleaning chemicals, cooking combustion gases, human dust, etc., are the sources of everyday human-derived indoor air pollutants. The IAQ is also influenced by the levels of outdoor pollutants, so if the concentration of the pollutants increases outdoors, there is always a corresponding rise in indoor pollutants (Shrestha et al., 2019). The occupants' behaviour concerning the use of ventilation, such as window opening, also influences the degree of penetration of various contaminants into the indoor air, implying that external ambient pollutants can be a strong determinant factor of internal air contamination (Meier et al. 2015; Li et al. 2017). Thus, IAQ is a function of many factors, both controllable (human activities) and uncontrollable (outdoor air quality) by the occupants.

2.3.1. Factors influencing Indoor Air Quality

Despite the energy-efficient quality of modern buildings, the internal air quality impacts the overall well-being and health of the occupants. There are several critical factors that influence the IAQ such as the types of ventilation system, operating equipment and appliances, the use of HVAC systems for thermal comfort, openings for ventilation and architectural design (Van Hoof et al., 2010; Kim et al., 2010; Lim et al., 2015; Li, 2020; Jain et al., 2020; Abdullah et al., 2021). One of the studies, by Asif et al. (2018), investigated the impact of IAQ and thermal comfort within school classrooms, constituting various forms of required heating, ventilation and air conditioning systems. The HVAC systems and passive ventilation are the principal sources for determining the IAQ within buildings. Mechanical ventilation has been reported as reducing the levels of indoor air pollution when compared with natural ventilation. A semi experimental field study was conducted on 123 residential buildings (62 highly energy-efficient and 61 conventional buildings) built in the years 2010 to 2012 in Austria. Indoor air quality of mechanically ventilated homes was significantly better as compared to those relying on passive ventilation from open windows and/or doors (Wallner et. al., 2015). The indoor thermal environment is also affected by poor ventilation in the context of indoor parameters such as air velocity at the windows, illuminance, light and envelope parameters, such as the size of window and door openings, the surface temperature of the walls, etc. (Kim et al., 2010; Jain et al., 2020; Wang et al., 2020; Abdullah et al., 2021).

The opening and closing of windows during different seasons affect the ventilation and contribute to the thermal indoor environment (Christensen et al., 2015; Zhou et al., 2017; Li et al., 2020). Furthermore, the variations in temperature, CO_2 level and RH as well as thermal comfort, outdoor climate and the building's orientation, are found to impose a significant influence on the IAQ (Asif et al., 2018). All these parameters affect the indoor thermal environment and help determine the actual energy consumption and efficiency of the buildings.

The influence of these factors on the IAQ is also dependent on the season. For instance, a well-oriented building avoids overheating and prevents cold air infiltration during winter (Li et al., 2020). Similarly, the use of a heating system during summer increases the building's energy consumption (Babota et al., 2018). The thermal comfort and ventilation, in affecting the IAQ, are also functions of the building-related architectural designs. Improving the thermal performance along with intermittent ventilation could help in improving the indoor air quality (Griego et al., 2012). Therefore, it can be inferred that well-ventilated rooms improve IAQ and, in addition to this, it can also be concluded that factors that contribute to the improvement of the indoor air quality would also influence energy efficiency in buildings.

2.3.2. Airtightness and ventilation

With more compact spaces being used for living, the occupants of the buildings tend to rely on mechanical ventilation systems that demand more energy due to improper use, while still affecting the indoor environment. The study by Wallner et al. (2015) on 123 residential buildings in Austria, claims that the indoor air quality and room climate parameters, including humidity, exhibited significantly better IAQ in mechanically ventilated rooms than in natural ventilation.

Airtightness is a primary factor in determining the overall air exchange rates in any energy-efficient building and plays a crucial role in IAQ (Crawley et al., 2019). Energy-efficient buildings, including homes, need to be checked for the correct balance of energy consumption and adequate ventilation so that a good IAQ can be maintained for the occupants' healthy living. Thus, it is important that when the internal functional aspects of a building, including the ventilation system, are designed, care must be taken to achieve the optimum balance between the energy-efficiency of electric automated ventilation devices and the indoor air quality achieved.

Moreover, with the recent Covid-19 pandemic, the time spent indoors has substantially increased, thereby, affecting the demand for ventilation in houses and commercial units with a resultant safety risk to human beings (Brasche et al. 2005; Schweizer et al. 2007; Du et al. 2020). Furthermore, this indoor environment has a significant impact on the health and well-being of a person and causes a significant impact on an occupant's performance, productivity and physical and mental health (Altomonte, 2008; Aries et al., 2010; Arif et al., 2016).

2.3.3. Factors responsible for inadequate ventilation in dwellings

In regard to building regulations, ventilation requirements have gained major attention and are recognised as an important component for healthy dwelling. However, in practice, the ventilation performance in dwellings in Europe can be quite poor (Dimitroulopoulou, 2012). Dimitroulopoulou’s study further asserts that a reduction in the ventilation rates much lower than 0.5 h^{-1} is likely to increase the concentration of indoor pollutants and, thus, expose occupants to higher health risks. The dependence on inadequate or poorly operated ventilation, in the absence of a proper mechanical ventilation system, contributes to poor health and affects the well-being of occupants (Wargocki, 2013). Similarly, the study conducted by Howieson et al. (2014) claims that mechanical air extraction, if properly used during bathing and cooking, can be sufficiently high in airtight dwellings to dilute the indoor pollutant concentrations and suppress the relative humidity below 70%, which is the accepted threshold for mould growth and condensation. It shows that the ventilation systems in airtight dwellings must be used efficiently to create a healthy IAQ.

Passivhaus and Code for Sustainable Homes (CSHs) have been introduced in the UK as assessment tools. It shows that the rating systems developed for assessing the efficiency of a building are dependent upon design features and not on the IAQ considering occupants' health and well-being (McGill et al., 2015a). The McGill study further states that these legislations can be responsible for poor IAQ in airtight dwellings.

Thus, it can be inferred that the energy demand is the primary consideration in assessing the energy rating systems for buildings, but it may result in a lack of proper ventilation and unsuitable occupant behaviour. The provision of adequate ventilation in dwellings may have been overlooked in reducing the contamination dilution due to the outdoor air and the amount of natural infiltrating air (Howieson et al., 2014). Hence, the current regulations and legislation utilised by the construction industry fails to recognise the importance of IAQ, by potentially overlooking the need for the proper use of ventilation in achieving thermal efficiency.

2.3.4. Indoor Air Pollutants

Indoor air pollutants are caused by several factors. Some pollutants in the building's indoor environment are common to the outdoor environment. These contaminants in the atmosphere may be inorganic, organic, biological, or even radioactive (Leung, 2015). Particulate matter (PM) is the most common air pollutant, which is found in solid and liquid states. It has several established ranges of particle size, from 2.5 micrometres to 10 micrometres, also known as $PM_{2.5}$ and PM_{10}, respectively (Xing et al., 2016). The impact of these PM particles is assessed by the fact that they contribute more to the death toll as compared to other pollutants (Jimenez et al., 2009). PM is also found outdoors but is often located indoors in a heavier concentration (Jimenez et al., 2009). Diapouli et al. (2008) suggested that $PM_{2.5}$ and PM_{10} particles are more prevalent in indoor environments, signifying the similar presence of ultrafine particles in indoor and outdoor environments. Moreover, ultrafine particles ($PM_{0.1}$) have the potential to pose health risks (Schraufnagel, 2020). A study by Spiru and Simona (2017) claims that indoor air pollution levels are usually 2-5 times higher than outdoor pollution levels at home, work, and in educational establishments and can quickly become 100 times worse than outdoor air pollution due to ineffective ventilation.

The second important component of indoor air pollution is chemical compounds. Houses contain evaporating chemical compounds from the surfaces of building materials and furnishings, which may include polyvinyl floors, mats, coverings, carpets, house paints, sealants, plywood, and furniture fumes (typically comprising alkanes, formaldehyde, glycols, esters, ketones, and texanols) (Kim et al., 2005; Liang, et al., 2017a; Leung, 2015; Olaoye et al., 2021). Moisture is also a risk factor for occupants' health when living in sealed buildings; it damages the building and provides the essential ecological environment for microorganisms to grow, such as bacteria and fungi (Hurrass et al 2017). Even more harmful chemical compounds, such as radon and formaldehyde, are present in dwelling pollutants. Radon is a chemically inert radioactive gas that naturally occurs without scent, colour, or taste. Radon reaches homes through concrete joints in the floor, holes in the floor, hollow-blocked tiny pores, and drainage (World Health Organization, 2021).

Apart from these, there are several human activities and occupant behaviours that lead to the formation and accumulation of pollutants in the indoor environment of buildings and houses. An occupant's presence and actions can affect the indoor environment in obtaining fresh air, improving visual illumination, achieving a comfortable temperature, and a quiet environment (Wang et al., 2021).

Similarly, the quality of the indoor environment is disturbed depending on the number of occupants and their routine behaviour which may differ based on their physical, physiological, and psychological differences (Wang et al., 2021). For instance, fuel burning, and cooking activities lead to concentrations of CO_2, SO_2 (sulphur dioxide), CO (Carbon monoxide) and NO_2 (Nitric oxide) in indoor air environments (Olaoye et al., 2021). Indoor CO and CO_2 levels rise higher than outdoor levels due to human respiration and fuel combustion, and improper ventilation restricts the fresh air supply in sealed buildings (Satish et al., 2012). Similarly, human daily practices contribute to waste gas, tobacco smoke, additives, solvents, cleaners, particulates, pollen, mould, fibres, and other indoor air contaminants and allergens (Micallef et al., 1998). The growth of billions of fungi, spores, bacteria, viruses, and insects, such as dust mites and roaches, is also supported by human activity and presence. The highly pathogenic microbes such as micrococci, staphylococci, streptococci, and corynebacteria may be found in indoor air generated during human exhaling, sneezing, and other activities (Mouldoveanu, 2015). Other kinds of indoor pollutants are allergens, endotoxins, (1 → 3)- β -D-glucans and mycotoxins. Allergens are derived from fungal species like *Alternaria, Penicillium, Aspergillus, and Cladosporium spp*. that elicit immunoglobulin E (IgE) mediated response (a type of allergy antibodies caused by food reactions) in humans, causing severe asthma and other respiratory diseases (Park et al., 2001; Mazique et al., 2011; Mouldoveanu, 2015), inducing respiratory diseases and increasing peak flow variability in asthmatic children (Douwes, 2005). Mycotoxins are the most toxic pollutants or toxins of secondary metabolites of the fungi and can interfere with the Ribonucleic acid (RNA) and cause Deoxyribonucleic acid (DNA) damage in humans. Some mycotoxins may be carcinogens, such as aflatoxins produced by *Aspergillus flavus* and *Aspergillus parasiticus* (Haalen and Karuppayil, 2012). Several pollutants and contaminants, like volatile organic compounds (VOCs), halocarbons, polycyclic aromatic hydrocarbons (PAHs), and ozone (O_3) are also emitted by computers, printers, photocopier devices, and refrigerators. Also, higher levels of terpenes such as alpha-pinene, limonene, and hexaldehyde are attracted by houses constructed with wood or wood-based materials (Derbez et al., 2014; 2018).

Thus, this section signifies that the indoor air quality in houses and buildings is influenced by a large number of complex contaminants and pollutants, induced to some degree by the occupant's behaviour, activities, use of different components of the house, and even variables uncontrolled by the occupant (such as external air contaminants). It is also crucial to note that these pollutants deteriorate the health and well-being of occupants, as described in the next section.

2.3.5. Impact of indoor air pollutants

Poor indoor air quality facilitates the growth of several microbes, like bacteria and fungi, with significant health implications for the occupants. The presence of moisture, carbon monoxide, and higher ozone concentrations become the reason for the growth of a variety of bacteria and pathogens (Siebielec et al., 2020). The indoor environments experiencing a higher level of humidity facilitate the growth of bacteria (either alive or bacterial spores), mycotoxins, chemical makers such as β - glucans and volatile organic compounds, and endotoxins (Nevalainen et al., 2009). Moreover, when the circumstances for fungal development are present, such as in damp buildings, the levels of fungus in the indoor air can reach dangerously high levels. Spores of fungi are widely available, and they can sprout any place accessible to water. Fungi can track down every different component in house dust, surface materials like organic painted surfaces, wood, paper and books, food, or latent materials like clay tiles (Nevalainen et al., 2009). Dust mites are microscopic parasites that contain some of the most common indoor allergens and can cause allergic reactions and asthma in many people. Hundreds of thousands of dust mites can be typically found in bedding, mattresses, upholstered chairs, carpets, and curtains (Engelhart et al., 2002; Salonen et al., 2013). Poor indoor air quality owing to a higher accumulation of CO and CO_2 concentration causes visual disturbances and the former has been particularly associated with the loss of consciousness

(Satish et al., 2012; Van et al., 2020) and even death, in the case where CO rises to 25% of the total indoor air (Lipsett et al., 1994). Higher humidity leads to the rise in microscopic airborne particles, some containing allergens or chemicals with the potential to induce inflammation in the respiratory system (Hanes et al., 2006; Naclerio et al., 2007). Furthermore, dry or highly humidified air can cause severe respiration problems such as asthma (Naclerio et al., 2007). Thus, it can be found that poor indoor air quality due to air pollutants is likely to cause a detrimental effect on vulnerable occupants and disturb their well-being. This issue is exacerbated in modern air-tight buildings, which are assessed in the next section.

Pathogenic viruses such as influenza and SARS-CoV-2 can cause severe spread after coughing or sneezing and may become infectious bioaerosols in airtight energy-efficient buildings (Qian et al., 2021). These viruses have the potential to cause mucous membrane inflammation, asthma, neurotoxic symptoms, and gastrointestinal disturbances (Nag, 2019). Chronic Fatigue Syndrome, characterised by prolonged severe and disabling fatigue, disorders generated due to prolonged exposure to poor indoor air, can lead to various psychological, environmental, and behavioural changes in the occupants (Pizzigallo et al., 1999; Tovalin-Ahumad et al., 2007). The HVAC systems (heating, ventilation, and air conditioning) in these types of buildings can increase SARS-CoV-2 infection rates (Felgenhauer et al., 2020), due to the rise in pollutants. The discussed indoor pollutants are summarised in Table 2.1 along with their sources and potential health issues in humans.

Table 2.1 Summary of indoor air pollutants and health impacts

Chemical Pollutants			
Pollutants	**Sources**	**Potential Health Issue**	**References**
Radon	Soil, rocks like granite, shale, phosphate rock, and pitchblende, well-water, natural gas sources, building	Lung cancer	Puskin et al, 2006; Kreuzer et al.; 2008; Amegah et al. ,2014

	materials. lead, and bismuth		
VOCs	Oil, wood and coal, wood products, combustion, cooking, computers, printer ink, photocopier, paints, sealants, furniture	Asthma, allergy, lung cancer, angina, impaired vision, reduced brain function, adverse pregnancy outcomes, tuberculosis, cardiovascular disease, liver, kidney, and central nervous system failure	Orozco-Levi et al., 2006; Kim et al., 2011; Bacaloni et al., 2011; Abdullahi et al., 2013; Rösch et al., 2014; Li et al., 2015
Carbon monoxide (CO)	Anthropogenic emissions, cooking, and heating, fossil fuels, tobacco smoke, wood-burning fireplaces	CO_2 blocks hemoglobin's capacity to carry oxygen to the body's cells. Angina, blurred vision, and decreased brain activity are also possible side effects at moderate doses.	Fazlzadeh et al., 2015; Bariss et al., 2016; Spiru et al., 2017
NO_2	Generated due to the burning of cooking oil or fossil fuels. Tobacco smoke also generates NO_2	Respiratory tract, eyes, and skin, irritation, pulmonary edema, bronchitis, bronchiolitis, and emphysema are all conditions that affect the lungs.	Meier et al., 2015; Li et al., 2017; Gineste et al., 2019; Ielpo et al., 2019; Salonen et al., 2019
Biological contaminants	Bacteria, viruses, moulds, pet’s dander and saliva, cockroaches, dust, and pollen	Allergies, lung diseases, asthma, and other breathing problems	Crimi et al., 1997; Kovesi et al., 2006; Husna et al., 2021

Formaldehyde, Asbestos	Furniture, plywood paints, cleaning products hardwood, laminate floorings, adhesives, synthetic fibre glasses, paints varnishes, candles, incense sticks, mosquito coils, tobacco smoking	Lung cancer, allergies	Lee et al., 2004; Ahn et al., 2015; Salthammer, 2019
Pesticides	Organochlorine compounds, DDT insecticide, Chlordane, Polychlorinated biphenyl, hexachlorobenzene	Cancer, toxicity, endocrine-disrupting	Loomis et al., 2015
Smoke	Cigarette smoking	Lung cancer, hypertension, and other respiratory diseases, pregnancy complications	Ni et al., 2019; Chu et al., 2021
Biological Pollutants			
Bacteria	Saprophytic bacteria actinobacteria, Bacillus species, micrococci, staphylococci, streptococci, and corynebacterial; Legionella spp	Airway allergies, Rhinitis, allergic asthma, pneumonia, food poisoning, chronic bronchitis, hypersensitivity pneumonitis, organic dust toxic syndrome, sore throat,	Simpson et al., 1998; Nevalainen et al., 2009

Fungi/Moulds	*Fusarium macroconidia, Alternaria spores, candida albicans, Memnoniella Conidiophore*	Atopic allergic dermatitis, allergic asthma, extrinsic allergic alveolitis	Simpson et al., 1998; Nevalainen et al., 2009; Prussin et al., 2015
Endotoxins	Gram-negative bacteria	Shortness of breath, coughing, wheezing, phlegm, asthma, and atopy	Von Mutius et al., 2000; Fransman et al., 2003; Rennie et al. 2012, Salonen et al., 2013
Mycotoxins	*Stachybotrys Chaetomium, Aspergillus, Penicillium,* and *Fusarium fungi*	Reduced immunity, mycotoxicosis, bronchitis, asthma, toxicity, and hepatitis	Ross et al.1992; Burge et al. 1999; Purokivi et al., 2001; Jarvis & Miller, 2005
(1 → 3)- β -D-glucans	*Aspergillus* and *Penicillium spp*	Lower and upper respiratory tract symptoms, eye irritations, headache, fatigue, joint pains, skin symptoms, flu-like symptoms, nausea, and gastrointestinal symptoms	Rylander, 1996; Rylander, 1999; Douwes et al., 2005; Giovannangelo et al., 2007
Household Appliances			
Inkjet, laser nanoparticles Elemental carbon, metal	Printers & photocopiers	Systemic inflammation and high oxidative stress, diarrhoea, and weight loss	Bello et al., 2013; Shi et al., 2015

oxide, and Ozone			
Halocarbon, Freon	Refrigerator and air conditioners	Lethargy, rapid respiration, foaming at the nose, irritation in eyes, salivation, and weight loss. neurotoxicity and cardiac sensitisation at long exposure	Mullin and Hartgrove, 1979

Indoor air quality has a considerable influence on the indoor environment and can be harmed by poor ventilation systems and occupant behaviour. Since people began to create energy-efficient, airtight buildings, the intensity of indoor pollution has increased dramatically. The energy-efficient buildings with higher indoor contaminants pose significant health hazards to occupants. At the same time, homes constructed using wood or wood-based products promote the additional build-up of unnecessary indoor chemical and biological pollutants, including $PM_{2.5}$, PM_{10}, endotoxins, mycotoxins, and (1 → 3)-β-D-glucans. These indoor pollutants bring the deadliest chronic obstructive pulmonary diseases, and a variety of lung-related illnesses. Moreover, due to energy efficiency, airtightness in the absence of adequate ventilation has increased, which can trap the polluted air indoors, leading to bacteria, pollen, and dust build-up. Thus, appropriate and satisfactory ventilation is expected to supply natural air and significantly reduce if not eliminate indoor toxins. Building occupants are an essential part of this since it has been observed that their improper interactions with the provided ventilation systems can prompt poor indoor air quality conditions inside airtight homes (Moreno-Rangel et al. 2020).

Indoor air pollutants are not examined in this research; however, the above section signifies the extent to which indoor air pollutants can deteriorate the health and well-being of occupants and the importance of further knowledge gained by studying these IAQ pollutants and their affect in poorly ventilated dwellings.

2.4. Energy-efficient buildings and the indoor environment

Climatic changes often contribute towards changing the various aspects of IAQ, such as high indoor temperature, related heat stress, changes in the indoor environmental quality associated with outdoor air pollution, etc. (Vardoulakis et al., 2015). Furthermore, buildings are known for consuming a higher fraction of energy resulting in the emission of CO_2 that changes the climatic conditions (Röck et al., 2020). Various energy efficiency measures in buildings have influenced the comfort conditions by affecting the IAQ with positive and negative aspects (Crump et al., 2009; Shrubsole et al., 2014; Davies & Oreszczyn, 2012). The airtightness of the buildings has been considered effective for reducing the outdoor air ingress and involves the sealing of the thermal insulation to the building envelope or membrane and is considered the most common energy efficiency retrofit measure for buildings that affect IAQ (Ortiz et al., 2020).

A report from a study conducted on two social housing schemes in Portugal has revealed that an increase in temperature was observed indicating an increase in winter-time comfort in retrofits concerning thermal insulation (Brandão & Lanzinha, 2021). Another survey on 2500 low-income dwellings in England revealed a rise in indoor temperature from 17.1 to 19.0°C, along with an increase in the households with comfortable condition rating from 36% to 79%, after adding thermal insulation and replacing the heating systems with an energy-efficient heating system (Hong et al., 2009).

However, it is further found that the energy efficiency rating in buildings increases the risk of asthma (Sharpe et al., 2015). The Sharpe et al. study on 3867 social housing properties has clearly implicated the prevalence of asthma to double among the occupants with the highest quartile in energy efficiency rating when compared to occupants' buildings with the lowest quartile of an energy efficiency rating (Sharpe et al., 2015). Thus, the existing literature provides many incidences for the association between the energy efficiency in buildings, and the resultant deteriorated IAQ.

2.4.1. Indoor Air Quality in energy-efficient buildings

Energy-efficient buildings, constructed using the latest standards for minimizing green-houses emissions, often suffer from poor indoor environment quality. They are mostly sealed environments that could significantly increase PM, thus offering a high risk to the occupants. Due to their urban area locations, these buildings have higher $PM_{2.5}$ and PM_{10} levels (Cheng et al., 2009; Li et al., 2009; Leung, 2015). Another reason that can be attributed to higher PM levels are high smoke levels (He et al., 2004; Liu et al., 2006), often due to the use of fireplaces (Chen and Zhao, 2011).

One of the main issues in A-rated energy-efficient buildings is condensation, which promotes poor indoor air quality, and leads to material degradation and microbiological activity (Hens, 1999; Viitanen et al., 2010; Lee and Yeo, 2020). Previous studies on dwellings indicate that at typical indoor temperatures ranging from 20 to 25°C, high relative humidity and condensation inside the building support fungal growth, causing respiratory health issues like asthma, eczema, and rhinitis (Fisk et al. 2007; Lin et al., 2015; Caillaud et al., 2018; Howard et al., 2021; Norbäck et al., 2021).

Improper heating, relative humidity (too much moisture, insufficient air renewal rate, too low ambient air temperature, radiator leakages or breakdown), and human interference in thermostat settings and air conditioning have been the cause of condensation issues in buildings (Ginestet et al., 2019). Several factors like the spread of contaminants through the thermostat system, ventilation systems, internal dampness sources (sealing defect, construction defect) unvented unfinished plumbing spaces or leakage (in toilets, bathrooms), and harmful construction materials (plywood, asbestos, internal foam) are likewise connected to mould growth in homes (Ginestet et al., 2019; Lopez-Arce et al., 2020). It signifies that various sources of humidity in the house, arising from poor ventilation and other sources, exhibit growth of mould, and therefore, poor IAQ.

The cross-section study by Roussel et al. (2008) on 500 rooms in 150 dwellings revealed that rooms without mechanical ventilation have a significantly higher concentration of mould. In a similar study, 123 buildings were examined for mould growth in which 62 buildings were highly efficient in ventilation terms, while 61 others had conventional ventilation in Austria (Wallner et al., 2015). Energy efficiency and favourable indoor environment in buildings can be attained at the same time, through appropriate optimization and adjustment of HVAC systems, heat exchanger efficiency of heat recovery facility and sun-shading systems etc. (Wang et. al., 2017), but only through occupant operational awareness.

2.4.2. Factors affecting the indoor environment of energy-efficient buildings

The indoor environmental quality within buildings has a major impact on the health and well-being of the occupants (Mallawaarachchi et al., 2012). Various factors such as indoor air quality, daylight and lightning quality, thermal comfort, acoustics, occupants' behaviour, etc. contribute to determining the indoor performance of the buildings (Kubba, 2017). Energy efficiency is considered as one of the most important requirements for maintaining the sustainability of buildings. Conventional buildings can be retrofitted using PH methods so that the consumption of energy is reduced. A study conducted on a passive house and conventional house over a year in northern England showed reduced energy demand and improved indoor air environmental performance (Liang et al., 2017b). Liang et al. further state that retrofitting a conventional house by using passive methods can improve its performance for reducing the energy demand and indoor comfort conditions.

Some of the other important factors such as the orientation of the building, size, temperature, humidity and light influence the energy consumption within buildings (Al-Tamimi, 2011; Khoshbakht et al., 2018; Pickering & Byrne, 2014). The energy efficiency of buildings is also affected by the building envelopes as they are responsible for distinguishing the indoor environment from the outdoor, resulting in exposure to temperature variations, caused by humidity, rain, air movement, solar radiation, and other natural factors (Ge et al., 2018). The orientation, shape, and size of the buildings are also major factors that affect the energy efficiency within the buildings (Pathirana et al., 2019). The study further claims that the natural factors, such as the movement of air and daylight entering within the buildings, are strongly influenced by the shape of the buildings. Also, the importance of external environment to influence the IAQ is revealed by the study that the buildings in the longitudinal direction of north-south often consume lesser energy when compared with the buildings in the east-west longitudinal direction in hot climates (Odunfa et al., 2018).

It is also found that the types of materials utilised in the construction of the building affect the thermal transmittance of the buildings and further have a major impact on energy consumption (Chen et al., 2015b). Further, the building and environmental parameters such as functional space, ventilation, external air infiltration, linear thermal bridges, hot water preparation, maintaining the operation of the ventilation system, and other services contribute towards the total energy consumption in buildings (Chen et al., 2015b). Thus, the previous studies signify that the building related factors, like orientation, shape etc. impact the internal IAQ, owing to different energy needs.

The climate change and seasons also pose an important bearing on the IAQ of the buildings. The design of the buildings as per the climate conditions in the region is one of the vital approaches used for reducing the energy consumption and costs (Abdeen, 2008). The study further restates that the design of the buildings as per the climatic conditions of the region reduces the need for mechanical temperature control. Another study by Orola (2020) investigated the impact of seasonal variation and the resultant outdoor air pollution sources on the IAQ in student hostel buildings in Nigeria. Although the previous research provided the relationship between seasons and building-related aspects on the IAQ, conclusive findings were not made. Moreover, the impact of these factors on different zones of the buildings are also not studied in the existing literature, signifying a major gap in research.

2.4.3. Scenario of indoor air quality in A-rated domestic buildings in Ireland

SEAI is the issuing authority for Energy Performance Certificates (EPCs) in Ireland, leading to a building energy rating (BER) of the asset. These certificates are accompanied by an advisory report that identifies the effective ways by which the energy performance of the buildings could be improved. Once the BER certificate is secured, it is valid for ten years and during that period, no significant change can be made to the building without re-assessment (Stanley et al, 2016). A BER is defined as rating that is given to any building or home based on the overall building's energy efficiency on a scale ranging from A to G. In Ireland, A-rated dwellings are most efficient in terms of energy performance and comply with nearly Zero Energy Buildings (nZEB) standards. A study conducted by Hyland et al. (2013) showed that a high A-rating home in Ireland has a premium price as compared to homes with lower ratings. A-rated dwellings are considerably more energy efficient and, since 2015, 97% of the homes built were given an 'A' rating, where Dublin had the highest number of A-rated buildings, having around 31% of all issued (CSO, 2019). However, there is necessarily an increase in the airtightness in A-rated dwellings leading to better energy efficiency. For example, the relative humidity in these dwellings could be above 80% for prolonged periods of time (Saini et al., 2020), resulting in mould growth on cold and unventilated surfaces. Such high levels of humidity have the potential to affect the well-being of occupants leading to allergies and respiratory infections as described heretofore. Furthermore, high carbon dioxide levels have become more prevalent in such A-rated dwellings, making occupants feel drowsy and lethargic (Howieson et al., 2014), and occasionally suffer from Sick Building Syndrome (SBS) (Ganesh et al., 2021). As the insulation levels and airtightness increase in A-rated buildings, there is a need to coordinate the dual objectives of the IAQ improvement and lower carbon dioxide emissions (Colclough et al., 2018). Although the construction industry in EU member States is focused on reduction of energy demand, the EU Commission has developed strategies that deal with IAQ in conjunction with deployment of the nZEB standard in A-rated dwellings (Fabbri et al., 2020).

Building occupants play a vital role in managing IAQ, as it has been observed that their interactions with the building ventilation system affect the IAQ within airtight A-rated dwellings. The study conducted by Hyland et al. (2013) revealed that occupants' preferences and their interaction with the dwellings has a significant impact on the IAQ in terms of carbon dioxide levels, humidity and temperature. Moreover, the preferences of closed or open trickle vents in doors and windows have a large impact on the indoor air quality in A-rated domestic buildings (Saini et al., 2020). Trickle vents are small openings in building envelope components that allow ventilation in small amounts in spaces that are intended to provide natural ventilation when doors or windows are closed. Closing trickle vents is not a good choice because closing them could result in high humidity and subsequent mould growth which can be harmful to the occupants.

A study conducted in Ireland showed that closed vents prevent airflow and open vents allow a small amount of air to be circulated around the room (Saini et al., 2020). Under the Technical Guidance Document Part F – Ventilation, as per the latest building regulations in Ireland, every habitable room should have background ventilation that serves a minimum 7,000 mm^2 equivalent area.

Therefore, from the above discussion, it can be said that ventilation can have a significant impact on the health of the occupants whose behaviour affects the IAQ in buildings.

2.5. Occupants' Behaviour

Another important aspect that directly impacts the indoor air quality of the building premises is the behaviour of the occupants and their use of different components, including the ventilation system. Occupant behaviour is the interaction between occupants and various building systems through their presence and activities (Delzendeh et al., 2017). Occupant behaviour can be categorised as adaptive actions and non-adaptive actions. Adaptive actions are those actions that adapt the indoor environment to their requirements, whereas non-adaptive actions are more extensive, including occupancy, movement, and the operation of electrical appliances (Laaroussi et al., 2019). It is important to understand the conditions created by different occupant behaviour in influencing the indoor air quality of building premises. The study by Mahdavi et al. (2008) presented the fact that the thermal performance of buildings and their energy consumption are strongly affected by the occupant's behaviour, principally in the form of latent heat emissions. Humans are responsible for controlling their indoor environment as they have the freedom to act. The occupant's behaviour changes according to the environmental conditions, with complex conditions such as their thermal comfort, physiological and psychological state (Elnabawi and Hamza, 2019). Hence, it becomes difficult to develop a specific model for analysing occupant behaviour as their behaviour is uncertain and unpredictable.

2.5.1. Occupants’ behaviour models

The IEQ and the energy efficiency of buildings is largely influenced by the behaviour and actions of occupants. To assess the findings, a number of occupants’ behaviour models utilised in the reviewed papers are considered. Some of the important models used include: Regression analysis to investigate energy consumption and its relationship with building characteristics and the actions of occupants (Zhang et al., 2021); Data mining technique for occupants' behaviour (Yu et al., 2011); Simulation software and survey questionnaires (Frontczak et al., 2011; Zhang et al., 2012; Jiang et al., 2014; Christensena et al., 2015; Chen et al., 2015a; Hashemi et al., 2015; Zhao et al., 2016; Zhou et al., 2017; Dong et al., 2022; Li et al., 2020); Normalised cumulative periodogram (Ahn et al., 2016); Post occupancy evaluation studies (such as in Hua et al., 2014); Human and building interaction toolkit (Langevin et al., 2016); And data driven engines for archetype models of schools (Schwartz et al., 2021). The simulation and field survey studies are the most popular modelling methods employed by researchers for studying the occupants’ behaviour in impacting the energy efficiency and IAQ.

Furthermore, a socio-technical building performance evaluation (BPE) approach was utilised in the study by Gupta and Gregg (2016) for assessing the pre-and post-actual performance of two discrete deep low energy retrofits in buildings in the UK. The results revealed that the approach had the potential for 80% reduction in annual CO_2 emissions by 2050, and a significant improvement in the occupant’s comfort and satisfaction (Gupta and Gregg, 2016).

Wang and Zheng (2020) have undertaken a comprehensive quantitative study that is dependent upon energy-environment-satisfaction (EES). It was observed from their study of existing literature that most of the publications involved the designing, energy simulation and post-occupancy evaluation of buildings, but none of the studies integrated the energy consumption, indoor environmental quality and occupant satisfaction. The indoor environmental parameters, including temperature, relative humidity, carbon dioxide, particulate matter (2.5 microns), illuminance, sound level, air velocity, and volatile organic carbons, were evaluated for their impact on the reduction in energy consumption while operating green buildings. The primary findings of the study included the association of these environmental parameters with the reduction in daily energy consumption. Hence, different IAQ parameters help in analysing the occupant's behaviour for improving the energy performance and for improving IAQ within the buildings. Gilani and O'Brien (2017) have presented a model for occupants' behaviour in analysing the performance of energy consumption within buildings and their comfort zones in accordance with the building design and operational activities. Studying the occupants in real environments provides insights into the intrinsic nature of occupant behaviour in their built environments in reality.

However, in-situ monitoring of occupant behaviour is a challenging research approach due to the lack of control over contextual factors and personal occupancy behaviour. Therefore, the study involved the integration of the model with real occupant behaviour for analysing their influence on energy consumption within buildings. The study utilised the data comprising the occupants' presence and behaviour in the integration of building performance simulation (BPS) tools. It resulted in predictions of environmental conditions within buildings. Occupancy related input data, such as standard occupancy schedules and simple rule-based behavioural models have been utilised for obtaining the pattern of occupants' behavioural analysis within buildings (Berger and Mahdavi, 2020). The results have evolved by integrating the agent-based modelling in the built environment domain that particularly involved building's energy and indoor environmental performance. An equation-based modelling approach was also utilised for studying the stochastic nature of occupant behaviour towards energy performance (Wang et al., 2019). The results presented the simulations in occupant behaviour with some factorial parameters such as lighting, windows, blinds, heating and air conditioning.

Thus, the models generally encompass the use of different occupants' actions and behaviour in studying their impact on the energy efficiency of and IAQ in buildings.

2.5.2. Impact of IAQ on the occupant's wellbeing and comfort

The IAQ is considered as one of the major issues that has involved the occupants' attention for improving the quality of air inside buildings. This quality of air is often represented by analysing the rate of air ventilation, the temperature and concentration level of CO_2 and relative humidity (Khoshbakht et al., 2018; Psomas et al., 2021). IAQ is mainly evaluated as per its impact on human health along with analysis of comfort level and productivity inside the buildings where the occupants are concerned. Past research has shown that poor IAQ inside school buildings tends to cause several health issues among the children who are more prone to air pollution (Clements-Croome et al., 2008). According to Arif et al. (2016) IAQ affects the comfort and well-being of occupants as people spend most of their time indoors. Health and comfort related factors are influenced by the building characteristics, such as building design, ventilation system, etc. Poor indoor environments in office buildings can significantly reduce the work performance of the occupants including the cultural, psychological and sociological dimensions (Arif et al., 2016). Various types of outdoor air pollution are also responsible for influencing the IAQ. CO_2 is considered the most common indicator of the degradation of air quality in buildings that has a major impact on the health of the occupants (Persily and de Jonge, 2017; Ramalho et al., 2015). The air temperature and relative humidity are other major indicators of occupant comfort (Kavgic et al., 2012). The thermal insulation of buildings is responsible for influencing the indoor temperature and thermal comfort and the optimum temperature provides the possibility for energy saving (Bekkouche et al., 2013; Vučićević et al., 2009). Hence, the utilisation of these variables, namely temperature, humidity and carbon dioxide levels, can be considered as important variables signifying the IAQ in buildings. In recent years, the problems associated with IAQ have become evident as the airtightness can affect the occupants' health. Therefore, IAQ assessment in the airtight buildings is important in terms of assessment of temperature, humidity and CO_2 levels along with VOC emissions and other air pollutants.

The adverse influence of the poor indoor environment on the occupant's health has been identified by various researchers (Joshi, 2008; Laumbach, 2008; Mentese et al., 2020). Similar findings are made by other studies claiming that the accumulation of multiple effects in buildings, such as the indoor environment, building characteristics or architecture, and the occupant's behaviour are attributed to the building-associated illness known as Sick Building Syndrome (Nag, 2019; Brunekreef and Holgate, 2002). These symptoms are not only related to houses or offices but to public buildings like schools and hospitals can also be affected (Laumbach, 2008; Takeda et al., 2009). The closure of natural openings or ventilation, emissions from office equipment, furniture or new construction materials could also contribute to SBS (Nag, P.K., 2019). Uncomfortable indoor humidity and temperature, biological and chemical pollution are some of the factors that cause SBS among the occupants of airtight homes with inadequate ventilation affecting their physical and psychological well-being (Joshi, 2008). The most common symptoms for Sick Building Syndrome noticed by the researchers includes headaches, respiratory difficulties, weakness, throat infections and skin problems (Douwes et al., 2005; Giovannangelo et al., 2007; Takigawa et al., 2009; Salonen et al. 2013). Takigawa established that hypersensitivity pneumonitis and asthma are also associated with inflammation and atopy problems where one's immune system is more likely to develop allergic disease, triggered by exposure to indoor air contaminated with biological or fungal concentrations. Furthermore, Moreno-Rangel (2020) showed that indoor air quality has a significant impact on the health and well-being of the occupants residing in airtight buildings. These health impairments have been related mainly to the poor indoor air quality, the presence of microbial contaminants, building airtightness, dampness, poor indoor design and unhealthy energy systems (Missia et al., 2010; Ng et al., 2013; Kumar and Imam, 2013).

Thus, it is crucial that buildings are designed not only considering the aesthetics, energy-efficiency, or operational aspects of different components but also considering the indoor environment impact of the relevant building characteristics and the assessment of the vulnerability of the occupants to SBS. The indoor conditions of the buildings involve several physical factors and chemical pollutants both of which influence the comfort of building occupants. Several studies have been conducted in determining the occupant's comfort zone within the indoor environment of the buildings (Haldi and Robinson, 2011; Frontczak and Wargocki, 2011; Yang et al., 2014; Zhao et al., 2016). The studies have indicated that different critical factors exist relating to the indoor environmental quality (IEQ) within a building, such as individual characteristics of building occupants (gender, age, country of origin), building-related factors (room interior, type of building, the possibility of user control), outdoor climate and seasonal factors, all of which pose a direct impact on the comfort, health, and productivity of the occupants (De Giuli et al., 2012). Several indoor factors, such as thermal, visual, acoustic, and chemical pollutants, have an influence on occupant behaviour causing short-term and long-term impacts on the individuals. Hence, the occupants attempt to adapt to the indoor environment to improve the IAQ. An analysis of this involves estimating the occupants' actions such as use of ventilation, air-conditioning and heating systems, which influence the building's occupants in the indoor environment (Delzendeh et al., 2017).

There are many critical factors that have been responsible for influencing occupant's behaviour towards energy use in domestic buildings. Moreover, there are different models used by different authors for studying the influence of different factors on the IAQ, as described previously.

2.5.3. Impact of occupants' behaviours on IAQ

The critical factors impacting IAQ are majorly controlled and regulated by the occupants' usage of different systems within the building. The occupants' behaviour, actions and perceptions about the use of the different building components are crucial for determining the energy consumption and the IAQ. Numerous researchers have shown that energy efficient houses and their ventilation systems have an impact on the IAQ, which is dependent upon the occupant's actions influencing thermal efficiency (Lim et al., 2015; Balvers et al., 2012; Hashemi et al., 2015). The main drivers of energy consumption in buildings are categorised into human-related factors and physical-related factors. The building characteristics, such as the U-values of the external façade, the floor area, ventilation and HVAC are the physical factors, while the occupants' related factors include their use of different equipment and building components.

The occupants' behaviour has an influence on the indoor air quality and building energy consumption through their activities and presence in the building (Ahn et al., 2016). For instance, in school buildings, children are not allowed to control the systems and devices for lighting, heating or ventilation; rather teachers are and their actions, such as turning on or off heating and lights, influence the IAQ and energy consumption in such buildings (Zhang et al., 2011). The occupants' energy behaviour, like the use of solar shading, use of appliances, hot water, set points and HVAC systems for their visual and thermal comfort, primarily impacts the IEQ and the efficient utilisation of energy (Frontczak et al., 2011; Balvers et al., 2012; Zhang et al., 2012; Christensen et al., 2015; Jeong et al., 2016; Dong et al., 2020; Abdullah et al., 2021). The use of lighting systems is a component that is considered vital in influencing energy consumption as well as IEQ in buildings. For instance, Zhang and Bluyssen (2021) studied the distribution of lights in classrooms and the frequency of light switching on and off by teachers. They concluded that the habit of switching on and off of lights impacts not only the energy consumption in school buildings, but also the IEQ, since lights emit heat and influence indoor temperature. Electrical appliances are also found to emit radiation, which impact the IEQ and pose health impacts on the occupants (Mannan et al., 2020; Ali et al., 2021). That is, the devices that consume electricity generate an electro-magnetic field, and prolonged exposure to this impairs human health, by causing insomnia, headaches, ear ringing problem, fatigue, cognitive disturbances and stress (Sage and Burgio, 2018; Samrajesh et al., 2018).

Furthermore, the opening and closing of windows by occupants affects the use of thermostatically controlled temperature and ventilation (Schakib- Ekbatan et al., 2015). The studies considered in the review also state that the influence of occupants’ behaviour on the IAQ is present in all types of buildings, including residential, commercial, school and academic institutions and even museum buildings (Delzendeh et al., 2017; Andersen et al., 2016; Schwartz et al., 2021; Ferdyn-Grygierek et al., 2014). All these findings signify that the occupants’ actions and behaviour pose an important bearing on the use of the thermal, ventilation through opening and closing of windows, electric appliances and HVAC systems, which impact the IAQ of the buildings.

2.6. Summary and identification of gaps in knowledge

The literature review has covered a wide selection of research topics which are relevant to the area of IAQ and the objectives of this thesis. In this Final section, the research findings are summarised and the potential gaps in the knowledge are discussed.

2.6.1. Literature Review Summary

Indoor air quality has a considerable influence on the indoor environment and can be harmed by poor ventilation systems and occupant behaviour. Since people began to create energy-efficient, airtight buildings, the intensity of indoor pollution has increased dramatically. Moreover, due to energy efficiency, airtightness in the absence of adequate ventilation has increased, which can trap the polluted air indoors, leading to high humidity, condensation, and high CO_2 levels. Thus, appropriate, and satisfactory ventilation is expected to supply natural air and eliminate indoor toxins.

Building occupants are an essential part of this since it has been observed that their improper interactions with the provided ventilation systems can prompt poor indoor air quality conditions inside airtight homes (Moreno-Rangel et al. 2020). Poor indoor air quality has an effect not only on human well-being but also on the efficiency and physical and mental welfare of the occupants. Moreover, since this review provides strong evidence that airtight buildings are associated with many respiratory diseases, it calls for policy changes across the public health, urban planning, and architectural design sectors, for maintaining good IAQ along with energy efficiency. Building-related illness and associated diseases mainly exacerbated due to inadequate ventilation, lack of air filtration, and air recirculation needs to be addressed. The review elaborated on occupant comfort topics along with analysing the impact of IAQ within A-rated buildings in the presence of occupants. The literature has examined the critical factors contributing towards the improvement of IAQ in A-rated buildings. Some major practices and regulatory policies concerning the EPBD have been adopted by the Member States of EU for reducing energy consumption within the existing buildings.

The literature showed that the IAQ in low energy houses is significantly affected by the variables like temperature, RH and CO_2, which further varies as per the occupants' behaviour and many design-related factors like house orientations, house types etc. The behaviour of occupants like opening of windows, relying on mechanical ventilation, consumption of gas and electricity etc. pose an impact on energy consumption, IAQ and satisfaction level of occupants. The occupants' actions influence the air change rate per hour and the concentration of CO_2 levels in different house zones and depends on windows handling and air grill extraction vents regulation.

Finally, the review suggests that ventilation regimes and occupier guidelines must be specified to explain the need for the provision of proper ventilation as controlled by the occupants on a time basis because excessive ventilation regimes can lead to sub-standard thermal efficiency, while ineffective ventilation can lead to persistent condensation and mould growth and poor IAQ.

2.6.2. Gaps in knowledge

The literature review has identified gaps in the research which are the bases of this thesis. They are outlined as follows:

1) There is inadequate research into the relationship between IAQ and design related components in energy efficient buildings. Although the previous researchers provide the relationship between seasons and building related aspects on the IAQ, conclusive findings based on occupancy, seasons and orientation are not made. Moreover, the impact of these factors on different zones of the buildings are also not studied in the existing literature, signifying a major gap in research.

2) There has been much research conducted on poor indoor air quality. However, there are still gaps in knowledge around indoor air quality in low-energy buildings.

3) The IAQ within buildings has been found to vary with the comfort preferences of the occupants which gives rise to their usage of building system and occupancy patterns. However, the impact of these factors on the IAQ of energy efficient buildings has not been fully explored.

4) The behaviour of occupants and the nature of their activities play an essential role in determining the IAQ within the buildings. The literature elaborated on in the present study has involved occupant comfort topics along with analysing the impact of IAQ within energy efficient buildings in the presence of occupants. There is a gap in examining the critical factors contributing towards the improvement of IAQ in A-rated buildings.

5) There is no proper set of ventilation regimes and occupier guidelines handed over to homeowners, which explain the need for the provision of proper ventilation and other IAQ factors as controlled by the occupants on a time basis because excessive ventilation regimes can lead to sub-standard thermal efficiency, while ineffective ventilation can lead to persistent condensation and mould growth and poor IAQ.

6) There is no conclusive set of guidelines for designers of A-rated homes to improve the predictability of outcomes compared to actual IAQ performance based on occupant actions.

3. Methodology

3.1. Introduction

This section describes the instrumentation and methodologies which were used to complete this research. At the outset, a mind map was prepared (Figure 3.1) elucidating the structure and components of the research. The research was planned to be completed in various interdependent stages.

Figure 3.1 Mind map for the structure of research

3.1.1. Stage 1 - Pilot Study of 5 Houses

In **stage 1**, the sensors were installed in 5 houses (layout attached in Appendix A) for 6 months (August 2018 to January 2019) and a pilot study was prepared. The purpose of this initial pilot study was to get to know some families in that locality to understand their behavioural patterns. Another objective was to identify unique signature trends in temperature and humidity in rooms to decide on key aspects to analyse while replicating the study on a larger scale. This study was undertaken using a temperature (T) and relative humidity (RH) data logger called an EL-USB-2 internally (Figure 3.2) and a Tinytag externally (Figure 3.3) as they were readily available and proven to be reliable.

The pilot study yielded some insights into Indoor conditions (Appendix B) of A-rated houses in Ireland and it was established that a similar study on a larger sample could reveal meaningful and statistically significant trends in IAQ. However, the following problems were encountered pertaining primarily to data retrieval, which would have to be overcome in the project:

- Data was to be retrieved every two weeks due to proper sensitivity tampering or accidental damage, so physical presence was required at the site.
- There was unavailability of occupants during data retrieval time, even with prior appointment.
- The integrity of equipment was compromised as it was placed in accessible locations and may have been tampered with.
- Families were skeptical of outsiders entering their private space, and the chances of the sensors being misplaced were high, or they did not allow access.
- The equipment had the capability to provide only limited data pertaining to temperature and humidity, which although they are necessary indicators of IAQ, they are not sufficient.
- Any discrepancy in the working of the sensors could not be noticed until the end of the two weeks sampling period.

Figure 3.2 Internal T and RH monitor

Figure 3.3 External T and RH monitor

Based on these concerns, a remotely accessible, well secured sensor which can provide continuous data wirelessly, and thus a more holistic view of IAQ, was used in the project. This led to the adoption of LoRaWAN Sensors for the project as described later, as opposed to the equipment used in the pilot study.

3.1.2. Stage 2 – 44 Houses at Location 1

In **Stage 2**, the LoRaWAN sensors were installed in the first set comprising 44 houses (in Location 1) for a year from April 2020 to March 2021. The location has been anonymised. A methodology was developed to record IAQ data in the likely most occupied rooms in each of these houses. Data was gathered using LoRaWAN battery-operated sensors, measuring CO_2, temperature and RH, transmitting every 5 minutes to a local Things Network (TTN) gateway. From the TTN, real-time data was gathered by a software analysis tool called iSCAN provided by project partners IES. Using iSCAN, results can be generated by configurable rules using pre-packaged analyses or user-specific rules using Python scripts. However, iSCAN has some limitations in terms of presenting the data. Therefore, another analytical tool called TIBCO SPOTFIRE, was used to analyse and present such large data sets. This tool was helpful in analysing and visualising the data through advanced analytics. Most of the graphs were generated in this multi-layered software for deeper insights. An extensive Excel tables including all the preliminary calculations/analysis/information (Appendix C) were prepared to generate graphs in TIBCO SPOTFIRE.

In order to assess the IAQ in these homes, the following method steps were developed:

- Ensure data transfer integrity from sensors located in the houses to the analysis tool. For assurance, all data paths are split to allow for permanent logging of all data independent of the analysis tool.
- Establish a baseline performance limit for temperature, CO_2 and RH based on Part F of the building regulations and CIBSE Guide A. This includes the environmental parameters as listed, but also the thermal performance of these houses based on external weather parameters.

- The collected data is analysed to understand the impact of occupants on different zones of the house, specifically the influence on temperature, RH and CO_2, using regression analysis, in which each of these variables is taken as dependent. A number of important independent variables are assessed, such as the orientation of the house, occupancy, advice by the researcher, type of the house etc. The entire data is divided into four seasons to investigate the different IAQ parameters which exist during Summer, Autumn, Winter and Spring.
- Within each house, for each type of room monitored, the level of exceedances based on Part F and CIBSE Guide A are determined. In practice, data sequences are sought where any parametric exceedance period is greater than 10% of the baseline and longer than 1 hour in duration.
- Correlate these exceedances with (a) any physical parameter, such as orientation or house type and (b) family structure, occupant ages or likely occupant actions.
- Report on these analyses with a view to generating advice to the occupants on how to better control their environment to stay within healthy guidelines.
- Report on these analyses to generate advice for the house designers in making the delivery of a healthy and energy-efficient environment a realisable outcome.

3.1.3. Stage 3 – 12 Houses at Location 2

In **stage 3**, the same sensors were installed on a further set of 12 houses (Location 2) for one year. Meanwhile, the data from houses at location 1 were modelled and tested virtually to learn of its suitability in the real-life building environment. The researcher utilised a virtual environment using Integrated Environmental Solutions (IESVE) software for data modelling, including calibrating and simulating the results. Once the model was successfully constructed in the IESVE software, the simulations of the internal environment of the sample houses were performed. Once the model was calibrated with the measured data from the site, then different simulations were run to solve the issues faced by different families.

3.1.4. Stage 4 – Modelling Family Behaviour

In **Stage 4**, the robustness of the model was tested in predicting whether it had the ability to be applied to other houses in another region. Thus, a sample of 12 houses (at Location 2) were considered for testing the model using reverse modelling. Using the derived model, important variables that impact the temperature, RH and the CO_2 levels in different house zones were assessed. The aim of this analysis was to substantiate the findings made from the study of the first set of the houses at Location 1, and whether the impact of occupant behaviour in these houses is justified and predicted using stage 1 model.

3.2. Site Layouts and House Plans

The site at Location 1 contains a total of 49 houses (Figure 3.4), of which 44 homeowners agreed to allow sensor deployment and environmental monitoring. The site at Location 2 contains 37 houses, of which 12 houses homeowners agreed to allow sensor deployment. Some houses were still under construction because the finishing date had been delayed due to the pandemic.

Figure 3.4 Layout and orientation of the 44 houses in the study

3.2.1. Houses at Location 1

The development was completed in 2019 and contains a mixture of 2, 3 and 4 bedroom houses whose layouts are as shown in Figures 3.5 (a) to (c).

Given the sealed nature of these A-Rated homes (Figure 3.6), demand-controlled ventilation (DCV) is installed to provide controlled airflow and automated extraction. A four-port Aereco V4A DCV unit is installed in each attic which is ducted to the following rooms in a ceiling-mounted inlet unit. As the common fan unit is located in the attic, no noise is detectable in the living parts of the house. The ceiling inlet units are located as follows:

- 2 bed – Kitchen, downstairs toilet, main bathroom
- 3 bed – Kitchen, downstairs toilet, main bathroom, en suite
- 4 bed – Kitchen, downstairs toilet, main bathroom, en suite

The particular unit installed in each room is as follows:

- BXC273 Humidity Sensor Extract: Kitchen
- BXC275 Humidity Sensitive delayed PIR Extract: Bathroom and ensuite
- BXC299 Delayed PIR Extract: Downstairs Toilet

The V4A DCV fan unit in the attic maintains a constant pressure in the system and, therefore, the fan increases in speed if any or all ceiling vents open beyond the minimum position (12m^3/h and 65% RH). Permitted airflow can increase at each inlet unit up to 80m^3/h at 100Pa pressure, depending on the level of RH up to 100%.

3.2.2. Houses at Location 2

These houses have a similar external fabric and interior structure as that of the houses at Location 1. There is, however, one distinction, that is, the living and kitchen designed for these houses are adjoining, without any walls or partition in between. The layout plan of these houses is presented in Figure 3.7.

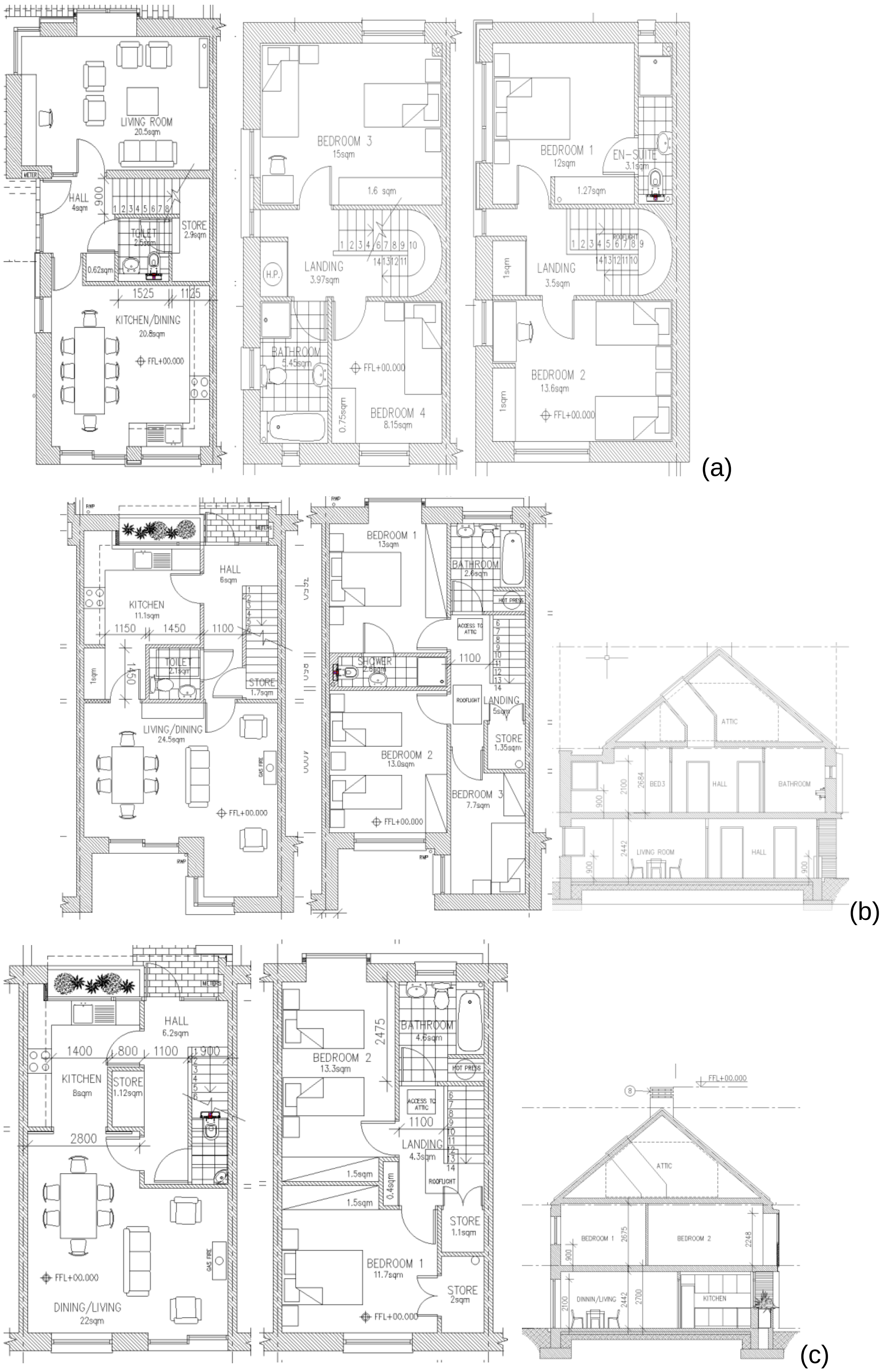


Figure 3.5 Typical plans for (a) four bedroom, (b) three bedroom and (c) two-bedroom houses in location 1

Figure 3.6 Houses at Location 1

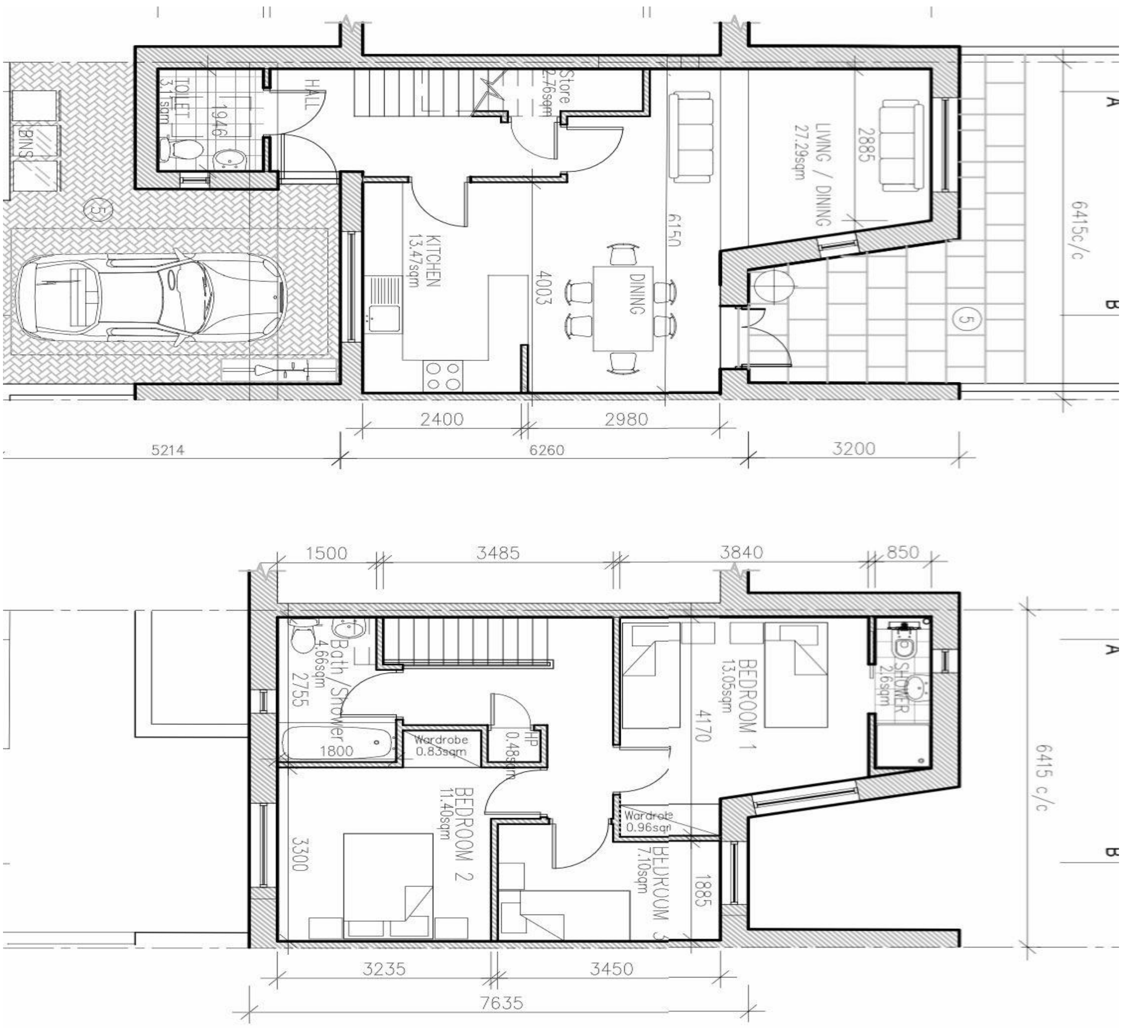


Figure 3.7 Layout of houses at Location 2

3.3. Material, Mechanical and Construction Assumptions

The following assumptions have been made in assessing the differences between any of the houses in the study:

1. Materials, glazing and construction quality are more or less uniform across the houses - U-Values are therefore as indicated in Tables 3.1 and 3.2. Wall make up and window types are explained in chapter 6.

Table 3.1 U-values of materials in the sample houses

PART L CONFORMANCE - Fabric					
Conformity with Maximum avg U-value requirements	**U-value [W/m²K]**	**Pass / Fail**	**Conformity with Maximum U-value requirements**	**U-Value [W/m²K]**	**Pass / Fail**
Pitched roof insulated on ceiling	0.11	Pass	**Roofs**	0.18	Pass
Pitched roof insulated on slope	0.00	Pass	**Walls**	0.15	Pass
Flat Roof	0.18	Pass	**Floors**	0.12	Pass
Floors with no underfloor heat	0.12	Pass	**External doors / windows / rooflights**	1.50	Pass
Floors with underfloor heat	0.00	Pass			
Walls	0.15	Pass			
Percentage of opening areas [%]	23.0	Pass			
Average U value of openings	1.40				

2. The same mechanical system is installed in each house type. This consists of a constant-pressure four port demand controlled ventilation (DCV) system (for data sheet see Appendix M) ducted to three or four room ceiling vents in both the bathrooms and kitchen. The vents are set for a particular airflow at the time of installation (a factory settings).
3. Pressure testing was carried out on each house and results were found to be within 10% of each other on an average air permeability of 1.9 $m^3/h/m^2$ at 50 Pa (Appendix D).
4. Building Energy Ratings (with BER A2) were generated, carried out by an SEAI registered energy assessor based on exactly the same material, air extraction parameters and permeability used in each house model. All that would vary in size (geometry), orientation and renewable energy system sizing. Furthermore, the author, who herself has done the BER course and training, undertook an assessment to check the rating.

5. The heating system in each house has been set up identically to allow for direct comparison between houses in mechanical heat-up rates and natural cool down rates. The heating system is supplied by a natural gas boiler which varies in size from 25kW to 38kW output depending on house size (2, 3 or 4 bedroom). The boiler feeds wall radiators which are sized depending on the room volume. Conventional controls consisting of two wall thermostats (upstairs and downstairs hallways with separate zone heating control) are in place, allowing the residents to control to an adjustable setpoint.

Table 3.2 Construction elements specifications

Element or system	**Spec.**	**Element or system**	**Spec.**
Floor	0.11 W/m^2K	Heating System Controls	Boiler Interlock and Time and Temperature Zone Control
Opaque door	1.5 W/m^2K	Hot water cylinder insulation	50mm thick foam injected
Windows and glazed doors	U=1.4 W/m^2K Double-glazed, air filled (low-E, en = 0.15, hard coat)	Secondary space heating	Electric
Thermal bridging	0.0407	Low energy light fittings	100% low e lighting
Ventilation strategy and Air Permeability ($m^3/hr.m^2$)	1.93 $m^3/hr.m^2$	Renewable Energy Source	1.77 kWp PV Panels
Minimum intermittent extract rate	15.06 l/s	Primary energy ($kwh/m^2/yr$)	48.4
Primary heating fuel (space and water)	Mains gas	CO_2 emissions ($kg/m^2/yr$)	8.7
Heat generator	90.2% efficiency	EPC	0.29
		CPC	0.26
Secondary Heating	Electric		Not being used

3.4. Ventilation Measures

3.4.1. Demand Controlled Ventilation (DCV)

Ventilation is provided to these homes by way of a combination of passive window frame-mounted trickle vents in the living room and bedrooms and DCV centrally extracting from high humidity areas, namely the ensuite, main bathroom and kitchen. The mechanical extract fans (see data sheet in Appendix M) are remotely triggered from the measurement points in bathrooms and the kitchen based on relative humidity (with a 65% RH set point). The extract operates as a variable speed fan which effectively alters the number of air-changes per hour (ACH) in each space.

3.4.2. Trickle Vent Windows

Windows in every house type are fitted with Aereco trickle vents (EHM1276 Humidity Sensitive Air Inlet) (Figure 3.8), but only in rooms which do not have a ceiling extract, that is, the bathrooms and kitchen. Manually, these vents can be "closed" (meaning they are 10% open), "opened completely" (meaning 100% open) or put in Auto mode where the measured RH varies the opening to give minimum airflow below 65% RH to maximum airflow at 100% RH. Airflow rates range from 5-35m^3/h, depending also on the external airflow direction and speed (datasheet in Appendix M).

Figure 3.8 Aereco air inlets in windows

3.5. IAQ Sensor Equipment Configuration

3.5.1. USB data logger and Tinytag

At the beginning of the project, it was decided to initially use a temperature (T) and relative humidity (RH) data loggers, called an EL-USB-2 (Figure 3.2), as they were readily available and proven to be reliable. This data logger, which is manufactured by Omega Engineering, uses calibrated internal sensors which measure temperature and RH in the range -35 ℃ to +80 ℃ and 0 to 100% RH. The accuracy of the data loggers is ±0.3 ℃, ±2.0% RH with a resolution of 0.5 ℃ and 0.5% RH, respectively. These wireless units can store up to 16,000 readings with a battery life of 3 months (depending on frequency and recording), requiring no accessories and are light and small.

A Tinytag TGP-4510 data logger (Figure 3.3) which is a rugged outdoor T and RH monitor, was used for external readings. This logger, like the USB-2, is independently powered with a battery. It can also be set to log readings at various times and with adjustable start and stop times. The unit requires Tinytag software to be downloaded to a laptop whereupon the results can then be displayed on an Excel spreadsheet. The unit does not need to be fixed to a building and is small enough to be unobtrusive.

3.5.2. LoRaWAN Sensors - ERS-CO_2

Each of the houses was equipped with 5 Lora wireless sensors (data sheet in Appendix M) connecting to an external LoraWAN gateway. The sensor to gateway communications pathway is capable of traversing approximately 10 concrete walls up to a maximum of approximately 8km, where the signal-to-noise ratio diminishes the more walls that are transmitted through. This signal strength is monitored in each data packet and sent from sensor to gateway. The general network architecture is shown in Figure 3.9.

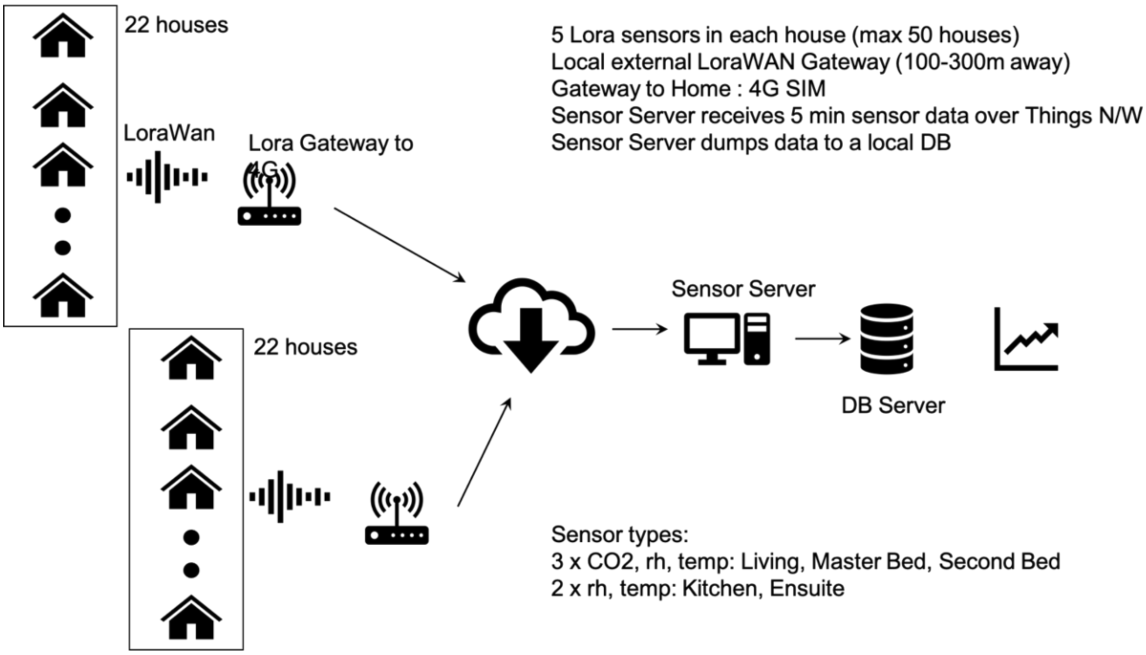


Figure 3.9 Schematic of the LoraWAN gateway system for data collection (Source: Shiel et al., 2021)

Of the five Lora IoT sensors installed, three (living room, master bedroom and second bedroom) have the capability of measuring and reporting temperature, RH, CO_2, occupancy and lux level. The remaining two sensors measure temperature and relative humidity only in the bathroom and en suite. Sensor specifications are quoted as:

- Accuracy: ± 0.5 °C, ±2% RH, ±30 ppm CO_2
- Resolution: 0.1 °C, 0.1% RH
- Range: 8km in free space or SNR reduction of -9db per 200mm concrete wall (they will operate down to approx. -130db)
- Battery: 2 x 3.6V AA lithium batteries giving approx. 10 years lifetime at 5-min. measurement interval

The sensors are connected to the provided local LoraWAN gateway located at an external pole-mounted location and provide coverage for all 220 sensors installed at location 1. Data is extracted and proactively managed in a cloud based LoraWAN Network Server and is downlinked to IES SCAN, a building modelling software analysis tool located in IES and TCD. Outside environmental conditions are also monitored using a local full-scale laboratory-grade weather station (see Section 3.6.5) provided as part of this project.

3.5.3. Data Structure

Sensors are configured to report data every 5 minutes, giving an approximate 10-year battery lifetime. That lifetime will depend in part on the distance between the sensor and gateway but also the number of solid obstacles between them. This level of quality in data reception can be monitored continuously from the attached data payload and envelope surrounding each data packet, as shown in Table 3.3.

In a typical short message from the sensor, the encrypted payload contains the sensor-specific data of environmental parameter measurements, including temperature, RH, CO_2, occupancy, lux level and remaining battery life. The received signal strength indicator (RSSI) can drop to approximately -130db before signal dropout occurs.

Table 3.3 Data payload for each Lora sensor


```json
{
  "gw_id": "trinity-college-ds1-015639",
  "payload": "QJRpASaA4yYFGGH3ksyrrf8HcCHfD2zN+PrOTQ8=",
  "f_cnt": 9955,
  "lora": {
    "spreading_factor": 11,
    "bandwidth": 125,
    "air_time": 905216000
  },
  "coding_rate": "4/5",
  "timestamp": "2021-01-11T10:06:10.120Z",
  "rssi": -109,
  "snr": -7.75,
  "dev_addr": "26016994",
  "frequency": 867300000
}
```


A rule of thumb suggests that signal strength will drop by about -10db for each 200mm concrete wall the signal passes through (or the metal film on a modern double or triple glazed coated window). Signal to noise ratio (SNR) is also monitored to detect interference levels. The value of SNR is usually negative in Lora communications since demodulation occurs between -7.5db and -20db confirming that Lora operates below the noise floor. For EU compliant installations, such as this project, the transmission frequency operates within a narrow 7MHz band from 863Mhz to 870MHz. There are designated sub-bands within that window comprising 48 channels, allowing multiple simultaneous transmissions to occur to each gateway.

3.5.4. Batteries and Calibration

Before installing the sensors, 2 x 3.6V AA lithium batteries giving approximately 10 years lifetime, were inserted in all 285 sensors using a screwdriver (Figure 3.10). Sensors were hung on the ceiling (Location 1) and on walls (Location 2), using Command interlocking picture hanging strips (Figure 3.11).

Figure 3.10 Inserting batteries in sensors

Figure 3.11 Strip tape for hanging sensors (black circle)

The final step to set up the sensors was to use an Android application running on a phone that had Near-Field Communications and set up a unique user id for each sensor to identify which sensor was which in the logged data.

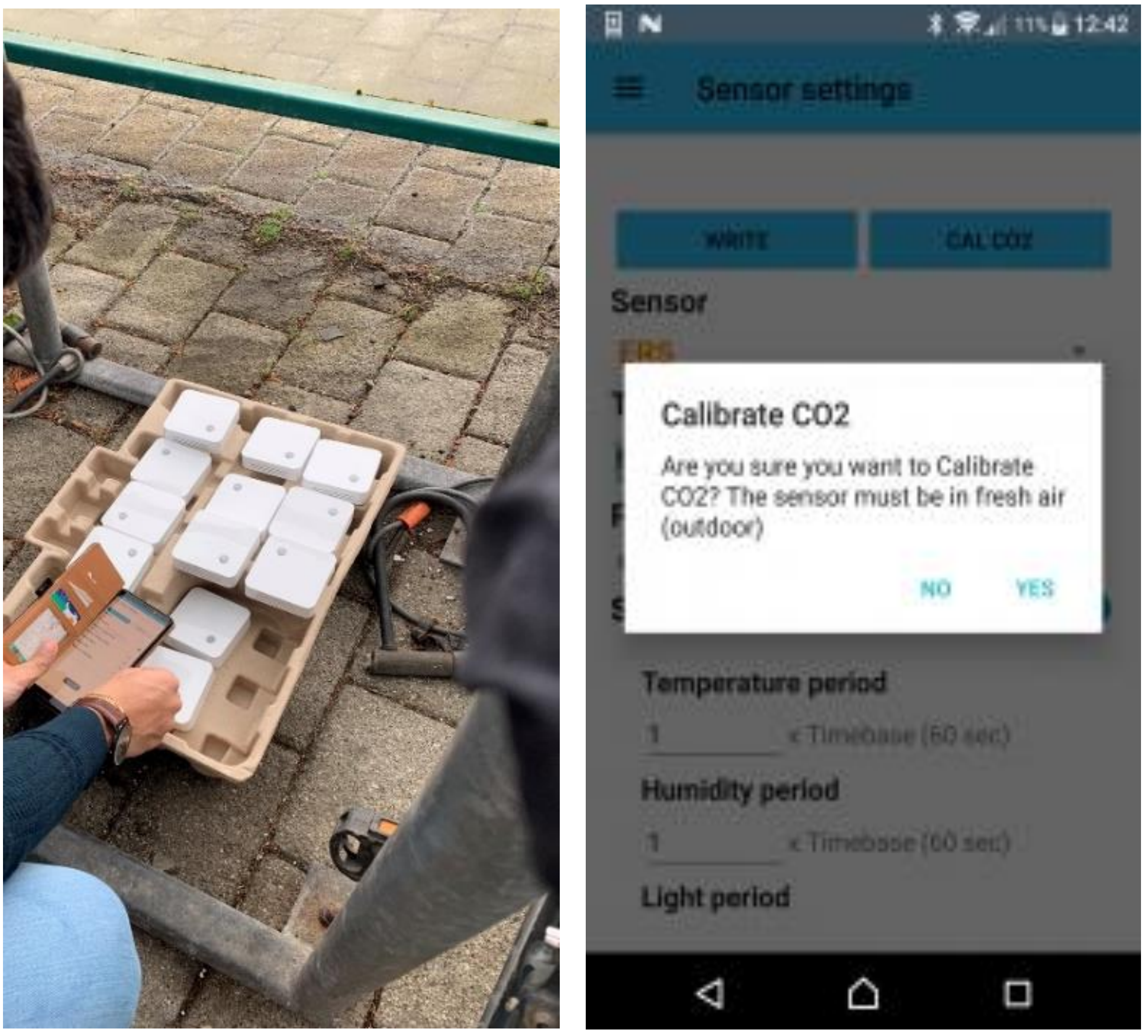


Figure 3.12 Calibrating sensors

Sensors were calibrated by placing in fresh air for some time (10-20 minutes) and then calibrated (Figure 3.12). These sensors can reset internal filters and reference values. Sensors also have an automatic background calibration of the CO_2, so it auto-calibrates the sensor over time. It is normal to do a recalibration after 6 months or at the end of a project. However, due to COVID restrictions this was not possible during the project. As such, it has been assumed that the data collected from all sensors was not impacted by drift and that the auto-calibration to background concentrations minimised any possible erroneous data.

3.5.5. External weather data

A weather station was installed near the site office to measure the external temperature, humidity, precipitation and sunlight (Figure 3.13). Weather data is used to get the baseline external readings which were used for IAQ analysis as well as for IESVE modelling. Rather than using the inbuilt data from the software, measured data from the weather station was uploaded into IESVE software to run the simulations.

Figure 3.13 External weather station

3.5.6. Sensor Placement

The location of the sensors (Figure 3.14) is shown schematically in Figure 3.15. Measurements have been taken over a full 24-month period (April 2019 to March 2021).

Figure 3.14 Sensor Placement

Figure 3.15 Drawing indicating the locations of the five sensors provided in each typical house

As per IET Code of Practice (2016) guide for Connected Systems Integration in Buildings, there are three vital considerations for the location of sensors which should:

- Minimise the risk of accidental damage
- Allow for easy access for battery replacement or wiring positions
- Allow for sufficient protection from malicious damage or interference.

All these parameters were considered while deciding the position of sensors in a house. Sensors were placed in areas of high occupancy, expected high CO_2 and/or high RH and not near door/window or radiator. At Location 1, sensors were placed high up on the ceiling to avoid any damage or interference. There is a blinking light in all sensors, which blinks every 5 minutes. Some residents felt disturbed with this light during night because it was right above their bed. Later it was decided to put sensors on a wall rather than the ceiling (location 2) to avoid any disturbance.

The objective of placing the sensors was to determine:

- The detection of moisture flow by air movement or diffusion from areas of high to low RH, such as a bathroom or en suite
- The rates at which both RH and CO_2 built up due to occupant activity in designated spaces
- The rate at which RH dissipates and the rates of diffusion and dissipation of CO_2 to adjoining spaces

The diffusion and dissipation rates would clearly differ from season to season, and, for this reason, the Summer period provided a baseline, and the Winter heating period was of particular interest for IAQ.

3.5.7. IESVE software

The researcher utilised “virtual environment by Integrated Environmental Solutions” (IESVE) software for data modelling, including calibrating and simulating the results. IESVE is a software package that contains several integrated tools for analysis, which can efficiently facilitate thermal condition, RH and CO_2 modelling in buildings, as well as having the potential to perform value engineering, cost planning, lighting assessment and lifecycle analysis (IES, 2012; 2015). A building’s performance can be assessed using this software from a retrospective perspective, or when considering design decisions.

The model produced within the software is well-integrated with a common user interface and a single integrated data model. Some of the applications offered by the software, which will be used for the present research, include *ModelIT*, *Apache* and *Vista*. *ModelIT* is the component of the software which allows the development of 3D models (IES, 2015). *Apache* is used to conduct thermal analysis, based on thermal input data and helps in further calculating, analysing and simulating the thermal response within a building to the various stimuli. *Vista* is utilised for performing the dynamic thermal simulations, as well as for viewing the results thereafter.

Two additional components of the IESVE software, namely *SunCast* and *MacroFlo*, were used for modelling the environmental conditions (IES, 2012). With the help of *SunCast*, investigations into external construction, self-shading of buildings, solar mapping using windows and other openings in the building and the influence of building orientation can be assessed. It provides the data on shadows and internal solar insolation from any position of the sun, and provides detailed data including date, time, latitude and longitude of the building and its orientation. *MacroFlo*, on the other hand, is used for evaluating information about infiltration and natural ventilation in the buildings. This component embeds a zonal airflow model, which computes the air movement in bulk and accounts for the air movements within and through the buildings, by considering the air pressures induced by wind and buoyancy.

3.6. Summary

A description of the equipment and methods that define this research has been presented in this chapter. A summary of the various stages describing the steps used in the research is presented in Section 3.1. The layout and construction/thermal properties of the houses are described in Section 3.2 and 3.3. Lastly, an overview of the various equipment and software used in this work is outlined in Sections 3.4-3.5.

4. Analysis of Parameters affecting IAQ

The aim of this chapter is to investigate a set of A-rated homes with different orientations, house types, family profiles and their influence on the internal environmental quality. One of the objectives of this study was to establish patterns of usage for each home leading to adverse IAQ through interpretation of gathered data.

4.1. Introduction

This study included data from 44 high-performance A2-Rated domestic buildings in Ireland. The buildings have been completed to a high standard in both materials and construction quality. They are laid out as two or three storey homes in the same geographical area and are of varying size (2, 3 and 4 bedrooms) and orientation. They are owned and occupied by families whose make-up varies from 1 adult up to 2 adults with 4 children. The houses are deemed to be in full compliance with the ventilation requirements under *Part F – Ventilation (*TGD Part -F, 2009) and the energy efficiency/materials requirements under *Part L – Energy Conservation of Fuel and Energy* (TGDL, 2011; 2017 amendments) *(Appendix E)*. The layout and orientation of the buildings have been presented in the previous chapter. Data has been collected over one year, which includes temperature, RH and CO_2 levels for commonly used rooms in each house. The five rooms selected were the master bedroom and adjoining en suite, second bedroom, living room and kitchen. The intention was to give a representative spread of data measurement over the areas of the homes most likely to be occupied for long periods and thus most likely to experience high humidity and/or high CO_2 levels.

Furthermore, the details of the houses considered for the analyses, including the house reference numbers (used to keep them anonymised), number of bedrooms in each house, orientation, household occupancy, descriptions of the occupants (number of people description), and average weekday and weekend occupancy in each house are given in Table 4.1. The orientations of the houses vary from North Orientation (NO), South Orientation (SO), East Orientation (EO), Northwest (NW), Northeast (NE), and Southwest (SW). There have been a number of documented similar studies on a small number of houses (Brandao et al., 2021; Fabbri et al., 2015; Liang et al., 2017b), but one unique aspect of this study is the large number of houses (56), which are monitored and analysed. It is advantageous that the houses have the same construction and heating/ventilation systems as this eliminates the other causes of differences in IAQ, leaving causes due to occupancy, use and user behaviour which, as shall be observed, will give rise to indoor conditions which vary unduly based on human behaviour.

Table 4.1 Description of the houses and family profiles

H.Ref.	No. of beds	Heat pump	Orientation	Household occupancy	Household description (age)	Average weekday occupancy	Average weekend occupancy
A1-SW3E5	3 Bed End	No	SW	5	couple with 3 children	24 Hours	17:00 - 09:00
A2-SW3M3	3 Bed Int	No	SW	3	couple with a single child	17:00 - 09:00	24 Hours
A3-SW3M4	3 Bed Int	No	SW	4	couple with 2 children	17:00 - 09:00	24 Hours
A4-SW3E2	3 Bed End	No	SW	2	couple	17:00 - 08:00	24 Hours
B1-NE3E2	3 Bed End	No	NE	2	couple	17:00 - 09:00	24 Hours
B2-NE3M3	3 Bed Int	No	NE	3	couple with one child	17:00 - 09:00	24 Hours
B3-NE2M1	2 Bed Int	No	NE	1	single occupant	17:00 - 08:00	24 Hours
B4-NE2E1	2 Bed End	No	NE	1	single occupant	17:00 - 08:00	24 Hours
C1-N4E3	4 Bed End	Yes	N	3	couple with one child	24 Hours	24 Hours
C2-N3M1	3 Bed Int	No	N	1	single occupant	17:00 - 08:00	17:00 - 08:00
C3-N3M2	3 Bed Int	No	N	2	two adults	14:00 - 08:00	14:00 - 08:00
C4-N3M3	3 Bed Int	No	N	3	couple with on echild	24 Hours	24 Hours
C5-N3M3	3 Bed Int	No	N	3	three adults	17:00 - 08:00	24 Hours
D1-NW4D5	4 Bed Det	Yes	NW	5	couple with 3 children	17:00 - 08:00	17:00 - 09:00
E1-S4E5	4 Bed End	No	S	5	couple with 3 children	24 Hours	17:00 - 09:00
E2-S3M1	3 Bed Int	No	S	1	single occupant	24 Hours	24 Hours
E3-S3M5	3 Bed Int	No	S	5	couple with 3 children	24 Hours	17:00 - 09:00
E4-S3M4	3 Bed Int	No	S	4	couple with 2 children	24 Hours	24 Hours
E5-S3M5	3 Bed Int	No	S	5	couple with 3 children	17:00 - 09:00	24 Hours
E6-S3M4	3 Bed Int	No	S	4	couple with 2 children	24 Hours	24 Hours
E7-S3M2	3 Bed Int	No	S	2	two adults	17:00 - 08:00	16:00 - 11:00
E8-S3M4	3 Bed Int	No	S	4	couple with 2 children	17:00 - 09:00	17:00 - 09:00
E9-S3M3	3 Bed Int	No	S	3	couple with single child	17:00 - 09:00	24 Hours
E10-S3M4	3 Bed Int	No	S	4	couple with 2 children	17:00 - 08:00	24 Hours
E11-S3E1	3 Bed End	No	S	1	single occupant	17:00 - 09:00	24 Hours
E12-S4E2	4 Bed End	No	S	2	couple	17:00 - 08:00	21 Hours
F1-E3M4	3 Bed Int	No	E	4	couple with 2 children	24 Hours	24 Hours
F2-E3M3	3 Bed Int	No	E	3	couple with a	24 Hours	24 Hours
F3-E3M5	3 Bed Int	No	E	5	couple with 3 children	14:00 - 08:00	17:00 - 09:00
F4-E3M2	3 Bed Int	No	E	2	couple	17:00 - 08:00	18 Hours
F5-E3M2	3 Bed Int	No	E	2	couple	17:30 - 05:00	24 Hours
F6-E4E2	4 Bed End	Yes	E	2	couple	17:00 - 09:00	24 Hours
G1-N3E4	3 Bed End	No	N	4	couple with 2 children	17:00 - 09:00	24 Hours
G2-N3M2	3 Bed Int	No	N	2	couple	17:00 - 09:00	17:00 - 09:00
G3-N3M4	3 Bed Int	No	N	4	couple with 2 children	17:00 - 09:00	MISSING
G4-N3M2	3 Bed Int	No	N	2	couple	17:00 - 08:00	24 Hours
G5-N3M5	3 Bed Int	No	N	5	5 adults	24 Hours	17:00 - 08:00
G6-N3M3	3 Bed Int	No	N	3	couple with a	MISSING	17:00 - 08:00
G7-N3M2	3 Bed Int	No	N	2	couple	17:00 - 08:00	17:00 - 09:00
G8-N3M3	3 Bed Int	No	N	3	couple with a	17:00 - 08:00	17:00 - 08:00
G9-N3M3	3 Bed Int	No	N	3	couple with child	24 Hours	24 Hours
G10-N3M1	3 Bed Int	No	N	1	single occupant	17:00 - 08:00	24 Hours
G11-N3M3	3 Bed Int	No	N	3	couple with a	17:00 - 08:00	24 Hours
G12-N4E2	4 Bed End	No	N	2	couple	17:00 - 09:00	17:00 - 09:00

Table 4.1 shows that the houses considered range between 3 bedroom and 4 bedrooms, with heat pumps installed in only three (4 Bed End Terrace) houses out of 44. The number of occupants in the houses also ranges from 1 to 5 people. The occupants' profiles in these houses comprise families with a single occupant, couple, couple with one, two, or three children. Finally, the average weekday and weekend occupancy show that the dwellings are mostly occupied for either 24 hours a day, or 17:00 to 9:00 hours, or 17:00 to 8:00 hours, or 14:00 to 8:00 hours.

4.2. General Data Analysis

The data analysis pertains to the overall evaluation of 44 houses at Location 1, which are assessed using the data acquired over the course of one year. While one year of data was collected, selected portions of this data was focussed on, in this project to highlight the key areas of interest. The entire data is divided into four seasons to investigate the different IAQ parameters for Winter, Spring, Summer and Autumn. There is varying weather in Ireland in each month of a season because weather in Ireland is highly unpredictable between seasons. One month is chosen for each season on the basis of representing that season: January is taken to represent Winter, March to represent Spring, July for Summer and November to represent Autumn. It is recognised that the other month may have slightly different data within their season but not substantially so.

The three key variables to test the houses' IAQ are the levels of CO_2 (in PPM), relative humidity (RH in %) and temperature (T in °C) during different seasons and times of the day, broken down into morning, mid-day, evening and night.

Outliers from data were removed using the interquartile range (IQR) method The IQR is the central 50% or the data which lies between the 75th and the 25th percentile of a distribution. A data point is an outlier if it is above the 75th or below the 25th percentile by a factor of 1.5 times the IQR. For example, if Q1= 25th percentile and Q3= 75th percentile then, IQR= Q3 – Q1 and an outlier would be a point below [Q1- (1.5) IQR] or above [Q3+(1.5)IQR]. A detailed descriptive summary of results is presented in Appendix F.

4.2.1. General data analysis for different seasons

The general data for the four seasons are analysed in this section:

Summer

Table 4.2 shows the average temperature, RH and CO_2 levels with the standard deviation (±) and coefficient of variance (CV), for the five key areas in the houses in Summer. It can be observed that the highest average temperature existed in the kitchen and master bedroom at 21.8^{o}C, while the minimum average temperature was in the living room at 21.3^{o}C, although they are very similar. This suggests that all rooms of the house have very similar temperatures despite the different room orientations and the houses are not cold in summer on average.

Similarly, the maximum average relative humidity was noted in the en suite at 58%, while the average humidity for the rest of the areas was identical – these are within experimental error and so can be considered as not significantly different. However, the results suggest that the moisture generated in some rooms dissipate well throughout the house. Finally, the average CO_2 levels were observed to be highest in the master bedroom at 785 ppm, while the lowest levels were found to be in the kitchen at 596 ppm. The CO_2 values reflect occupancy levels with closed doors as CO_2 is anthropogenic. It can also be observed that there is not much difference in temperature, which can be attributed to the fact that the houses are well-insulated. Higher coefficient of variance (CV) in some cases show the level of dispersion around the mean. For instance, in master bedroom, there is 52% variation around the average value of CO_2. Temperature values seem to be less dispersed because CO_2 has more variation than temperature in different zones.

Similarly, no major issues exist with the average RH. The CO_2 is higher in bedrooms, which can be due to higher time spent there, and it is least in kitchen probably as it is occupied for a short time period on average. CIBSE guide A suggests an average temperature between 20 and 22^{o}C in Winter and 23 and 25^{o}C in Summer for living room and between 17 and 19^{o}C average in Winter and 23 and 25^{o}C in Summer for bedrooms. The relative humidity should, on average, typically be between 40 and 50%, but any values below 60% are usually deemed acceptable. For CO_2, below

1,000 parts per million (ppm) is quite normal, while up to 1,500 ppm can make less alert, and above 1500 ppm can have an effect on energy and concentration levels.

Table 4.2 Average temperature, RH and CO_2 levels for 44 houses in Summer

Average of all 44 houses						
	T °C		**RH %**		**CO_2 ppm**	
	Mean (SD)	**CV**	**Mean (SD)**	**CV**	**Mean (SD)**	**CV**
Living Room	21.3 (± 1)	4.4	56 (± 5.1)	8.8	632 (± 214)	35.4
Kitchen	21.8 (± 1.1)	4.5	56 (± 5.5)	9.5	596 (± 180)	31.4
En suite	21.5 (± 1.1)	4.5	58 (± 7)	11.9	-	-
Master Bed	21.8 (± 1.2)	5.2	56 (± 5.7)	10.2	785 (± 368)	46.8
Second Bed	21.5 (± 1)	4.4	56 (± 5.5)	9.9	738 (±390)	52.8

Winter

Table 4.3 shows that during the Winter season, the second bedroom experienced the lowest average temperature at 18.9°C, and the kitchen experienced the highest average temperate at 20.4°C. Similarly, the lowest average relative humidity was found in the kitchen, and it was highest in the en suite. Finally, the average levels of CO_2 were lowest in the kitchen at 658 ppm, and the highest in the master bedroom at 858 ppm. The temperature differences were not high though marginally lower than the summer due to lower outside temperatures, indicating again that houses are well-insulated.

Similarly, the average CO_2 in the master bedroom was highest (858 ppm), indicating that it is occupied for more time without proper ventilation, while it was least in kitchen (658 ppm) due to the lesser time spent there. The CO_2 levels in winter are slightly higher, plausibly due to less ventilation to outside. There is no dining space in the kitchen of these houses, so the average time spent in the kitchen is much less than might otherwise be. Also, it should be noted that the houses were about 2°C colder in the Winter on average, compared to the Summer.

Table 4.3 Average temperature, RH and CO_2 levels for 44 houses in Winter

Average of all 44 houses						
	T °C		RH %		CO_2 ppm	
	Mean (SD)	**CV**	**Mean (SD)**	**CV**	**Mean (SD)**	**CV**
Living Room	19.8 (±1.9)	9.8	52 (±7.1)	13.8	710 (±303)	42.7
Kitchen	20.4 (±2.1)	10.3	51 (±7.2)	14	658 (±255)	38.7
En suite	19.4 (±2.5)	12.7	57 (±9.9)	17.3	-	-
Master Bed	19.0 (±2.2)	11.6	56 (±7)	12.6	858 (±437)	50.9
Second Bed	18.9 (±3.1)	16.4	54 (±7)	12.9	781 (±451)	57.8

Autumn

Table 4.4 shows that during the Autumn, the second bedroom experienced the lowest average temperature at 19.2°C, and the kitchen experienced the highest average temperature at 20.4°C. Similarly, the lowest average RH was found to be in the kitchen at 53% and the highest in the en suite at 58%. Finally, the average levels of CO_2 were lowest in the kitchen at 673 ppm, and the highest in the master bedroom at 881 ppm. The difference across these house zones may be attributed to the way they are occupied and used by the occupants. This will be discussed in detail in next chapter.

Table 4.4 Average temperature, RH and CO_2 levels for 44 houses in Autumn

Average of all 44 houses						
	T °C		RH %		CO_2 ppm	
	Mean (SD)	**CV**	**Mean (SD)**	**CV**	**Mean (SD)**	**CV**
Living Room	20.0 (±2.2)	10.9	53(±7.3)	13.6	697 (±296)	42.5
Kitchen	20.4 (±2.3)	11.3	53 (±7.3)	13.9	673 (±266)	39.5
En suite	19.3 (±2.6)	13.4	58 (±9.1)	15.8	-	-
Master Bed	19.3 (±2.4)	12.6	57 (±7.1)	12.5	881 (±692)	78.6
Second Bed	19.2 (±2.3)	11.9	56 (±6.6)	11.9	836 (±518)	61.9

Spring

Table 4.5 shows that during the Spring, the second bedroom experienced the lowest average temperature at 19.3ºC, and the kitchen experienced the highest average temperature at 20.6ºC. Similarly, the lowest average relative humidity was found in the kitchen at 48% and the highest in en suite at 53%. Finally, the average levels of CO_2 were lowest in the kitchen at 694 ppm, and the highest in the master bedroom at 949 ppm.

Table 4.5 Average temperature, RH and CO_2 levels for 44 houses in Spring

Average of all 44 houses						
	T ºC		**RH %**		**CO_2 ppm**	
	Mean (SD)	**CV**	**Mean (SD)**	**CV**	**Mean (SD)**	**CV**
Living Room	20.1 (±1.8)	9	49 (±7)	14.4	753 (±318)	42.2
Kitchen	20.6 (±1.9)	9.5	48 (±7.2)	14.8	694 (±263)	37.9
en suite	19.7 (±2.4)	12.2	53 (±9.8)	18.4	-	-
Master Bed	19.5 (±2.2)	11.2	52 (±7.4)	14.2	949 (±568)	59.8
Second Bed	19.3 (±1.8)	9.6	51 (±6.6)	12.9	834 (±456)	54.6

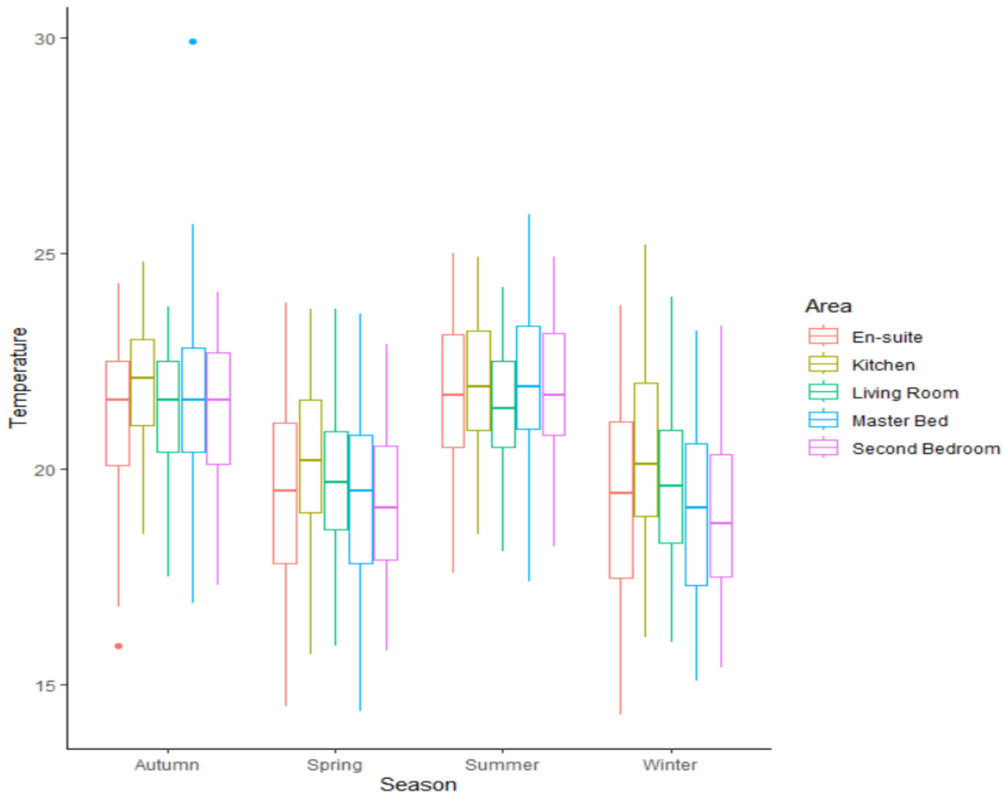
Season comparison

It is evident that the insulation and airtightness are such that there is little difference between the seasons, on average, though some differences do exist.

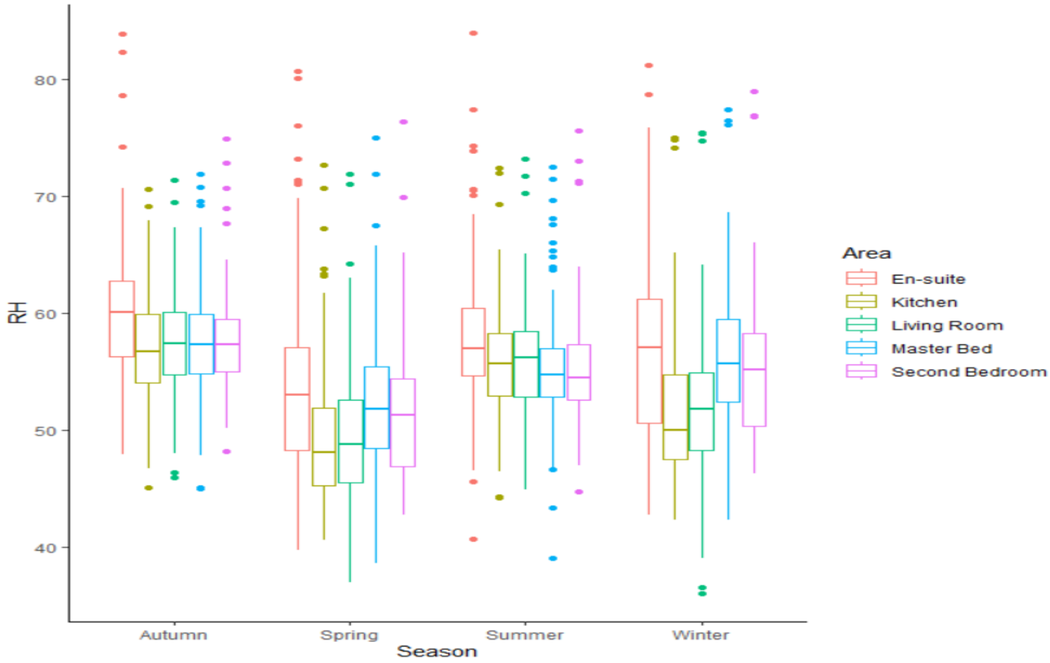
The analysis in Figure 4.1 shows that the three variables vary somewhat among the different zones of the houses, and also vary among different seasons. It can be observed that there is not much difference in temperature and RH, which can be attributed to the fact that the houses are well-insulated, evenly heated and doors are left open at certain times of the day. The CO_2 is higher in the bedrooms, which can be due to the higher time spent there and is least in the kitchen as it is occupied for a shorter time period. For instance, from Tables 4.2 - 4.6 and Figure 4.1 (a) to (c), it can be observed that the average temperatures and RHs are generally similar during Winter, Spring and Autumn, but somewhat higher in Summer. This may be due to the fact that the solar gain (or higher external ambient temperatures) in

Summer helps to make the houses warmer. In contrast, during the other seasons, solar gain is lesser, and due to the lower outside temperatures, indoor temperatures become more dependent on the application of heating, which depends somewhat on occupancy. In contrast, the CO_2 levels are higher during the Autumn and Winter and are the lowest in the Spring.

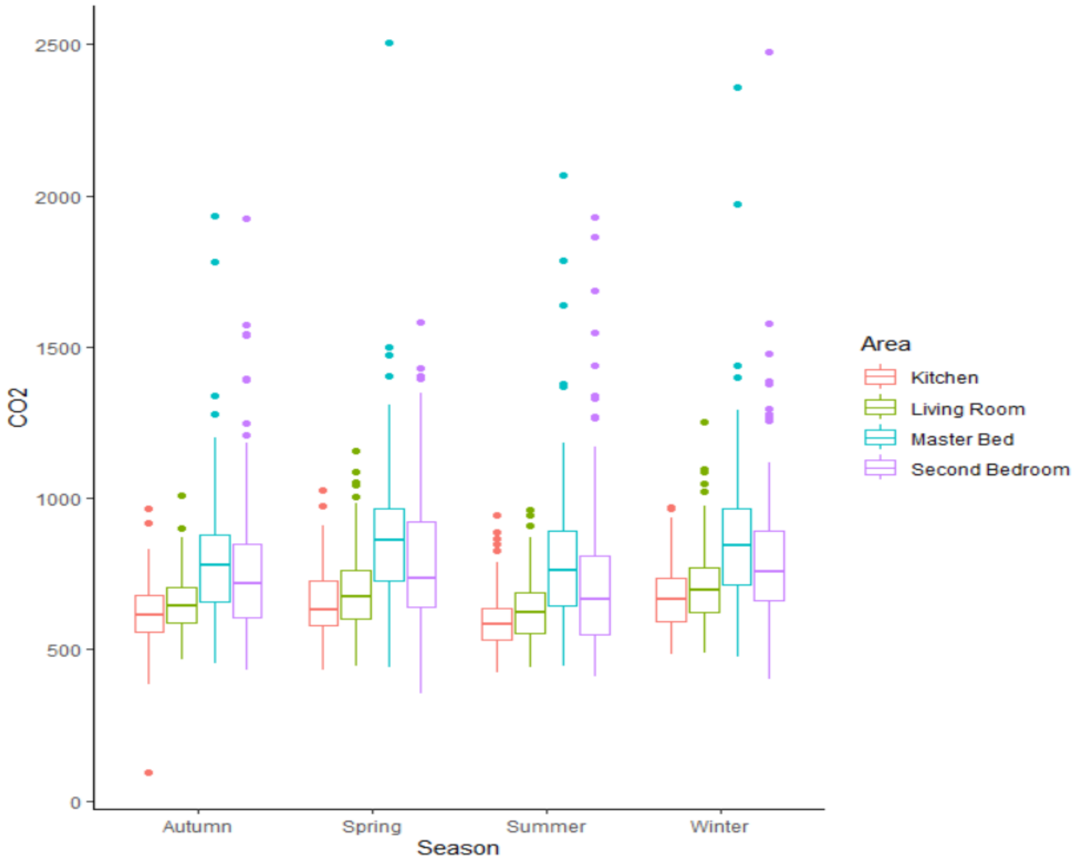
It is also observed that there are differences with respect to the average lowest and highest values in each of these variables across the house zones. For instance, the average temperature during Summer was lowest in the living room (perhaps due to open windows), but in Winter and Autumn, the second bedroom experienced the lowest temperature (perhaps due to lesser heating). Similarly, the highest temperature across all seasons except Spring was found in the kitchen (in Spring, the highest average temperature was experienced by the master bedroom, but the variation is negligible). These differences are owing to the behaviour and zone usage patterns of the occupants: for instance, the kitchen generally encompasses a high temperature due to the heat produced by cooking activities.



(a)



(b)



(c)

Figure 4.1 (a), (b), (c) Overall summary of average temperature, RH and CO_2 levels for 44 houses in all seasons

The RHs also showed slightly different highest and lowest values across the four seasons and, thus, there is a need to understand the reason for this and to understand whether these differences are due to the outdoor environment or indoor occupancy behaviour. Finally, the CO_2 levels were noted lowest in the kitchen for all four seasons, but the highest CO_2 showed some variations. It shows that the time spent by the occupants in the kitchen is much lesser due to the separate dining area and does not lead to the accumulation of CO_2. Furthermore, of all rooms monitored, the master bedroom experienced the highest average CO_2 levels during all four seasons due to higher occupancy. It shows that the living patterns of the occupants changes according to the season, and needs further analysis.

4.2.2. General data analysis for different times of the day

This section will discuss the average temperature, RH and CO_2 levels across the four seasons in all five house zones for different times of the day. The day is divided into four quadrants, namely morning (6am to 10am), mid-day (10am to 5pm), evening (5pm to 12 midnight) and night-time (12 midnight to 6am) so that data can be analysed based on different time intervals. The analysis of this data will help understand the living and occupancy pattern of the occupants, and how different activities performed during different times of the day influence the IAQ variables. For instance, night time data can provide non-occupied baseline data for living rooms and day time data will give the baseline when most of the occupants are not using their bedrooms. It is assumed that most of the occupants go to bed before 12 midnight and start their morning activities after 6 am. The summaries for these data sets are given hereunder:

Morning Time

Table 4.6 shows that the average temperature, relative humidity and CO_2 levels vary to some degree across different zones in the house and in different seasons in the morning. It is found that the minimum average temperature in morning is measured in the second bedroom during Winter at 18.8^{o}C, which could be due to the external temperature, orientation, occupancy or low solar gain, while the highest average is in master bedroom during Summer at 23.5^{o}C, possibly due to solar gain/orientation.

Table 4.6 Average temperature, RH and CO_2 levels for 44 houses for all seasons in morning time

Morning Time		T °C (SD)	RH % (SD)	CO_2 ppm (SD)
Summer	Living Room	22.7 (±1)	59 (±4.7)	571 (±172)
	Kitchen	23.2 (±0.9)	58 (4.9)	554 (±149)
	En suite	23.3 (±1)	59 (±7.3)	-
	Master Bed	23.5 (±1.3)	57 (±5.6)	770 (±405)
	Second bed	23.2 (±4.5)	57 (±5.3)	754 (±405)
Winter	Living Room	19.4 (±1.8)	51 (±6.9)	584 (±175)
	Kitchen	20.1 (±2)	51 (±6.8)	582 (±171)
	En suite	19.3 (±2.4)	57 (±10)	-
	Master Bed	19.0 (±2.1)	57 (±7.1)	969 (±473)
	Second bed	18.8 (±1.9)	55 (±7.6)	873 (±546)
Autumn	Living Room	19.5 (±2)	53 (±7)	596 (±189)
	Kitchen	20.1 (±2.3)	52 (±7)	614 (±198)
	En suite	19.2 (±2.5)	58 (±9.3)	-
	Master Bed	19.1 (±2.4)	58 (±7)	1022 (±615)
	Second bed	18.9 (±2.1)	57 (±6.9)	940 (±596)
Spring	Living Room	20.2 (±1.4)	49 (±4.7)	618 (±214)
	Kitchen	20.5 (±1.8)	49 (±5.9)	582 (±167)
	En suite	20.3 (±1.9)	52 (±8.6)	-
	Master Bed	20.1 (±1.7)	52 (±7.2)	891 (±484
	Second bed	19.9 (±1.6)	50 (±5.8)	773 (±390)

Similarly, the level of RH varies considerably across different zones and seasons in the same set of houses during the morning. It is found that the minimum average RH was present in the kitchen in the Spring at 48.6%, while the highest average was in the en suite in Summer at 59%, which is not surprising because showering leads to an accumulation of RH in the en suite, and is only dissipated by the extract fan or open internal doors after sometime.

The levels of CO_2 also vary, and exist least in kitchen during Summers at an average of 554 ppm, perhaps due to low occupancy or windows being opened, and the highest in the master bedroom in Autumn, and surprisingly not the winter, at an average value of 1022 ppm.

These values reflect the pattern of occupancy which affect the IAQ variables of temperature, RH and CO_2. It shows that during Summer, the CO_2 is least as the people tend to open their windows, which prevents the accumulation of CO_2. In contrast, in Autumn and Winter season, high CO_2 is possibly due to their behavioural characteristics of using spaces without proper ventilation and/or due to keeping inside doors closed for most of the time, probably for heat retention reasons. These variations may be due to a number of variables such as the orientation, seasons, house types, and an individual's behaviour in the houses, which will be studied in the next section of the chapter.

Mid-day

Table 4.7 shows that the average temperature, RH and CO_2 levels vary across different zones in the house, in different seasons, at midday. It is found that the minimum average temperature in the morning is measured in the bedrooms during Winter at 18.7^{o}C, while the highest is in the master bedroom during Summer at 23.7^{o}C, similar to the morning patterns. This latter may be due to the difference in the use of heating systems and occupancy behaviour and usage pattern, as it is usually South facing, and thus, experiences high temperature.

Similarly, the level of RH also varies across different zones and seasons in the same set of houses at midday. It is found that the minimum average RH was present in the kitchen in Spring at 48%, while the highest average was in the en suite in Summer at 58%. It can be observed that there is not much noticeable difference in average RH, the only exception being the en suite, possibly due to leaving doors between rooms open at this time of the day. Of course, the en suite experiences a slightly higher average humidity because showering leads to an accumulation of RH in the en suite and is only dissipated by the extract fan after some time.

Table 4.7 Average temperature, RH and CO_2 levels for 44 houses for all seasons around mid-day

Midday Time		**T °C (SD)**	**RH % (SD)**	**CO_2 ppm (SD)**
Summer	Living Room	23.2 (±1)	57 (±5.3)	574 (±204)
	Kitchen	23.5 (±1.1)	57 (±5.7)	549 (±185)
	En suite	23.4 (±1)	58 (±7)	-
	Master Bed	23.8 (±1.2)	55 (±5.8)	526 (±177)
	Second bed	23.6 (±1)	55 (±5.4)	631 (±276)
Winter	Living Room	19.6 (±1.9)	52 (±7.2)	656 (±269)
	Kitchen	20.2 (±2.1)	51 (±7.3)	629 (±242)
	En suite	19.1 (±2.4)	57 (±10.4)	-
	Master Bed	18.7 (±2)	56 (±6.9)	647 (±289)
	Second bed	18.7 (±1.9)	54 (±6.9)	613 (±277)
Autumn	Living Room	19.7 (±2.1)	53 (±7.2)	654 (±267)
	Kitchen	20.2 (±2.3)	53 (±7.4)	645 (±256)
	En suite	19.0 (±2.5)	58 (±9.5)	-
	Master Bed	18.8 (±2.3)	57 (±6.8)	641 (±274)
	Second bed	18.8 (±2.1)	56 (±6.6)	655 (±326)
Spring	Living Room	20.7 (±1.5)	49 (±5.7)	714 (±291)
	Kitchen	21.1 (±1.8)	48 (±7.1)	667 (±259)
	En suite	20.3 (±1.8)	52 (±8.4)	-
	Master Bed	20.3 (±1.7)	50 (±6.7)	607 (±250)
	Second bed	20.3 (±1.6)	48 (±5.9)	621 (±307)

The levels of CO_2 also vary, and are the least in the master bedroom during Summer, at 526 ppm, and highest in the living room during Spring at 714 ppm. These variations are most likely due to the living patterns of the occupants, use of mechanical ventilation systems and the time for which the area is occupied. Thus, it is needed to study and better understand the reasons for these changes, and for which the variables under study, namely orientation, season, house type, and an individual’s behaviour in the house, and these will be assessed and discussed in a subsequent section.

Evening

Table 4.8 shows that the average temperature, RH, and CO_2 levels vary across different zones in the house, in different seasons in the evening. It is found that the minimum average temperature in the evening is measured in the second bedroom during Winter at 19.1^oC, while the highest is in the master bedroom during Summer at 23.8^oC. These differences show that during the evening, the lowest temperature may be due to low occupancy, while high average temperature in master bedroom could be due to residual maximum solar gain in that zone.

Similarly, the level of RH also varies across different zones and seasons in the same set of houses at evening time. It is found that the minimum average RH was present in the second bedroom in Spring at 48%, which may be due to the fact that the room had no en suite attached. The highest average was in the en suite in Summer at 59%, which is probably due to the accumulation of RH due to bathing activities with residual standing water on surfaces.

The levels of CO_2 also vary, and is the least in the kitchen during Summer at an average value of 631 ppm, and highest in the living room during Winter at an average value of 868 ppm where occupants may gather in the evenings. The former is attributed to the fact that the kitchen is probably occupied for least time, while the living room is generally occupied for longer time and with a higher number of occupants. These variations may be affected by a number of variables such as the orientation, seasons, house types, and an individual’s behaviour in the house, which will be studied in the next section of the chapter.

Night

It is found that the minimum average temperature at night-time is measured in the second bedroom during the Winter season at 18.9^oC (Table 4.9). This is possibly due to the fact that second bedroom is generally occupied by children, or will be vacant when there are no children in that zone, thereby, affecting the average. It is highest in the master bedroom during the Summer at 23.5°C, which is probably due to occupants staying inside the room for the whole night, and more so when the door of the room is closed, also causing accumulation of CO_2. It is found that the minimum average RH was present in the kitchen in Spring at 49%, while the highest average was in the living room in the Summer at 59%, which is the same as the last case.

Table 4.8: Average temperature, RH and CO_2 levels for 44 houses for all seasons in the evening

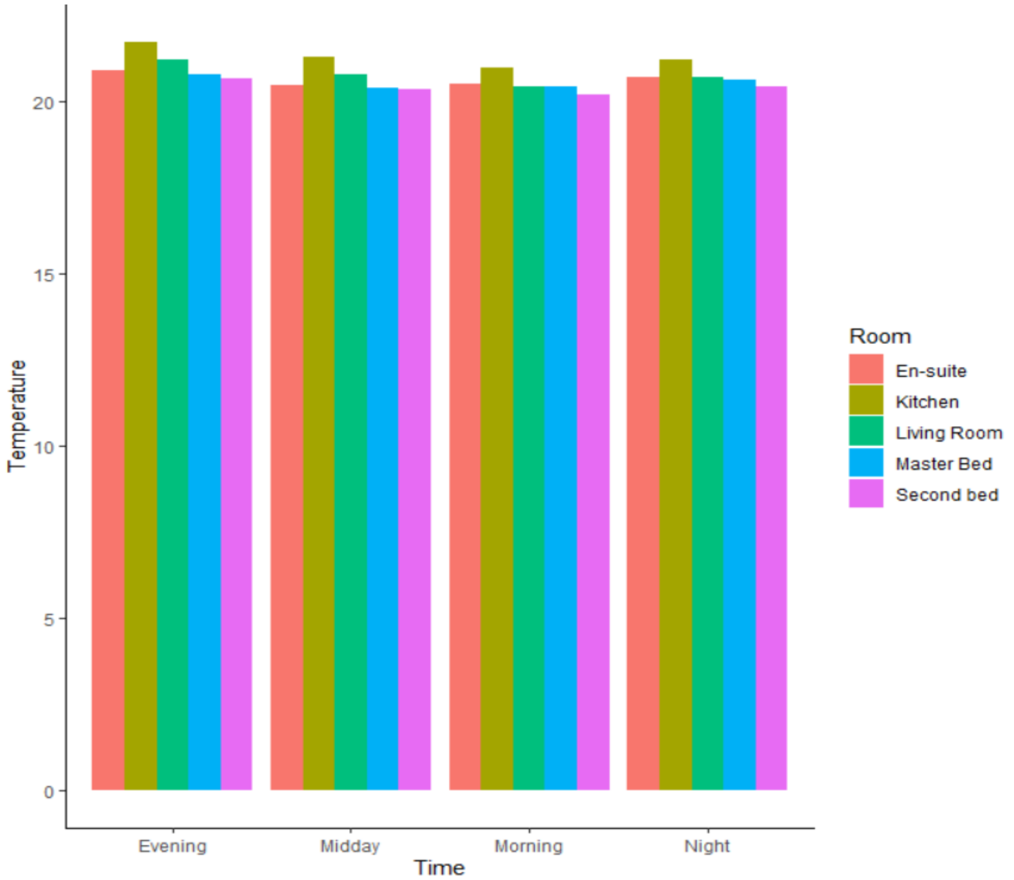
Evening		**T°C (SD)**	**RH % (SD)**	**CO_2 ppm (SD)**
Summer	Living Room	23.2 (±0.9)	58 (±5.4)	688 (±259)
	Kitchen	23.7 (±1.1)	58 (±5.9)	631 (±218)
	En suite	23.5 (±1)	59 (±7.3)	-
	Master Bed	23.8 (±1.2)	56 (±5.7)	634 (±261)
	Second bed	23.6 (±1)	56 (±5.6)	676 (±323)
Winter	Living Room	20.4 (±1.9)	52 (±7.2)	868 (±349)
	Kitchen	21.0 (±2.2)	52 (±7.6)	783 (±300)
	En suite	19.7 (±2.6)	57 (±10)	-
	Master Bed	19.3 (±2.4)	55 (±7.2)	770 (±345)
	Second bed	19.1 (±4.3)	54 6.7)	716 (±315)
Autumn	Living Room	20.5 (±2.1)	54 (±7.3)	857 (±349)
	Kitchen	21.0 (±2.4)	54 (±7.9)	797 (±318)
	En suite	19.7 (±2.7)	58 (±9.4)	-
	Master Bed	19.5 (±2.5)	56 (±7.3)	789 (±898)
	Second bed	19.4 (±2.3)	56 (±6.5)	772 (±409)
Spring	Living Room	20.8 (±1.4)	50 (±5.3)	866 (±348)
	Kitchen	21.3 (±1.9)	49 (±6.7)	750 (±262)
	En suite	20.6 (±1.9)	52 (±7.8)	-
	Master Bed	20.5 (±1.8)	50 (±6.5)	737 (±320)
	Second bed	20.4 (±1.7)	48 (±5.3)	711 (±865)

Table 4.9 Average temperature, RH and CO_2 levels for 44 houses for all seasons at night-time

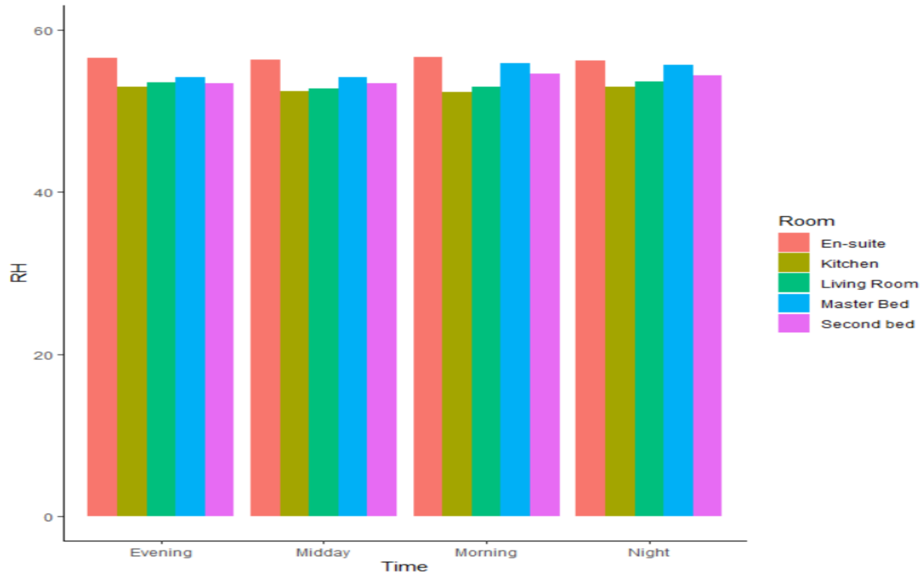
Night		T °C (SD)	RH % (SD)	CO_2 ppm (SD)
Summer	Living Room	22.7 (±0.9)	59 (±4.6)	573 (±168)
	Kitchen	23.2 (±0.9)	58 (±4.9)	549 (±124)
	En suite	23.3 (±1)	59 (±6.2)	-
	Master Bed	23.6 (±1.2)	57 (±5.3)	949 (±448)
	Second bed	23.3 (±0.9)	57 (±5.5)	862 (±477)
Winter	Living Room	19.5 (±1.8)	52 (±6.9)	650 (±250)
	Kitchen	20.1 (±1.9)	51 (±6.6)	594 (±195)
	En suite	19.4 (±2.4)	56 (±8.8)	-
	Master Bed	19.1 (±2.2)	57 (±6.9)	1104 (±477)
	Second bed	18.9 (±1.9)	55 (±7.4)	962 (±556)
Autumn	Living Room	19.6 (±1.9)	54 (±6.9)	633 (±228)
	Kitchen	20.6 (±2.2)	53 (±6.8)	601 (±187)
	En suite	19.4 (±2.5)	58 (±8.3)	-
	Master Bed	19.3 (±2.4)	58 (±7.2)	1151 (±601)
	Second bed	19.2 (±2.1)	57 (±6.9)	1023 (±612)
Spring	Living Room	20.1 (±1.3)	50 (±4.6)	606 (±202)
	Kitchen	20.5 (±1.7)	49 (±5.8)	569 (±142)
	En suite	20.4 (±1.8)	52 (±6.8)	-
	Master Bed	20.3 (±1.8)	52 (±6.8)	1096 (±516)
	Second bed	20.0 (±1.6)	50 (±5.5)	871 (±458)

Finally, the levels of CO_2 also vary, and is least in the kitchen during Summers at an average value of 549 ppm and is highest in the master bedroom in Autumn at an average value of 1151 ppm. This signifies that these variations can be due to reasons like high solar gain in summers, use of heating system for different times of the day, use or abuse of mechanical vents, and even occupancy levels indicating that bedrooms are occupied for a much larger time as compared to a kitchen. To understand the reasons, the variables considered in the study, namely orientation, seasons, house types, and other individual behaviours in the house, need to be ascertained, so that the outliers can be identified, and the right restorative measures can be recommended.

The overall data of the three variables for different times of the day for all seasons combined is given in Figure 4.2 (a) to (c).



(a)



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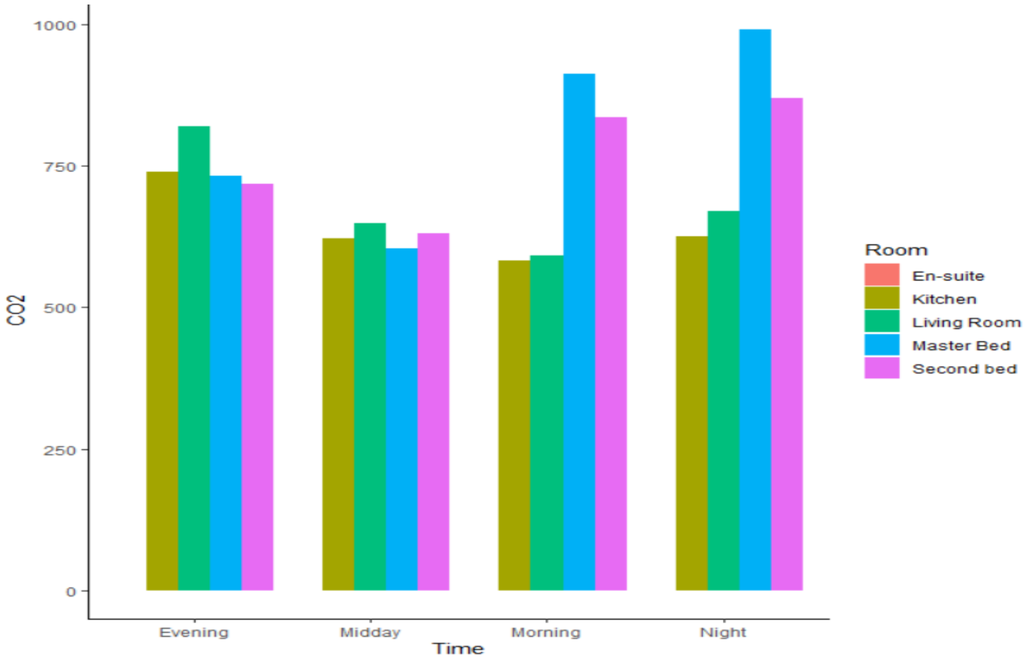


(c)

Figure 4.2 (a), (b), (c) Overall summary of the average temperature, RH and CO_2 levels for 44 houses in different times of the day

This graph shows that identifiable variations in the three variables exist among different zones of the houses, and also significantly varies among different times of the day. It shows a 3-dimensional data of:

(1) Time (Morning, Midday, Evening, Night)

(2) Type (T, RH, CO_2)

(3) Type of room

In this three-dimensional data, the average values in each cohort (subgroup/sub sample) are shown. It is only a unique value not a combination of values hence it has been kept as a histogram plot where the individual measures can be observed.

For instance, from Tables 4.6 to 4.9 and Figure 4.2, it can be observed that the temperature variations are not very high, but still are perceptively higher during evening and night, as compared to morning and mid-day, which may be due to the use of heating systems for different times of the day or sustained solar gain during the day. Also, the average RH is observed to be a minimum at midday, and is high during the night and morning (especially in the en suite), which could be due to the use of mechanical vents or daily activities like sitting in certain zones for extended times, bathing, showering, cooking, etc. The lowest levels of CO_2 are observed around midday, and the highest during the night-time. This is likely due to higher occupancy rates during the night as compared to the daytime.

There are also some notable variations for the highest and lowest averages in all the three variables. The variability of temperature and RH, however, are the same, that is, during different times of the day, the lowest and highest average temperatures are consistently in the second bedroom and kitchen respectively. This may be due to similar working and occupancy patterns of the occupants in these two-house zones.

The largest variations have been for the levels of CO_2. For instance, the lowest average levels of CO_2 were observed in the kitchen during the morning and night times, but at midday, the minimum CO_2 was noted in the master bedroom, and in the second bedroom in the evening time. The reason could be due to the lower use of the kitchen, by a lesser number of people during specific hours in the day (morning and night), as indicated by the fact that the CO_2 tends not to accumulate. Similarly, in daytime, low CO_2 in the master bedroom implies that the room is vacant, not surprisingly, and thus, the pattern of occupancy plays a vital role in understanding these differences.

Also, the highest levels of CO_2 in the morning and night-time were observed in the master bedroom, while it was the living room that measured the highest CO_2 at midday and evening. This is clearly due to the fact that the master bedroom is occupied throughout night and early morning, leading to higher CO_2 and the occupants spend more time in the living room in the evening, so these trends are not at all surprising, but are reassuring.

Evaluating these overall analyses, and the existing variations in each of the three variables, it is found that the variations of temperature, RH and CO_2 significantly varies across seasons as well as over different times of the day. Thus, to gain a better understanding, further analysis of the collected data for each of the three variables is undertaken and discussed in the next sub-section of the chapter.

4.3. Analysis of parameters affecting indoor air quality

In this section, the aim is to understand the implications of different factors on each of the three variables, helping to form meaningful analysis for the set of 44 houses at Location 1.

Before undertaking the analysis, a number of key assumptions are important to identify:

- No CO_2 is computed for the en suite zones due to the limitation of no CO_2 sensors in that zone.
- When considering a regression analysis, each house will be attributed only one of the given orientations and house types, such that the other orientations and house types will assume the value of 0. That is, in regression analysis, while the active orientation variable is given the value of 1, all others are kept as 0 so that the impact on the particular zone orientation is found precisely. Of the different variables considered, a number of baseline/dummy variables are considered (one from each type of variable) which include the end terrace house type (from house types), the orientation EO (from orientation group) and advice given to occupiers to change their behaviour or influence the use of house ventilation/appliances after studying 6 months of data (as provided by the author). These baseline or dummy variables in the regression analysis will have the least impact on the overall coefficients, and hence the most important factors affecting the considered IAQ variables; Temperature, RH and CO_2 are computed.
- The significant factors affecting the temperature, RH and CO_2 trends in different house zones were investigated through multiple linear regression, in which a number of variables have been included, including occupation, advice, orientations (of which there were six: North Orientation, North-East orientation, North-West orientation, South Orientation, South-West orientation, and East Orientation - none of the houses is situated in a Westerly orientation), humidity (in respective of house zones), CO_2 and house types (end terrace, 4 bedroom end terrace (4End Terrace) and mid terrace).

All assumptions have been tested for normality assumptions of error terms whether the errors are following a mean of 0 or not and also a correlation between the independent variables were checked. The sample size was quite high enough so, lesser variation and more reliable data to assume normality.

4.3.1. Temperature trends

The first variable considered is the temperature in different zones of the houses. Firstly, the analysis of temperature for different houses during different seasons is performed.

Summer Season

The range of temperature for the 44 selected houses during the Summer season is given in Figure 4.3. Figure 4.3 shows that during the Summer season, the minimum temperature was noted in B3, B4, G5, G6 and G12 at about 16.6°C, while the maximum temperature was about 35.0°C in house F2. Figure 4.4 shows the average temperature variation for the 44 houses ranged between 17.4°C for G12 to 25.9°C for E2.

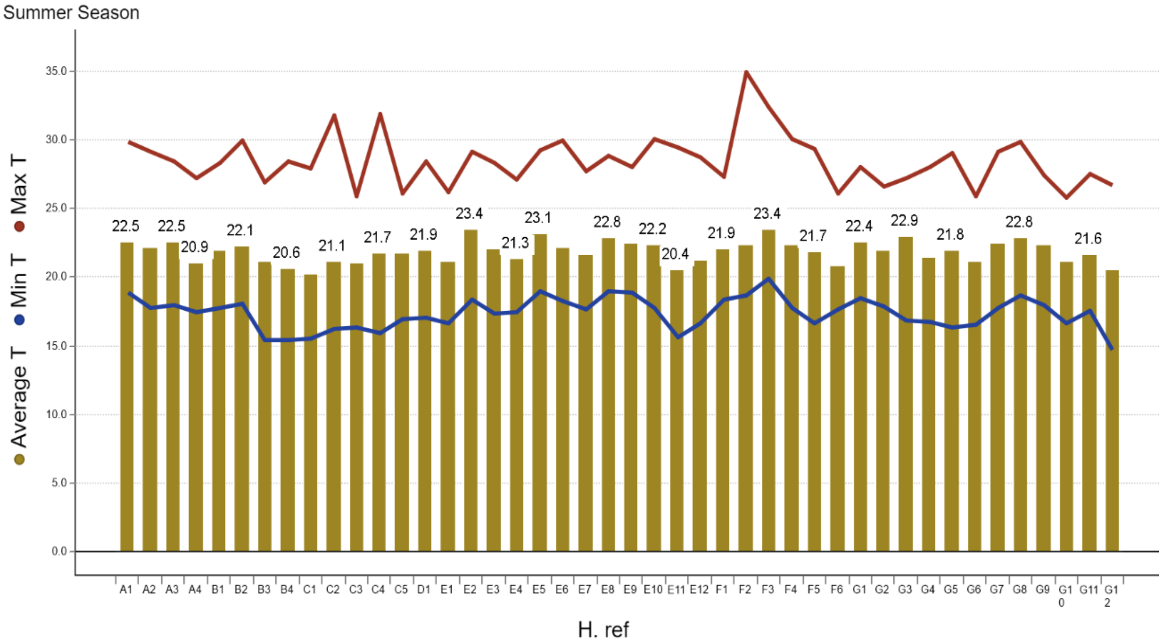


Figure 4.3 Minimum, maximum and average temperature for 44 houses during Summer

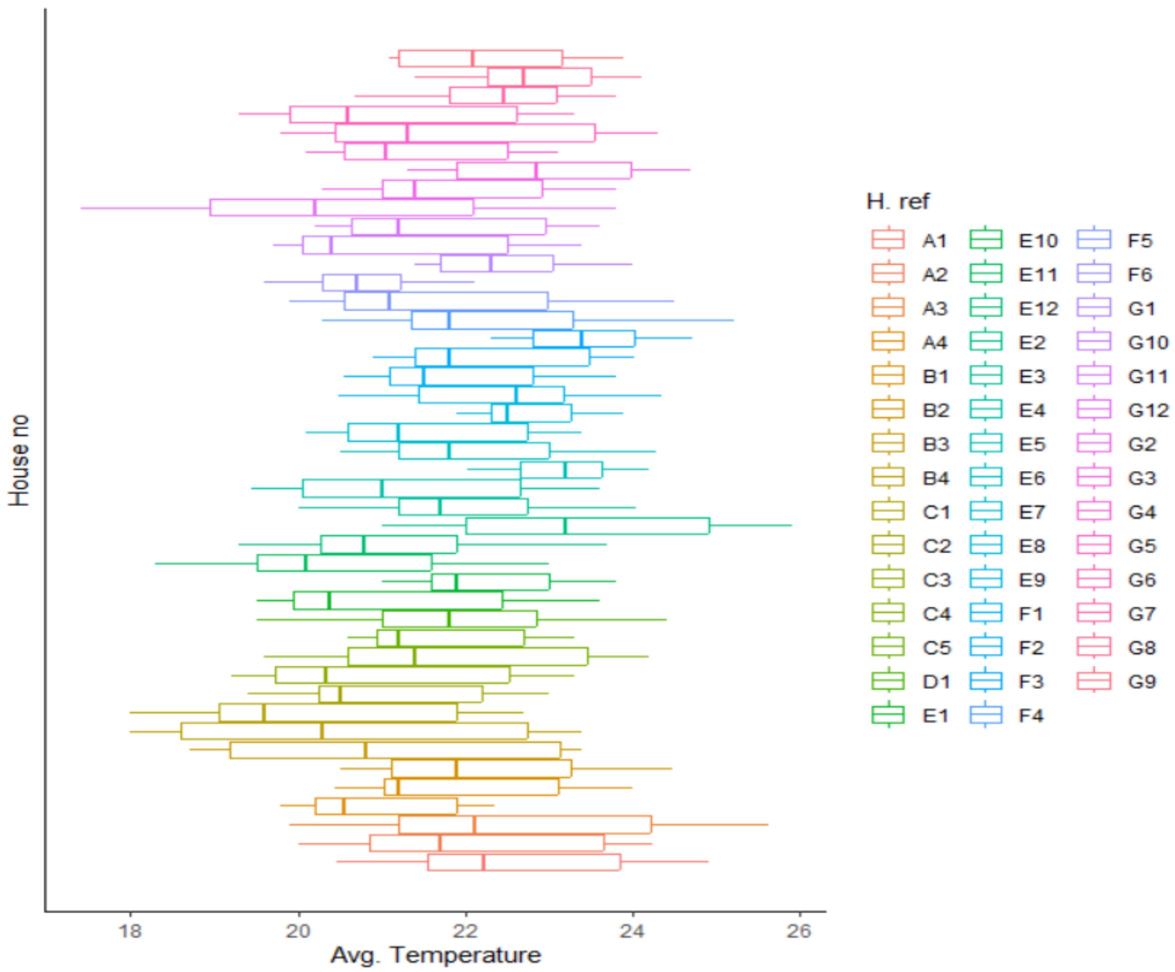


Figure 4.4 Box plot of average temperature for 44 houses during Summer

These data signify that there is a large variation in the temperature of these largely identical houses in the one season and there may be scope for omitting the outliers so that the average values become more representative of the temperature for the houses generally. The explanation for the variations may be due to their location, orientation or zone/area or the occupier's working status, advice taken or general behaviour. Thus, the impact of each of these variables is studied using regression analysis to establish how each of them might impact on the average temperature of houses in general.

Living Room

The regression analysis for temperature in the living rooms during the summer period is given in Table 4.10. From this, it can be observed that the p-value (likelihood for the model to be close to the null hypothesis of there being no difference between the variables considered) of the entire model is less than 0.05, indicating that the model is statistically significant in predicting the temperature.

Table 4.10: Regression results to study the impact of different variables on temperature in Summer in the living room

```
Call:
lm(formula = temperature ~ Occupancy + Orientation + co2 + humidity +
    `House Type`, data = dm)

Residuals:
    Min      1Q  Median      3Q     Max
-4.7999 -0.6037 -0.0231  0.5500  9.0815

Coefficients: (1 not defined because of singularities)
                          Estimate Std. Error  t value Pr(>|t|)
(Intercept)              2.172e+01  2.081e-02 1043.679  < 2e-16 ***
Occupancy                2.702e-01  1.460e-03  185.031  < 2e-16 ***
OrientationNE            3.853e-01  7.638e-03   50.446  < 2e-16 ***
OrientationNO           -2.232e-02  5.268e-03   -4.237 2.26e-05 ***
OrientationNW            5.841e-01  1.317e-02   44.346  < 2e-16 ***
OrientationSO           -1.230e-01  5.408e-03  -22.738  < 2e-16 ***
OrientationSW            1.624e-01  7.783e-03   20.872  < 2e-16 ***
co2                      1.508e-03  9.777e-06  154.219  < 2e-16 ***
humidity                -5.527e-03  3.335e-04  -16.574  < 2e-16 ***
`House Type`Detached            NA         NA       NA       NA
`House Type`End Terrace  2.087e-01  7.470e-03   27.933  < 2e-16 ***
`House Type`Mid Terrace  3.938e-01  5.286e-03   74.487  < 2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.9268 on 311133 degrees of freedom
Multiple R-squared:  0.2373,    Adjusted R-squared:  0.2373
F-statistic:  9679 on 10 and 311133 DF,  p-value: < 2.2e-16
```

Some variables, namely occupancy, orientations NW, NE and SW, end terrace and mid terrace house types and CO_2 positively impact the temperature indicates that the mean of the temperature tends to increase as the independent variable increases while the remaining variables, orientation (NO and SO), negatively impact the temperature. For instance, the positive relationship between temperature and CO_2 signifies that there are occupants in the houses, which can increase the temperature in the dwelling because heating and other appliances are being used, and the presence of higher CO_2 levels confirms their presence. Similarly, the impact of different orientations on the temperature entails solar gain, affecting the indoor temperature in a room. The degree of impact of each of these variables is provided by the following regression equation:

Equation 4.1

$$Temperature = 21.7 + 0.27 * occupancy + 0.39 * orientation\ NE - 0.02 * orientation\ NO + 0.58 * orientation\ NW - 0.12 * orientation\ SO + 0.16 * Orientation\ SW - 0.01 * humidity + 0.002 * CO_2 + 0.21 * end\ terrace\ house\ type + 0.39 * mid\ terrace\ house\ type$$

The coefficients suggest that for a NW orientation, the temperature increases by 0.58°C, the highest among the orientations. This implies that the living room of houses facing the NW orientation is most likely to be facing the sun, because the living room is at the back of the house and, thus, receives the highest solar gain, which positively impacts/increases the temperature of the room. The implication of these coefficients is further computed in a few dwellings (as an example) with different orientations, which are stated in Table 4.11.

Table 4.11 Effects of the coefficients on temperature

Coeff.	occupancy	NE	NO	NW	SO	SW	RH	CO_2	end terrace	mid-terrace	T
Values	0.27	0.39	-0.02	0.58	-0.12	0.16	-0.01	0.002	0.21	0.39	-
A1SWE5	5	0	0	0	0	1	value	value	1	0	23.6
B1NE2E2	2	1	0	0	0	0	value	value	1	0	23.0
A4SW3E2	2	0	0	0	0	1	value	value	1	0	22.8

Thus, Table 4.11 shows that house A4 has a lower temperature compared to B1 and A1; and that the difference between A1 and A4 is statistically significant. The rationale for these differences can be explained thus:

- Both B1 and A4 have the same number of occupants (2), yet the temperature of the living room varies, which is due to the orientation, as per the regression equation, but also may be owing to other occupant behaviours. That is, house B1 is facing the NE orientation, while A4 is facing SW (and their living room faces the opposite orientation). NE has a stronger association with temperature (due to the position of the living room to the south), and thus, experiences higher temperature. Moreover, these differences may also be due to the behaviour of the occupants concerning the heating system use.

- Both A1 and A4 have the same orientation, SW, yet they experience a difference in temperature, which could be due to differences in the number of occupants and how occupants use the space. Hence, the house A1, despite being in the same orientation, is likely to experience a higher temperature due to the level of activity in the room which is affected by number of people in that space. Another reason could be an increase in the use of appliances with occupancy which can generate more heat.

The R squared value of 0.24 suggests that only 24% of the variation of temperature can be explained by the regression equation with these independent variables. The R^2 value is low, the correlation is very weak and, therefore, this equation cannot be used for prediction. R2 and adjusted R aquared are same which suggests instead of addition so many independent variables, the model is not compromised. The overall F statistical value (the F-test measures the overall significance and determines whether the regression model used provides a better fit as compared to a model with no independent variables) and p value (measuring the overall significance of the model at a high confidence interval) of the model suggest that the model is significant in estimating the temperature level for some of the given values of the independent variables. There is enough evidence that there is a significant relationship between the independent and dependent variables explained through the model. P value is less than 0.05 hence model also supports the goodness of fit that there is a relationship.

Kitchen

Similarly, the results of regression for the kitchen are described by the following equation 4.2. Again, the R squared value (0.24) suggests 24% of the variation of temperature can be explained by the regression equation, a low value. The results are similar to that of the living room due to the layout of the house, such that the kitchen and living room have an adjoining door, and the heat in the kitchen travels to the living room and impacts its temperature. Thus, the impact of orientations can be roughly similar for both the kitchen and living area.

Equation 4.2

$$Temperature = 21.7 + 0.27 * occupancy + 0.38 * orientation\ NE - 0.01 * orientation\ NO + 0.6 * orientation\ NW - 0.12 * orientation\ SO + 0.16 * orientation\ SW - 0.01 * humidity + 0.002 * CO_2 + 0.21 * end\ terrace\ house\ type + 0.40 * mid\ terrace\ house\ type$$

Other house zones

Similar to the above analysis, the regression equations for the en suite, master bedroom and second bedroom are presented in Table 4.12. The following findings can be drawn from the set of equations in table 4.12:

- In the master bedroom, temperature is most influenced by the mid terrace house type, where the temperature increases by a factor of 1.4 times higher than the other variables. It implies that the houses of mid-terrace type are most likely to experience high temperature in the master bedroom. This finding is owing to the layout of the house, such that the master bedroom receives high solar gain and it's not exposed to external conditions on two walls due to the party walls with neighbouring dwellings.

- In a similar way, for the second bedroom, the houses with mid-terrace are most likely to experience highest temperature as well, although less than the master bedroom but still the highest among all variables. It will be analysed later in detail, whether there a significant difference, or if it can be ignored.

Table 4.12 Regression equations for the different house zones during Summer

House Zone	Regression equations
en suite	$Temperature = 20.5 + 0.2 * occupancy + 0.00 * orientation\ NE - 0.6 * orientation\ NO - 1.37 * orientation\ NW - 0.31 * orientation\ SO - 0.06 * orientation\ SW + 0.02 * ensuite\ humidity + 0.79 * end\ terrace\ house\ type + 1.49 * mid\ terrace\ house\ type$

Master Bedroom	$Temperature = 22.9 + 0.14 * occupancy + 0.08 * orientation\ NE - 0.56 * orientation\ NO - 0.49 * orientation\ NW - 0.19 * orientation\ SO + 0.11 * orientation\ SW - 0.02 * humidity + 0.001 * CO_2 + 0.79 * end\ terrace\ house\ type + 1.42 * mid\ terrace\ house\ type$
Second bedroom	$Temperature = 19.9 + 0.25 * occupancy + 0.46 * orientation\ NE + 0.037 * orientation\ NO - 0.07 * orientation\ NW - 0.25 * orientation\ SO + 0.27 * orientation\ SW + 0.03 * humidity + 0.000 * CO_2 + 0.54 * end\ terrace\ house\ type + 1.16 * mid\ terrace\ house\ type$

It is also important to note that while analysing the effect of these coefficients on temperature, variables like CO_2 and RH can be ignored since they do not directly impact the temperature although variables which can affect temperature will also affect the RH level for equal moisture in the air. And it can be summarised that variables like house types and orientations are vital and impact the temperature of the indoor house zones.

Winter Season

Next, the analysis of the temperature for the winter season is conducted. Figure 4.5 shows that during the Winter season, the minimum temperature was noted in B4 at 11.9°C with one occupant, while the maximum temperature was about 35.6°C in F3. Moreover, the average temperature for each of the 44 houses ranged between 14.3°C for E13 to 25.2°C for D1 (Figure 4.6). Comparing the mean values with that of the maximum and minimum, the data signify that there is a large variation in the temperature of these similar houses for the same season, thereby, signifying the need to exclude the outliers or provide an explanation. The rationale for the variations is assumed to be due to their location, orientation, whether dwelling is occupied, working status, advice and house zone/area. This section, therefore, studies whether there is any difference in the variables (as was found during the summer season) in influencing the temperature in different house zones.

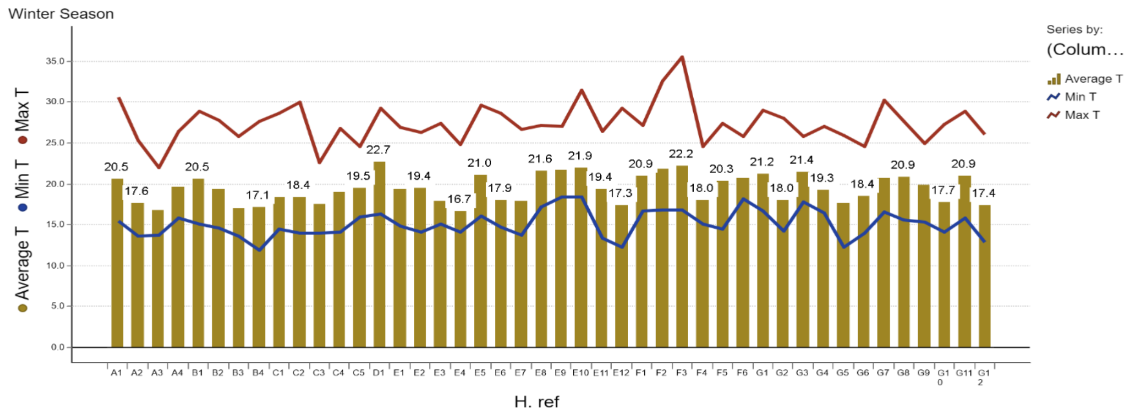


Figure 4.5 Minimum, maximum and average temperature for 44 houses during Winter

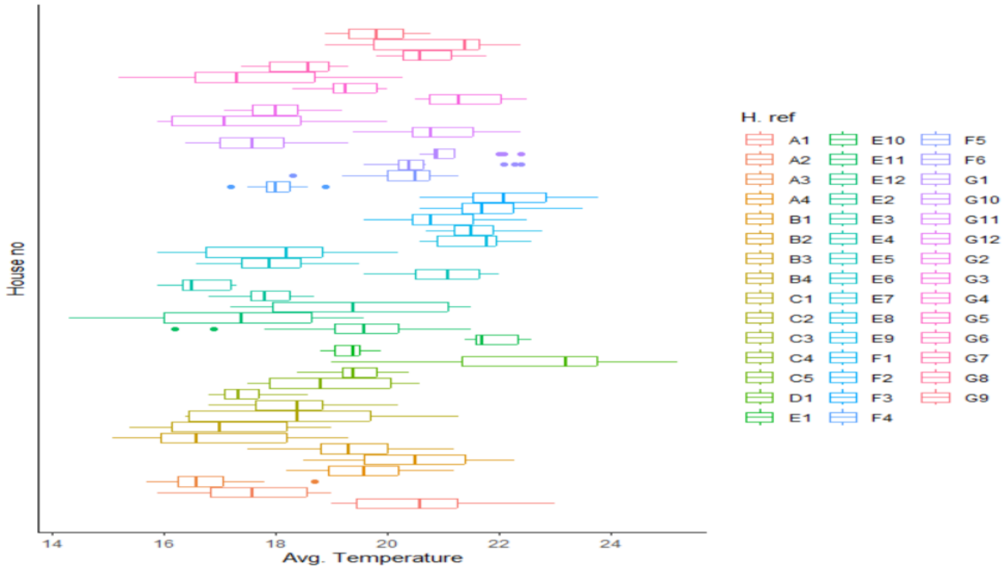


Figure 4.6 Box plot of average temperature for 44 houses during Winter

The regression equations for the different house zones during Winter are presented in Table 4.13. From this table, it can be summarised that the temperature during Winter in different zones is most influenced by the NW orientation (in the living room and kitchen), while the master and second bedrooms are most influenced by the NE and SW orientations respectively. These differences contrast with the summer season largely due to the fact that the solar gain during winter is low, and the layout of the dwelling plays an important role in determining the impact from the external environment.

Table 4.13 Regression equations for the different house zones during winter

House Zones	Regression Equations
Living area	$Temperature = 24.9 + 0.28 * occupancy - 0.26 * advice - 1.61 * orientation\ NE - 1.01 * orientation\ NO + 0.63 * NW\ orientation - 1.15 * orientation\ SO - 1.38 * orientation\ SW - 0.14 * humidity + 0.003 * CO_2 + 1.00\ end\ terrace\ house\ type + 0.32 * mid\ terrace\ house\ type$
Kitchen	$Temperature = 26.8 + 0.34 * occupancy - 0.34 * advice - 1.03 * orientation\ NE - 0.49 * orientation\ NO + 1.26 * NW\ orientation - 1.16 * orientation\ SO - 1.25 * orientation\ SW - 0.17 * humidity + 0.004 * CO_2 + 0.4\ end\ terrace\ house\ type - 0.18 * mid\ terrace\ house\ type$
Master Bedroom	$Temperature = 27.6 + 0.32 * occupancy - 0.32 * advice - 1.62 * orientation\ NE - 0.71 * orientation\ NO + 1.41 * NW\ orientation - 0.82 * orientation\ SO - 1.49 * orientation\ SW - 0.2 * humidity + 0.002 * CO_2 + 0.95 * end\ terrace\ house\ type + 0.48 * mid\ terrace\ house\ type$
Second Bedroom	$Temperature = 23.8 + 0.51 * occupancy - 0.40 * advice - 2.04 * orientation\ NE - 0.67 * orientation\ NO + 0.21 * NW\ orientation - 0.86 * orientation\ SO - 1.89 * orientation\ SW - 0.12 * humidity + 0.001 * CO_2 + 0.55 * end\ terrace\ house\ type - 0.13 * mid\ terrace\ house\ type$

Spring Season

Figure 4.7 shows that the during the Spring season, the minimum temperature was noted at 12.4°C for G12, while the maximum temperature was about 34.4°C in F13. Moreover, the average temperature for all the 44 houses ranged between 14.4°C for G12 and 23.8°C for F3, which is a considerable difference in temperature (Figure 4.8).

To understand the rationale for the differences in temperature, the regression equation for each of these zones is presented in Table 4.14.

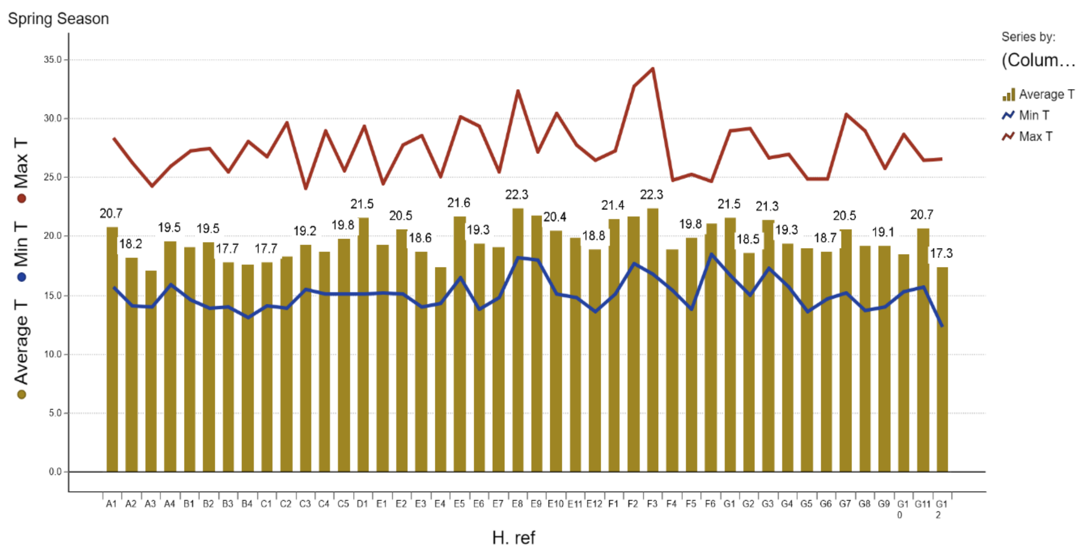


Figure 4.7 Min, max and avg. temperature for 44 houses during Spring

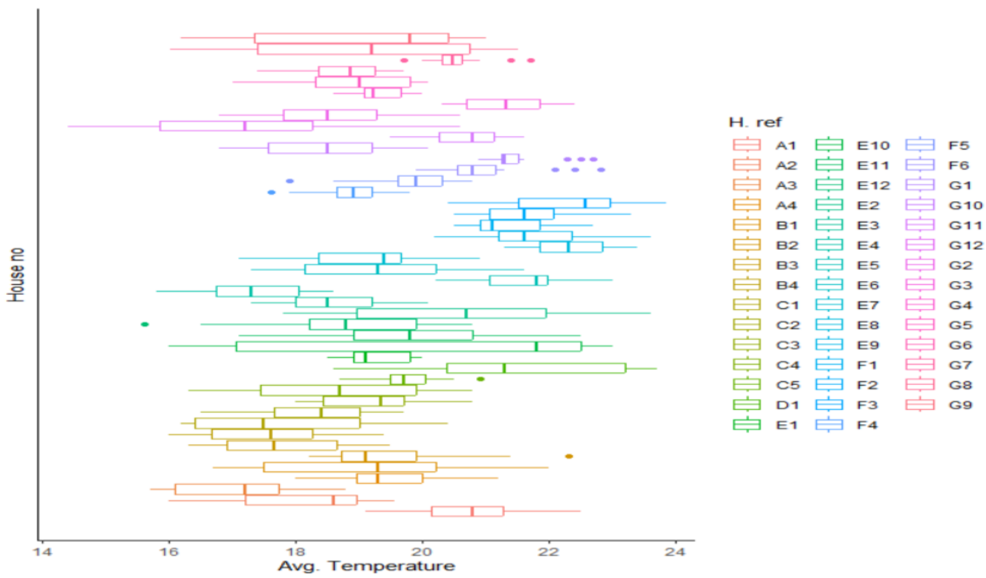


Figure 4.8 Box plot of avg. temperature for 44 houses during Spring

Table 4.14 Regression equation for each zone in Spring

House Zones	Regression Equation
Living Room	$Temperature = 24.2 + 0.23 * occupancy - 0.01 * advice - 1.5 * orientation\ NE - 0.71 * orientation\ NO + 0.20 * orientation\ NW - 0.86 * orientation\ SO - 1.26 * orientation\ SW - 0.13 * humidity + 0.002 * CO_2 + 1.17\ end\ terrace\ house\ type + 0.56 * mid\ terrace\ house\ type$
Kitchen	$Temperature = 25.4 + 0.21 * occupancy + 0.03 * advice - 1.36 * orientation\ NE - 0.64 * orientation\ NO + 2.10 * NW + 0.70 * orientation\ SO - 1.15 * Orientation\ SW - 0.15 * kitchen\ humidity + 0.003 * kitchen\ CO_2 + 0.65\ end\ terrace\ house\ type - 0.06 * mid\ terrace\ house\ type$
Master Bedroom	$Temperature = 26.5 + 0.19 * occupancy - 0.17 * advice - 2.39 * orientation\ NE - 1.03 * orientation\ NO + 1.84 * orientation\ NW - 0.29 * orientation\ SO - 1.15 * orientation\ SW - 0.17 * humidity + 0.001 * CO_2 + 1.58 * end\ terrace\ house\ type + 0.62 * mid\ terrace\ house\ type$
Second Bedroom	$Temperature = 23.1 + 0.44 * occupancy - 0.02 * advice - 1.72 * orientation\ NE - 0.39 * orientation\ NO + 0.30 * orientation\ NW - 0.81 * orientation\ SO - 1.43 * orientation\ SW - 0.11 * humidity + 0.001 * CO_2 + 0.72 * end\ terrace\ house\ type + 0.01 * mid\ terrace\ house\ type$

The following key findings are drawn from the above table:

- The temperature in the living area is mostly impacted by the SW orientation, while in the kitchen, it is mostly impacted by a NW orientation. This may be due to the number of occupants or usage behaviour of families living in this orientation of houses.
- Temperature in the master bedroom and second bedroom are impacted most by the NE orientation. This may be due to the direction of the sun leading to solar heat being trapped inside the zone.
- Temperature change is not caused by a humidity change, but humidity can be affected by temperature. Similarly, temperature change can be caused by the fresh air which also changes CO_2.

Autumn Season

Figure 4.9 shows that during the Autumn season, the minimum temperature was noted at 13.4°C for E13, while the maximum temperature was about 34.8°C in F3. Moreover, the average temperature for all 44 houses ranged between 15.9°C for E12 to 29.9°C for B2 (Figure 4.10).

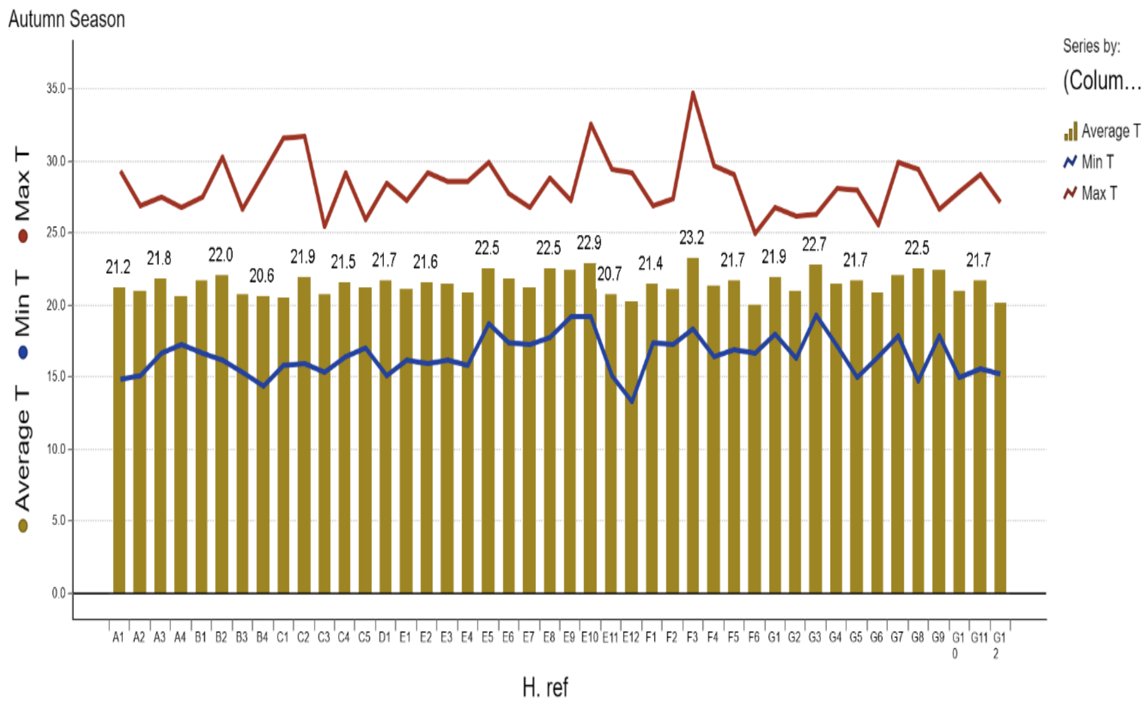


Figure 4.9 Minimum, maximum and average temperature for 44 houses during Autumn

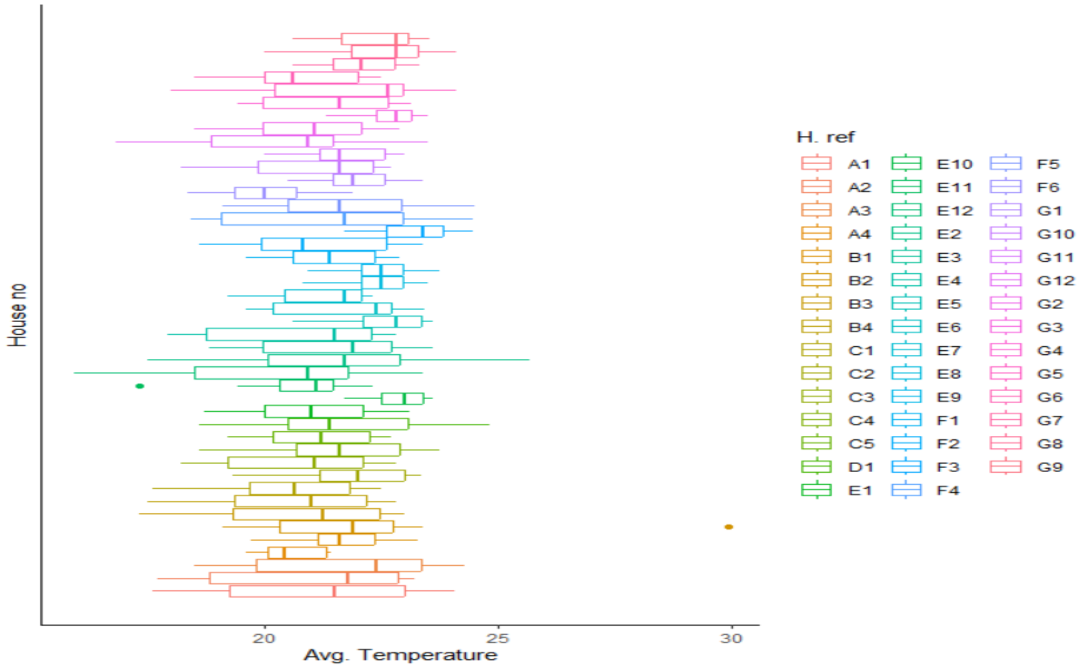


Figure 4.10 Box plot of average temperature for 44 houses during Autumn

The variations in temperature among the houses is signified by the regression coefficients, as presented in Table 4.15.

Table 4.15 Regression equation of different zones in Autumn

House Zones	**Regression Equation**
Living Room	$Temperature = 24.8 + 0.24 * occupancy - 1.45 * orientation\ NE - 0.90 * orientation\ NO + 1.43 * orientation\ NW - 1.28 * orientation\ SO - 1.36 * orientation\ SW - 1.38 * humidity + 0.003 * CO_2 + 1.05\ end\ terrace\ house\ type + 0.35 * mid\ terrace\ house\ type$
Kitchen	$Temperature = 25.9 + 0.21 * occupancy - 1.12 * orientation\ NE - 0.49 * orientation\ NO + 3.18 * NW - 1.1 * orientation\ SO - 1.30 * orientation\ SW - 0.15 * humidity + 0.003 * CO_2 + 0.47 end\ terrace\ house\ type - 0.07 * mid\ terrace\ house\ type$

Master Bedroom	$Temperature = 26.4 + 0.3028 * occupancy - 1.86 * orientation\ NE - 1.14 * orientation\ NO + 3.13 * orientation\ NW - 0.88 * orientation\ SO - 1.3 * orientation\ SW - 1.56 * humidity + 0.001 * CO_2 + 1.28 * end\ terrace\ house\ type + 0.67 * mid\ terrace\ house\ type$
Second Bedroom	$Temperature = 24.3 + 0.44 * occupancy - 1.29 * orientation\ NE - 0.63 * orientation\ NO + 2.56 * orientation\ NW - 1.26 * orientation\ SO - 1.29 * orientation\ SW - 1.26 * humidity + 0.001 * CO_2 + 0.21 * end\ terrace\ house\ type + 0.01 * mid\ terrace\ house\ type$

The following observations may be made:

- the houses in the NE orientation are most likely to experience the highest temperature in the living room among all houses, and those in the NW orientation experienced highest temperature in kitchen. These figures may be attributed to the layout of the houses and the solar gain.
- the houses in the NE orientation are most likely to experience the lowest temperatures in the master bedroom, and those in the NW orientation will experience the highest temperature in the master bedroom and second bedroom. Apart from the orientation and the solar gain, it can also be due to the heating system duration used by the occupants as per their desired comfort level, as would also apply in Winter.

4.3.2. RH trends

So far, the trends in movements in temperature have been analysed, as influenced by various factors, such as house orientation and occupancy. In this section, the impact of different factors on RH is computed for the different zones in the set of 44 identified houses in different seasons.

Summer Season

The variations in the minimum, maximum and average RH for the 44 houses for the Summer season is presented in Figure 4.11 and Figure 4.12.

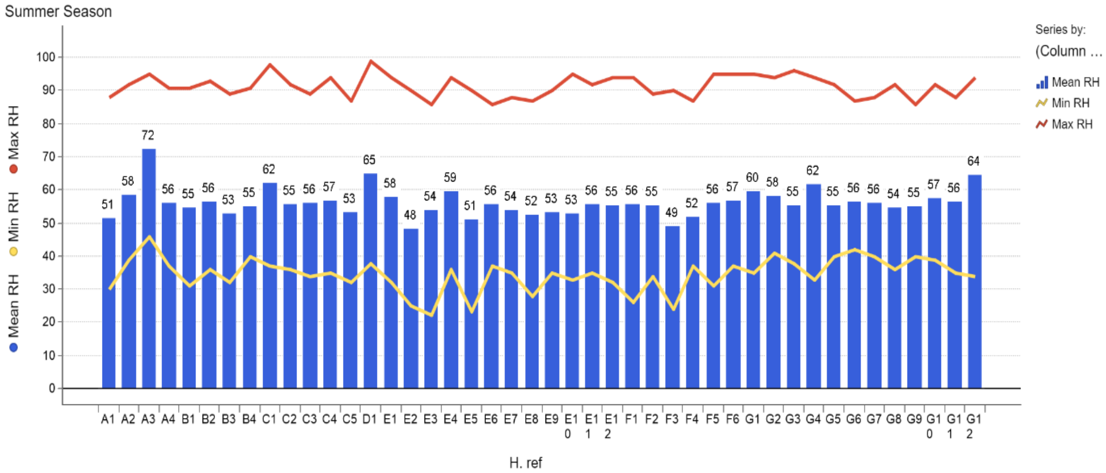


Figure 4.11 Minimum, maximum and average RH for 44 houses during Summer

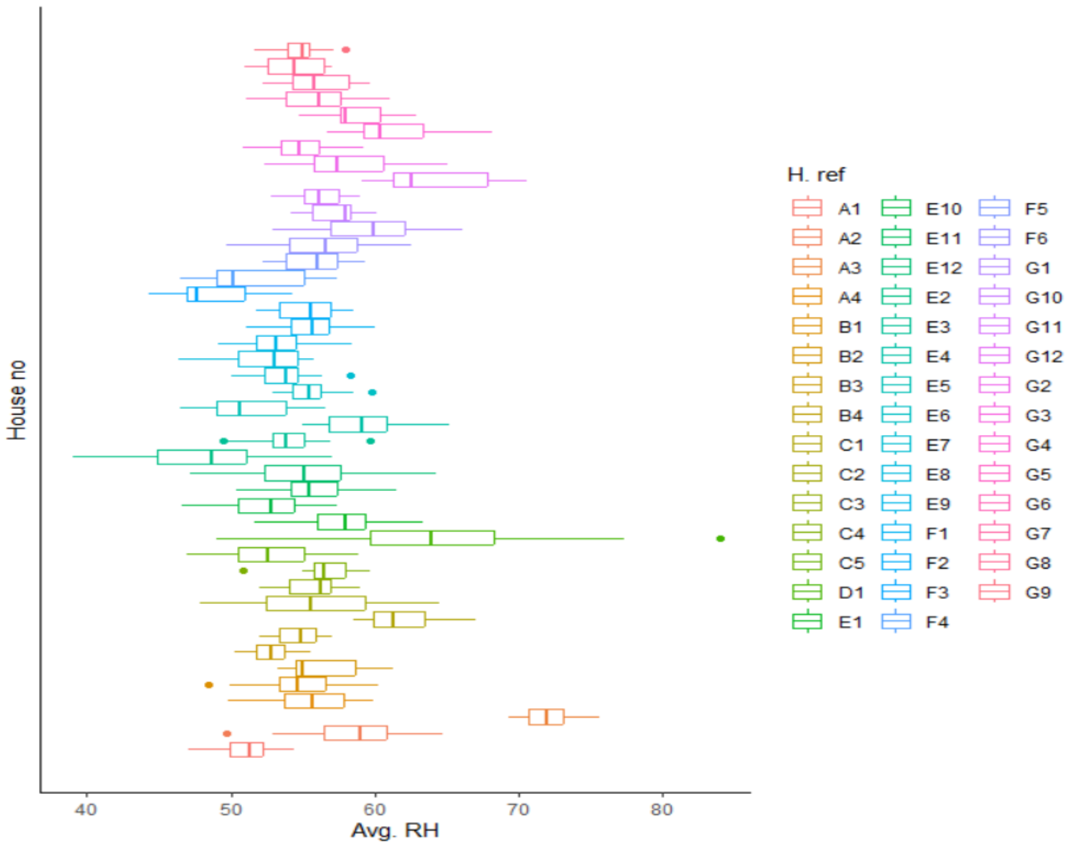


Figure 4.12 Box plot of average RH for 44 houses during Summer

As shown in the figure, during the Summer season, the minimum RH is found at 22.3% in house E3, while the maximum RH reported is 99% in house D1. The average RH is also shown to range between 48% and 72% for houses E2 and A3 respectively. The deviations in RH during Summer in different zones of the house is better studied using a regression analysis, as presented in Table 4.16. It shows that the humidity is positively related to the orientations. The living area, kitchen, en suite and second bedroom for the houses facing a NW orientation are most likely to experience higher humidity than other orientations. Also, the houses with a SW orientation are most likely to experience the highest humidity in the master bedroom. This can be attributed to the temperature in these zones, or the use of well ventilation in some of the houses.

Table 4.16 Regression equation for RH in different zones in Summer

House Zones	Regression Equation
Living Room	$Humidity = 59.99 - 0.59 * occupancy + 1.38 * orientation\ NE + 2.12 * orientation\ NO + 7.93 * orientation\ NW + 0.29 * orientation\ SO + 5.21 * orientation\ SW - 0.02 * temperature + 0.006 * CO_2 - 4.45 * end\ terrace\ house\ type - 1.35 * mid\ terrace\ house\ type$
Kitchen	$Humidity = 59.8 - 0.58 * occupancy + 1.38 * orientation\ NE + 2.1 * orientation\ NO + 7.93 * orientation\ NW + 0.29 * orientation\ SO + 5.21 * orientation\ SW - 0.02 * temperature + 0.006 * CO_2 - 4.46 * end\ terrace\ house\ type - 1.36 * mid\ terrace\ house\ type$
En suite	$Humidity = 37.83 - 0.13 * occupancy + 2.04 * orientation\ NE + 5.55 * orientation\ NO + 13.84 * orientation\ NW + 0.87 * orientation\ SO + 6.58 * orientation\ SW + 1.07 * temperature - 7.93 * end\ terrace\ house\ type - 8.05 * mid\ terrace\ house\ type$

Master Bedroom	$Humidity = 60.69 + 0.15 * occupancy + 1.01 * orientation\ NE + 4.01 * orientation\ NO + 3.17 * orientation\ NW + \ 0.79 * orientation\ SO + 4.77 * orientation\ SW - 0.32 * temperature + 0.006 * CO_2 - 5.35 * \ end\ terrace\ house\ type - 4.58 * mid\ terrace\ house\ type$
Second Bedroom	$Humidity = 53.27 - 0.12 * occupancy + 0.15 * orientation\ NE + 2.23 * orientation\ NO + 13.99 * orientation\ NW + \ 2.01 * orientation\ SO + 5.49 * orientation\ SW + 0.19 * temperature + 0.000 * CO_2 - 4.95 * \ end\ terrace\ house\ type - 3.92 * mid\ terrace\ house\ type$

Winter Season

The variations in the minimum, maximum and average RH for the 44 houses for the Winter season are presented in Figure 4.13 and Figure 4.14.

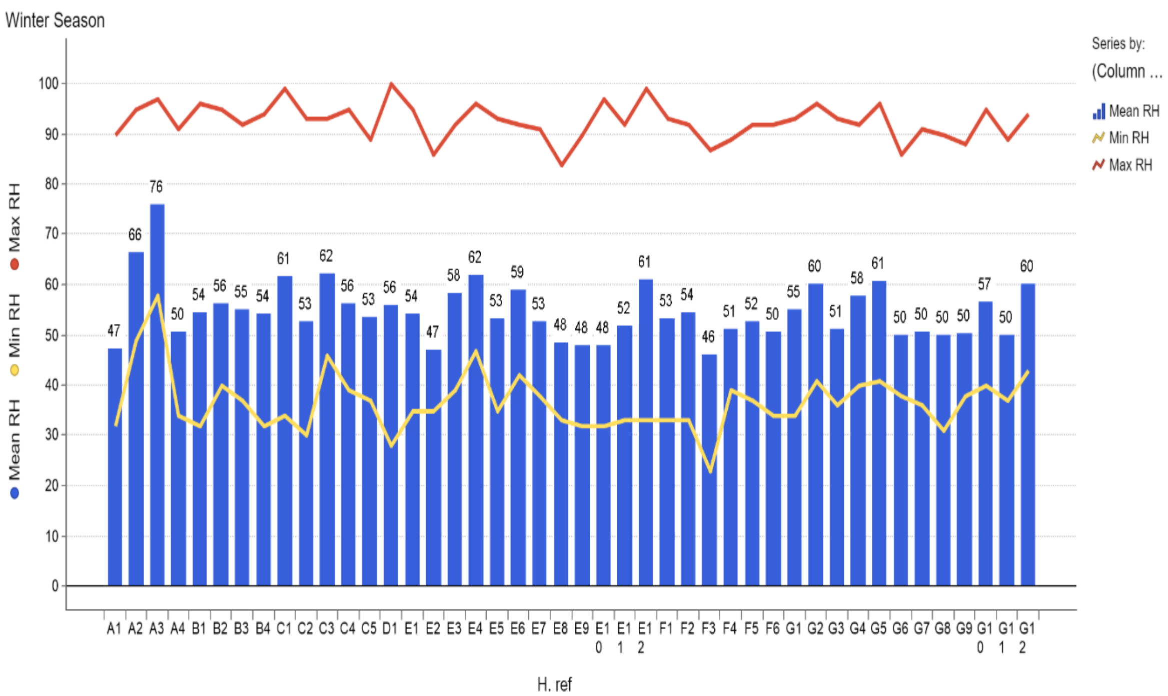


Figure 4.13 Minimum, maximum and average RH for 44 houses during Winter

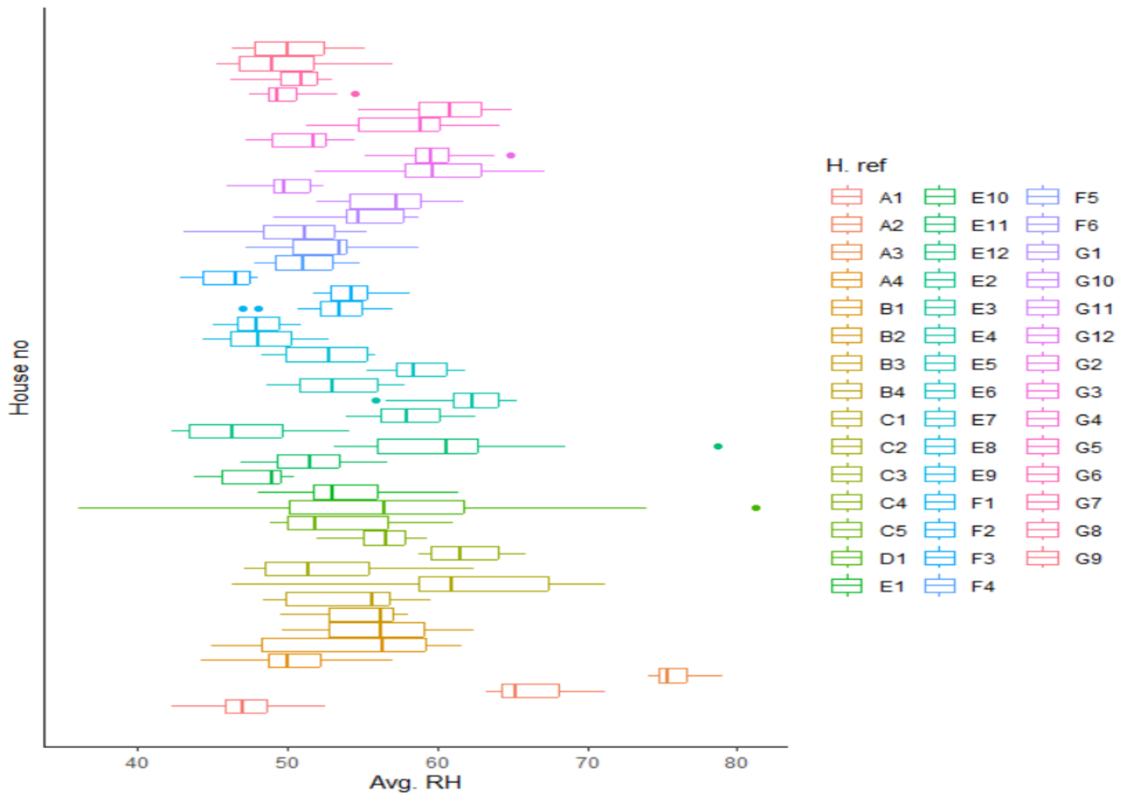


Figure 4.14 Box plot of average RH for 44 houses during Winter

Figure 4.13 shows that during the Winter season, the minimum RH occurred at 23% in house F3, while the maximum RH reported is 100% in house D1. The average RH also shows a range between 47% and 78% for houses A1 and A3 respectively (Figure 4.14). These figures show a large variance in the minimum and maximum values of RH among these houses, which is largely due to occupancy behaviour, such as the use of manual extracts and the ventilation system. To understand these deviations, each zone is studied using regression analysis, as presented in Table 4.17.

From this table, it can be observed that the houses in the NW orientations are likely to face higher humidity in their living area, kitchen and en suite, while those in the SW will have highest humidity in their second bedroom. However, in general, the orientation has little effect on the RH, and it is more about the use of ventilation and extract fans as well as trickle vents. The reason for these variations can be due to the temperature preferences, ventilation regimes or behavioural aspects of families living in these groups of houses.

Table 4.17 Regression equation for RH in different zones in Winter

House Zones	Regression Equation
Living Room	$Humidity = 86.61 + 0.40 * occupancy - 1.09 * advice - 1.31 * orientation\ NE + 0.29 * orientation\ NO - 7.42 * orientation\ NW - 1.14 * orientation\ SO + 3.75 * orientation\ SW + 0.01 * CO_2 - 2.17 * temperature - 1.67 * end\ terrace\ house\ type + 1.15 * mid\ terrace\ house\ type$
Kitchen	$Humidity = 88.71 + 0.36 * occupancy - 1.57 * advice - 0.13 * orientation\ NE + 1.13 * orientation\ NO - 1.76 * orientation\ NW - 0.30 * orientation\ SO + 5.51 * orientation\ SW + 0.001 * CO_2 - 2.13 * temperature - 6.92 * end\ terrace\ house\ type - 3.31 * mid\ terrace\ house\ type$
En suite	$Humidity = 88.57 + 0.58 * occupancy - 2.84 * advice\ no\ change + 5.44 * orientation\ NE + 3.57 * orientation\ NO + 0.14 * orientation\ SO + 6.80 * orientation\ SW - 1.48 * temperature - 10.96 * end\ terrace\ house\ type - 7.01 * mid\ terrace\ house\ type$
Master Bedroom	$Humidity = 83.92 + 0.83 * occupancy - 0.45 * advice + 2.84 * orientation\ NE + 2.45 * orientation\ NO + 6.00 * orientation\ NW - 0.38 * orientation\ SO + 5.03 * Orientation\ SW + 0.007 * CO_2 - 1.87 * temperature - 5.29 * end\ terrace\ house\ type - 2.12 * mid\ terrace\ house\ type$

Second Bedroom	$Humidity = 58.20 - 0.15 * occupancy - 0.44 * advice + 5.03 * orientation\ NE + 1.46 * orientation\ NO + 2.7 * orientation\ NW + 3.25 * orientation\ SO + 8.33 * orientation\ SW + 0.007 * CO_2 - 5.69 * temperature - 3.782 * end\ terrace\ house\ type + 0.25 * mid\ terrace\ house\ type$

Spring Season

The variations in the minimum, maximum and average RH for the 44 houses for the Spring season are presented in Figure 4.15. The graph shows that during Spring, the minimum RH is found to be 20% in house F3, while the maximum RH reported is 99% in house C1. The average RH also shows a range between 43% and 69% for house E2/E3 and A3 respectively (Figure 4.16). These figures show a large variance in minimum and maximum values of RH among these houses, but the overall averages do not show much variation, with similar exceptions to the last case.

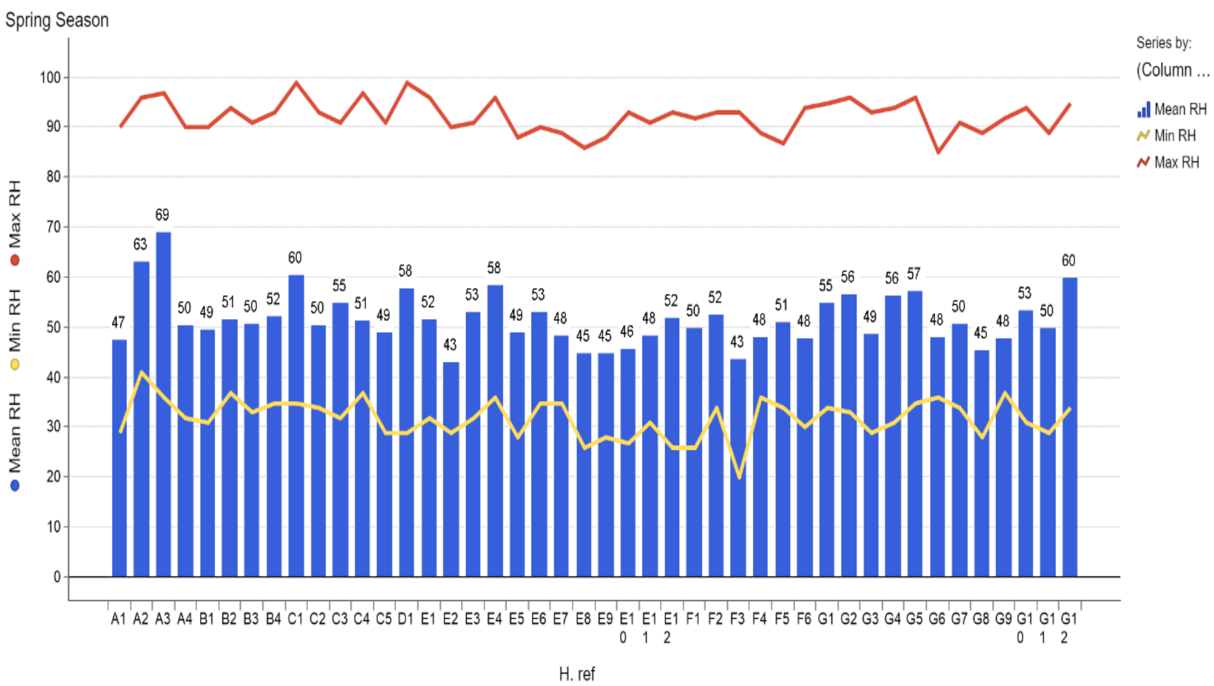


Figure 4.15 Minimum, maximum and average RH for 44 houses during Spring

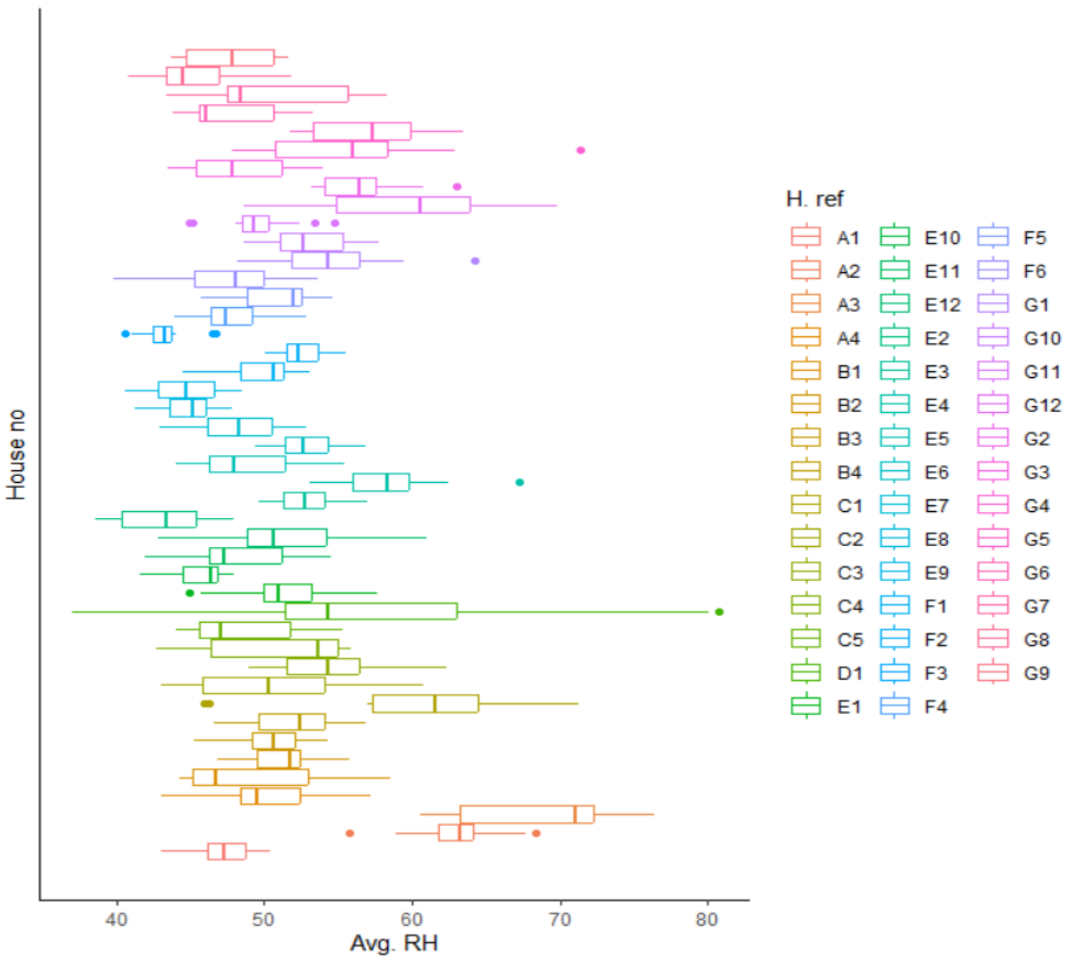


Figure 4.16 Box plot of average RH for 44 houses during Spring

But there is still some variation, which is studied with the help of the regression analysis, as given in Table 4.18:

Table 4.18 Regression equation for RH in different zones in Spring

House Zones	Regressions Equations
Living Area	$Humidity = 81.57 + 0.39 * occupancy - 0.55 * advice\ no\ change - 0.97 * orientation\ NE + 0.33 * orientation\ NO - 7.26 * orientation\ NW - 1.28 * orientation\ SO + 5.19 * orientation\ SW + 0.009 * CO_2 - 2.04 * temperature - 0.73 * end\ terrace\ house\ type + 0.95 * mid\ terrace\ house\ type$

Kitchen	$Humidity = 82.47 + 0.19 * occupancy - 1.38 * advice - 0.27 * orientation\ NE + 0.99 * orientation\ NO + 4.332 * orientation\ NW - 0.07 * orientation\ SO + 7.08 * orientation\ SW + 0.011 * CO_2 - 1.92 * temperature - 6.17 * end\ terrace\ house\ type - 3.52 * mid\ terrace\ house\ type$
En suite	$Humidity = 80.52 + 0.31 * occupancy - 2.41 * advice\ no\ change + 4.09 * orientation\ NE + 4.11 * orientation\ NO + 20.87 * orientation\ NW + 0.35 * orientation\ SO + 10.62 * orientation\ SW - 1.23 * temperature - 9.86 * end\ terrace\ house\ type - 6.98 * mid\ terrace\ house\ type$
Master Bedroom	$Humidity = 76.25 + 0.50 * occupancy - 0.37 * advice + 1.83 * orientation\ NE + 2.93 * orientation\ NO + 8.59 * orientation\ NW - 0.22 * orientation\ SO + 6.99 * orientation\ SW + 0.053 * CO_2 - 1.53 * temperature - 4.65 * end\ terrace\ house\ type - 2.97 * mid\ terrace\ house\ type$
Second Bedroom	$Humidity = 69.66 + 0.187 * occupancy - 0.21 * advice + 1.87 * orientation\ NE + 0.21 * orientation\ NO + 3.401 * orientation\ NW + 1.21 * orientation\ SO + 7.68 * orientation\ SW + 0.057 * CO_2 - 1.32 * temperature - 1.28 * end\ terrace\ house\ type + 0.25 * mid\ terrace\ house\ type$

The table presents that the houses with NW orientations experience the lowest humidity in the living room, while there is high humidity in the en suite and master bedroom, which is due to the use of shower in the en suite and night-time breathing in the bedroom. It may be also attributed to the layout of the house, as temperature is affected by orientation, but it is also important to understand here that the humidity is not strongly a function of exterior weather and house layout, and it will also be the indoor activities and behaviour of the occupants that are more likely to influence the humidity levels, and thus, this aspect needs further analysis.

Autumn Season

Figure 4.17 shows the variations in the minimum, maximum and average RH for the 44 houses in the Autumn season. The figure 4.17 shows that during the Autumn season, the minimum RH is found to be 29% in house F3 (which is exceptionally low), while the maximum RH reported is 99.8% in house D1. The average RH also shows a range between 50% and 68% for houses F3 and D1 respectively (Figure 4.18).

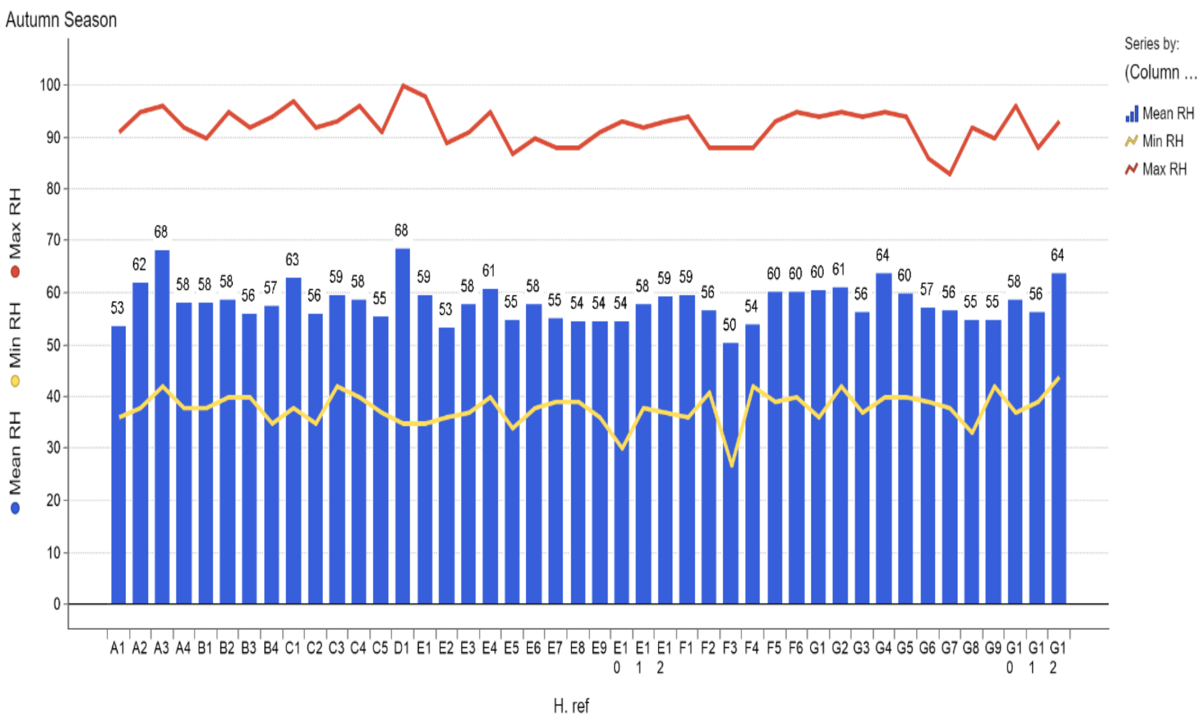


Figure 4.17 Minimum, maximum and average RH for 44 houses during Autumn season

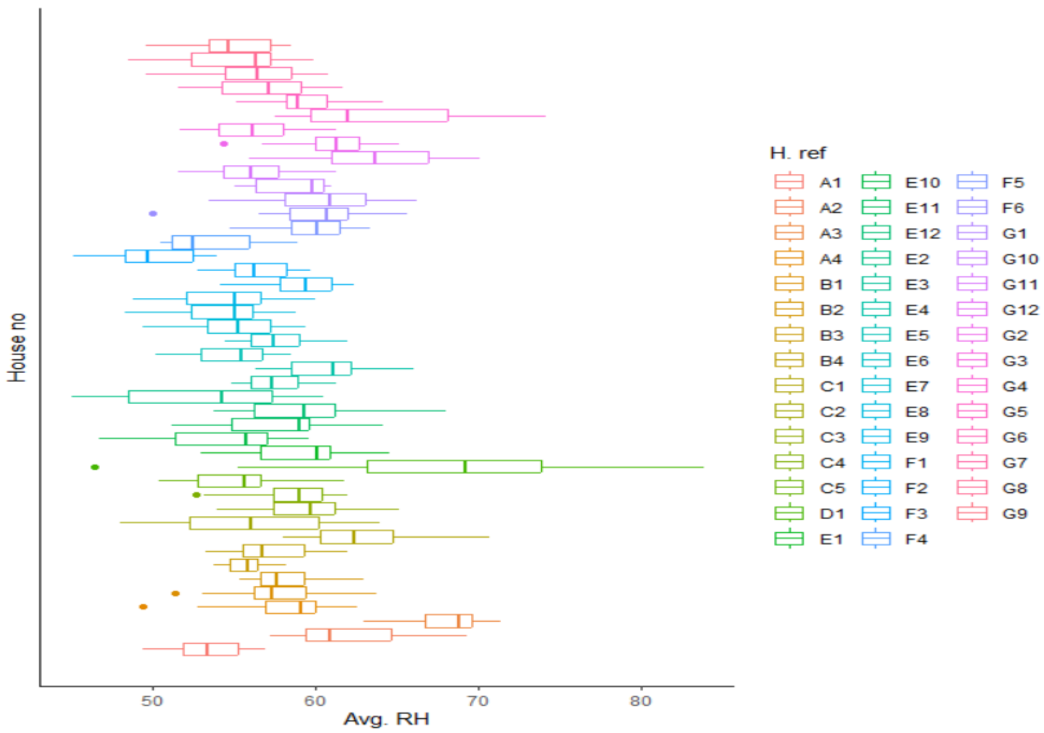


Figure 4.18 Box plot of average RH for 44 houses during Autumn season

It shows that there is a large variance in the amount of RH among these houses. To understand these variations, regression analysis is conducted, and the results are presented in Table 4.19.

Table 4.19 Regression equation for RH in different zones in Autumn

Zones	**Regressions Equations**
Living Area	$Humidity = 83.60 + 0.31 * occupancy + 0.04 * orientation\ NE + 0.86 * orientation\ NO - 4.67 * orientation\ NW - 0.93 * orientation\ SO + 4.14 * orientation\ SW + 0.009 * CO_2 - 1.97 * temperature - 1.43\ end\ terrace\ house\ type + 1.57 * mid\ terrace\ house\ type$
Kitchen	$Humidity = 85.89 + 0.18 * occupancy + 0.93 * orientation\ NE + 1.31 * orientation\ NO + 1.8 * orientation\ NW + 0.09 * orientation\ SO + 6.4 * orientation\ SW + 0.011 * CO_2 - 1.86 * temperature - 8.58 * end\ terrace\ house\ type - 4.18 * mid\ terrace\ house\ type$

En suite	$Humidity = 83.82 + 0.61 * occupancy + 7.23 * orientation\ NE + 3.40 * orientation\ NO + 10.89 * orientation\ NW - 0.70 * orientation\ SO + 8.97 * orientation\ SW - 1.22 * temperature - 11.46 * \ end\ terrace\ house\ type - 7.42 * mid\ terrace\ house\ type$
Master Bedroom	$Humidity = 78.75 + 1.11 * occupancy + 4.36 * orientation\ NE + 2.22 * orientation\ NO + 3.03 * orientation\ NW - 0.47 * orientation\ SO + 6.71 * orientation\ SW + 0.003 * CO_2 - 1.37 * temperature - 6.25 * \ end\ terrace\ house\ type - 3.08 * mid\ terrace\ house\ type$
Second Bedroom	$Humidity = 75.49 + 0.45 * occupancy + 3.2 * orientation\ NE + 0.01 * orientation\ NO + 4.22 * orientation\ NW + 0.57 * orientation\ SO + 3.72 * orientation\ SW + 0.006 * CO_2 - 1.36 * temperature - 3.14 * \ end\ terrace\ house\ type - 0.81 * mid\ terrace\ house\ type$

The houses in the NW orientation are likely to face the highest humidity in the living area and second bedroom, while the ones with end-terrace house types will experienced high humidity in the kitchen, en suite and second bedroom due to lower temperatures, and the houses in SW orientations will have highest humidity in master bedroom. It shows that the humidity of the different house zones is affected by different orientations and house types, due to temperature differences in these zones.

4.3.3. CO_2 trends

In this section, the level of CO_2 is assessed among the set of 44 houses for different seasons. It is divided into two parts, such that firstly an overall analysis of the average, maximum and minimum CO_2 levels for different seasons is undertaken.

Thereafter, in each of the seasons, the CO_2 levels for different house zones are analysed with the help of regression equations.

The variations in the minimum, maximum and average CO_2 for the 44 houses in the Summer, Winter, Spring and Autumn seasons are stated in Figures 4.19- 4.26.

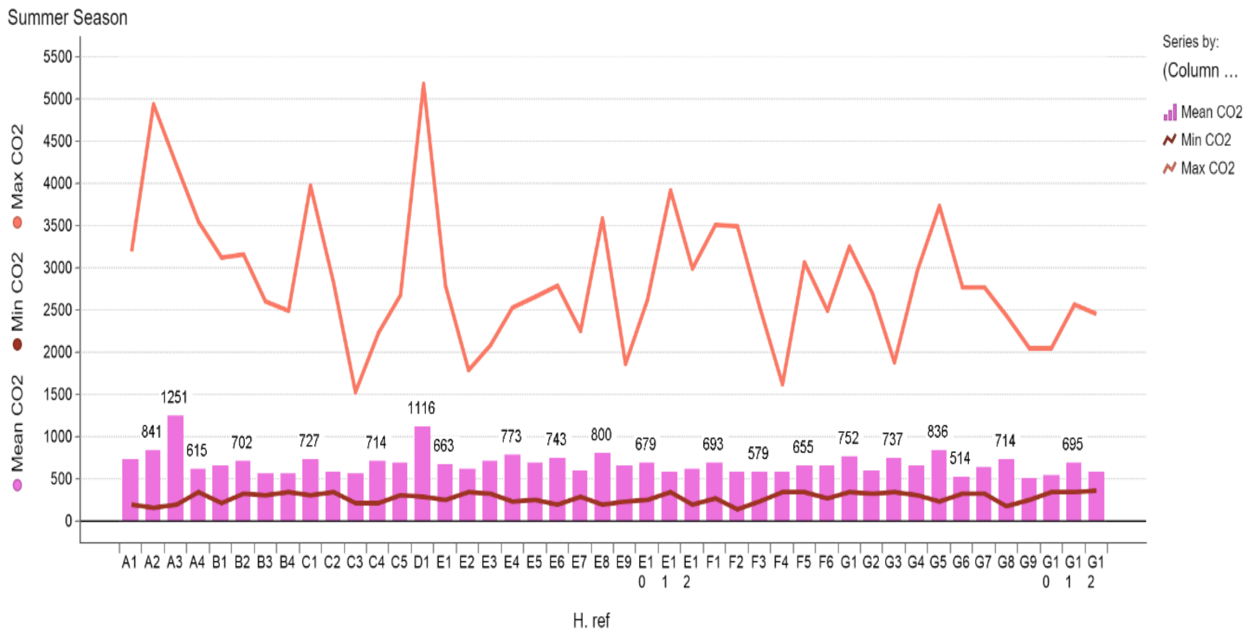


Figure 4.19 Minimum, maximum and average CO_2 for 44 houses during Summer

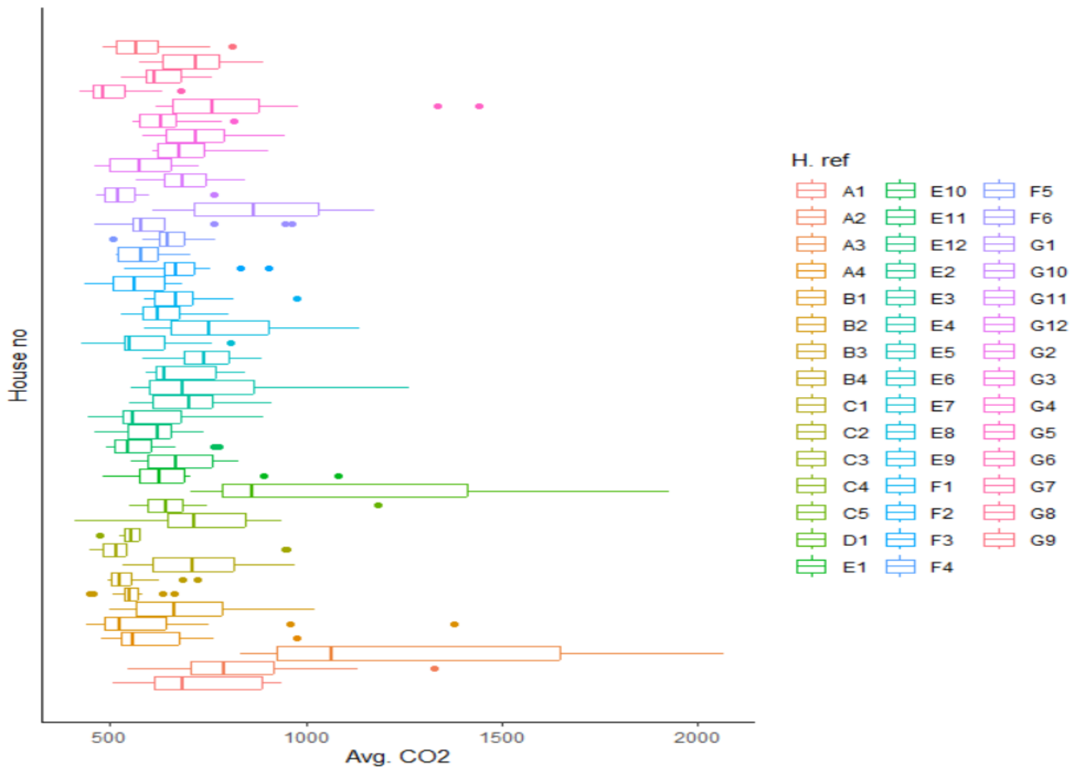


Figure 4.20 Box plot of average CO_2 for 44 houses during Summer

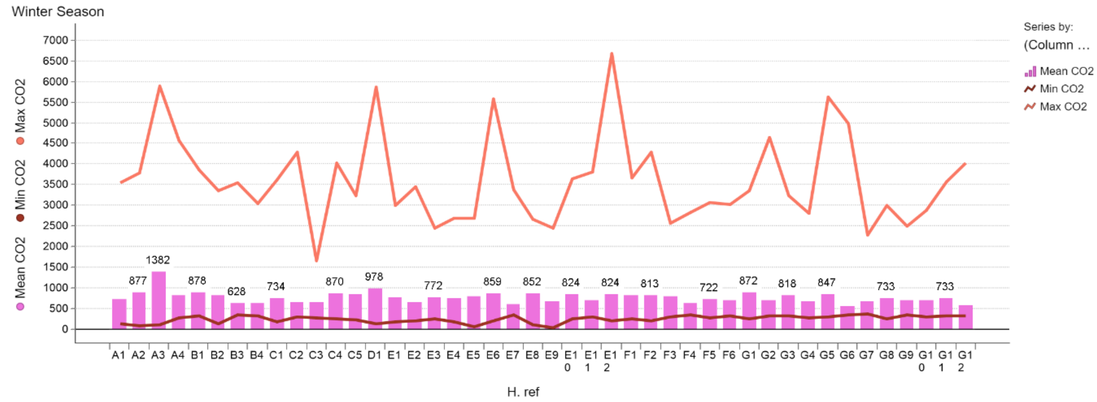


Figure 4.21 Minimum, maximum and average CO_2 for 44 houses in Winter

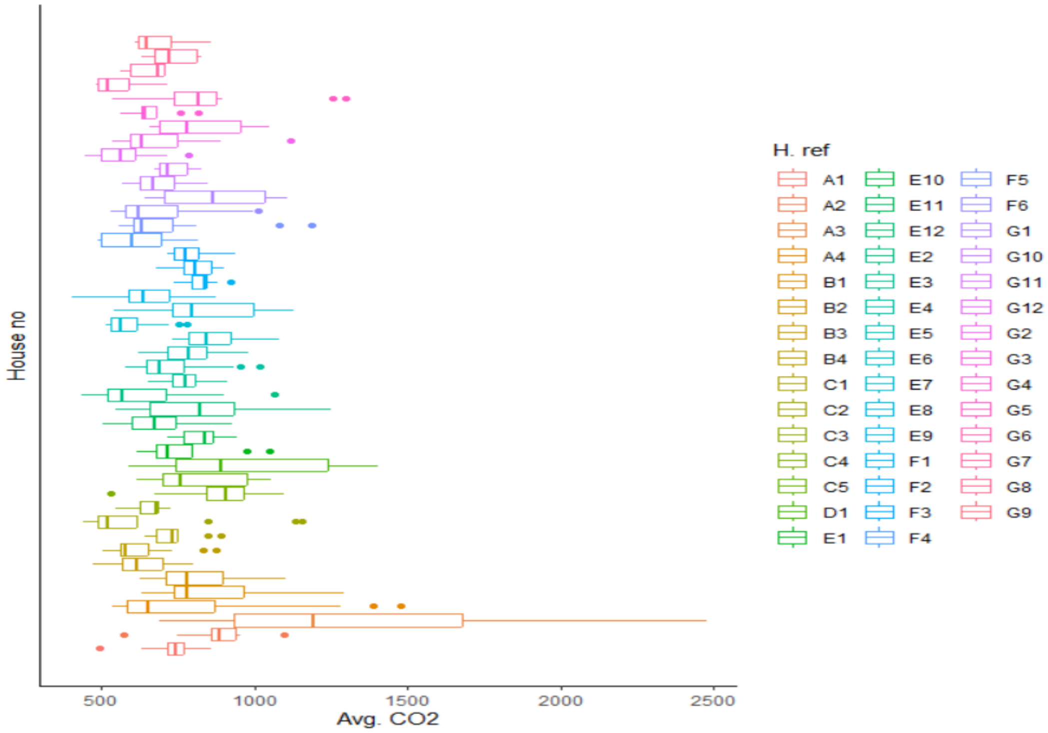


Figure 4.22 Box plot of average CO_2 for 44 houses in Winter

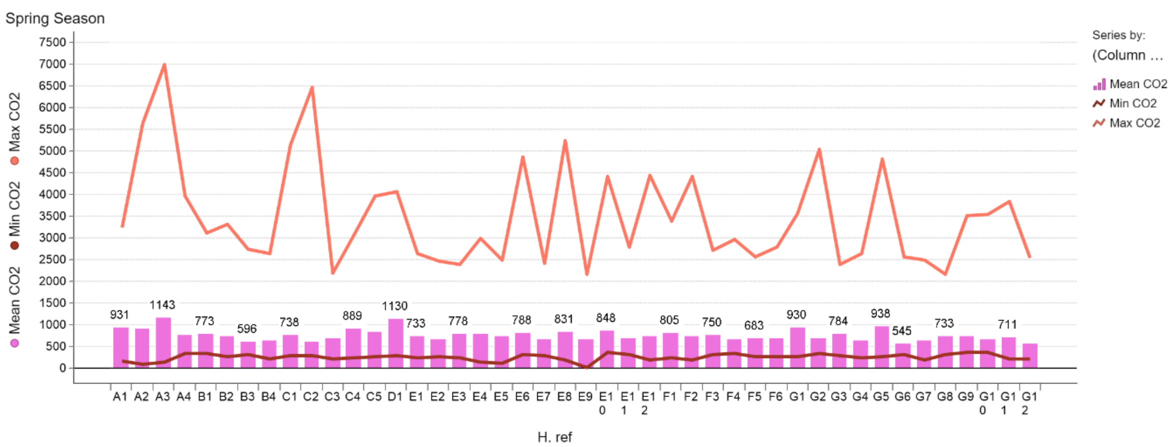


Figure 4.23 Minimum, maximum and average CO_2 for 44 houses in Spring

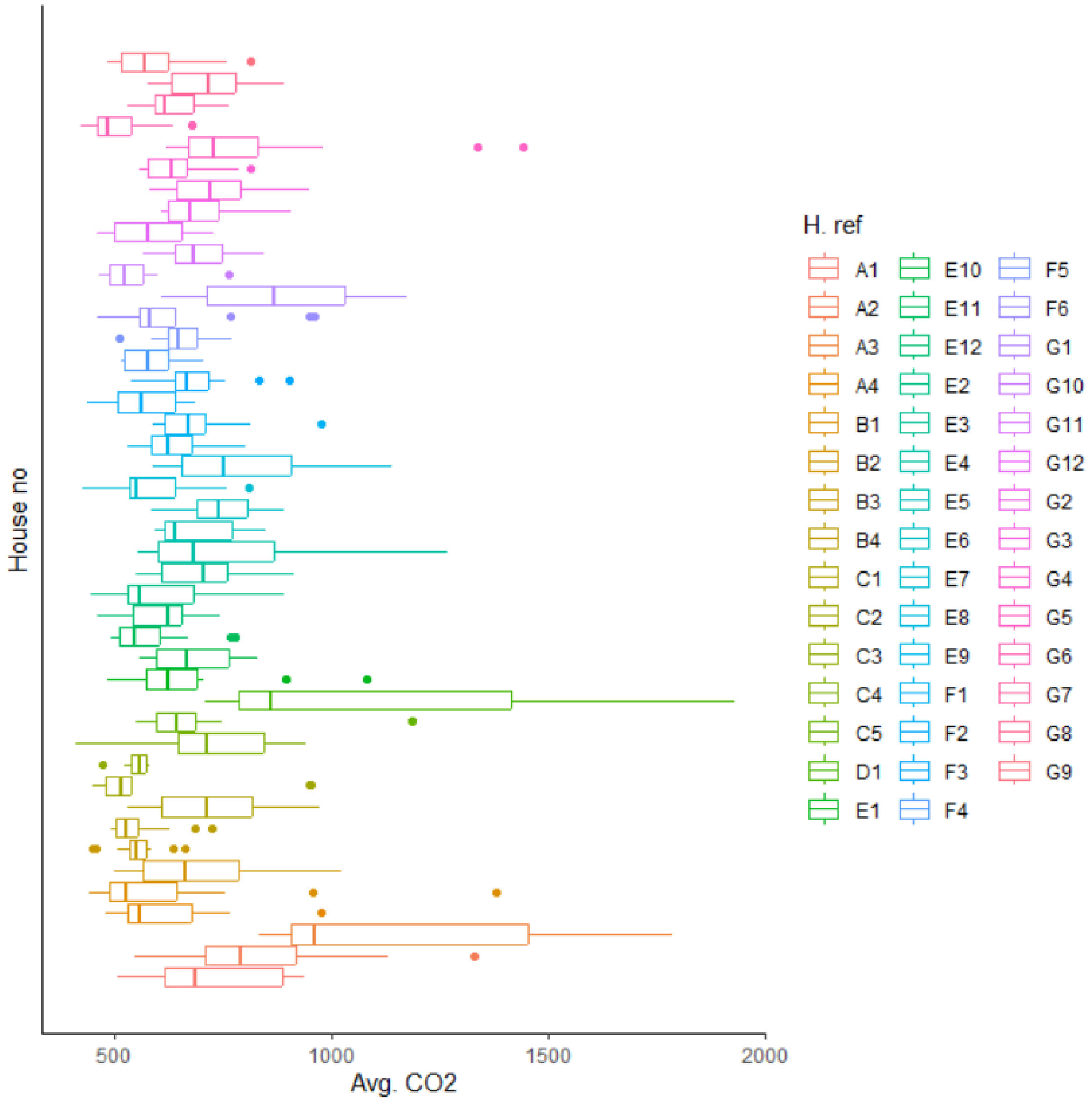


Figure 4.24 Box plot of average CO_2 for 44 houses in Spring

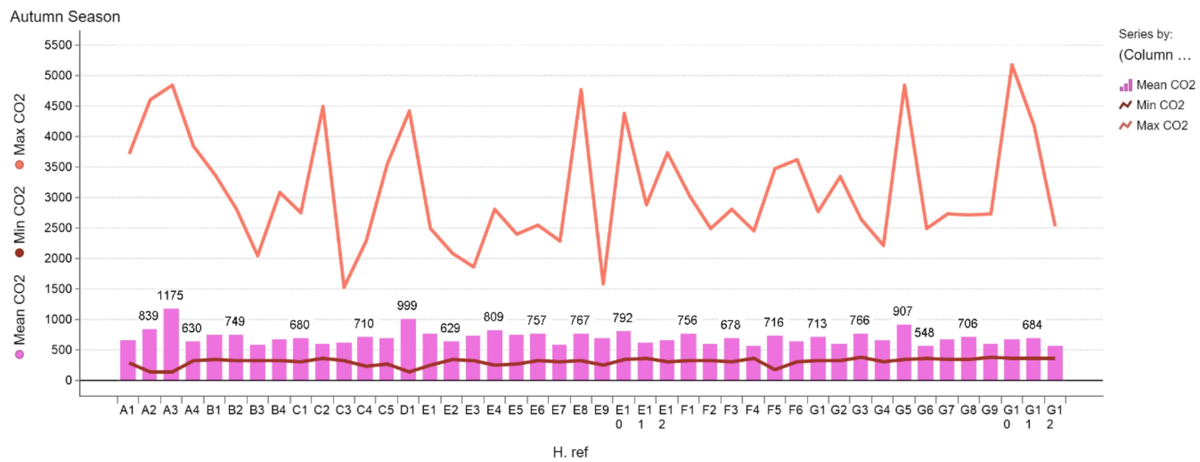


Figure 4.25 Minimum, maximum and average CO_2 for 44 houses in Autumn

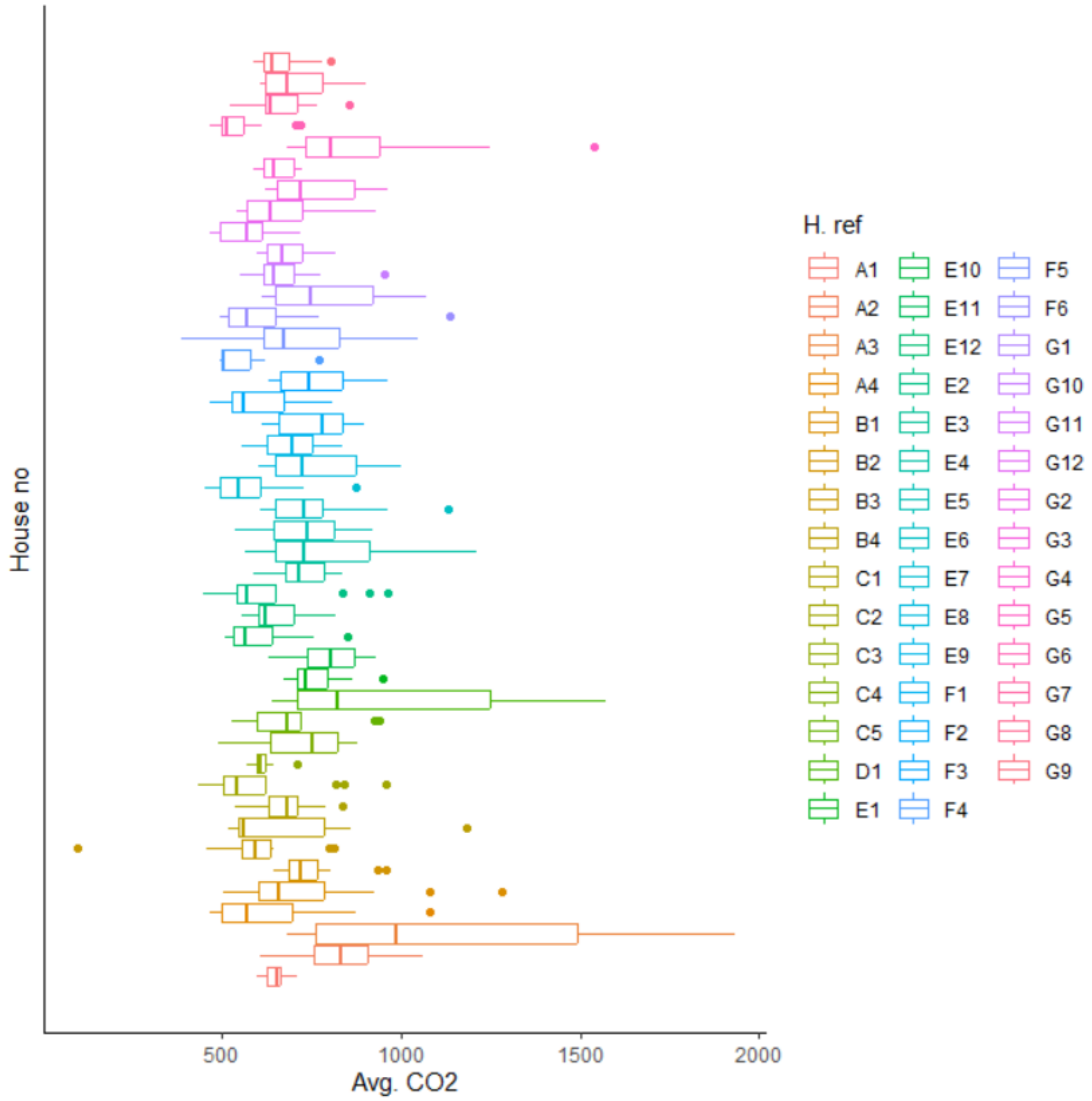


Figure 4.26 Box plot of average CO_2 for 44 houses in Autumn

Figures 4.19 and 4.20 show that during the Summer season, the minimum CO_2 is found at 375 ppm in house A1, while the maximum CO_2 reported is 4232 ppm in house A3. The average CO_2 also ranges between 437 ppm and 1784 for houses F2 and A3 respectively, which is a large disparity. Figure 4.21 shows that during the Winter season, the minimum CO_2 is found at 44 ppm (due to a sensor's fault) in house E9, while the maximum CO_2 reported is 6684 ppm in house E12, which is very high, but it dropped very quickly.

The average CO_2 also ranges between 195 ppm and 1051 ppm for houses E9 and A3 respectively (Figure 4.22). Figure 4.23 shows that during the Spring season, the minimum CO_2 is found at 176 ppm in house E9, while the maximum CO_2 reported is 7001 ppm in house A3, which is exceptionally high. The average CO_2 also ranges between 352 ppm and 2508 ppm for houses E9 and A3 respectively (Figure 4.24). Figure 4.25 shows that during the Autumn season, the minimum CO_2 is found at 144 ppm in house A3, while the maximum CO_2 reported is 5193 ppm in house G10. The average CO_2 also ranges between 93 ppm and 1932 ppm for houses B3 and A3 respectively (Figure 4.26).

These figures show a large variance in the amount of CO_2 among these houses. The large deviations between the minimum CO_2, maximum CO_2 and the average CO_2 shows the presence of certain outliers, which must be excluded, and for this, one may even consider the median value for the data. Furthermore, the presence of these deviations in CO_2 calls for studying the impact of other variables, like occupancy in houses, orientation of house, temperature, humidity, working status of occupants, zone of the house etc. There are significant differences in the CO_2 levels during different seasons. To understand the seasonal impact, the regression analysis performed to understand the impact of different factors in different house zones is given in Table 4.20.

From the below equations, it has been found that the CO_2 levels in these houses are affected by the house types and orientations (due to their need for ventilation), but in a real sense, the CO_2 levels are majorly the function of occupancy and the occupant behaviour such as opening and closing of the ventilation system, doors and windows, so that the CO_2 levels in different house zones are dissipated or accumulated.

Table 4.20 Regression analysis of CO_2 in different zones in different seasons

Season	House Zone	Regression Equation
Summer	Living Room	$\mathrm{CO_2} = -894 + 2.1 * occupancy - 34.8 * orientation\ NE - 11.6 * orientation\ NO + 111.1 * orientation\ NW - 14.3 * orientation\ SO + 54.7 * orientation\ SW + 47.09 * temperature + 6.20 * humidity - 27.9 * end\ terrace\ house\ type + 11.7 * mid\ terrace\ house\ type$

	Kitchen	$CO_2 = -887 + 2.7 * occupancy - 34.2 * orientation\ NE - 14.0 * orientation\ NO + 109.5 * orientation\ NW - 14.6 * orientation\ SO + 54.7 * orientation\ SW + 47.00 * temperature + 6.11 * humidity - 28.8 * end\ terrace\ house\ type + 10.02 * mid\ terrace\ house\ type$
	Master Bedroom	$CO_2 = -2136 + 6.7 * occupancy - 43.8 * orientation\ NE - 60.1 * orientation\ NO - 0.5 * orientation\ NW - 5.1 * orientation\ SO - 28.7 * orientation\ SW + 50.8 * temperature + 28.07 * humidity + 95.2 * end\ terrace\ house\ type + 96.7 * mid\ terrace\ house\ type$
	Second Bedroom	$CO_2 = -1501 + 54.8 * occupancy + 114.1 * orientation\ NE - 41.8 * orientation\ NO + 832.3 * orientation\ NW + 33.5 * orientation\ SO + 584.2 * orientation\ SW + 9.36 * temperature + 29.70 * humidity - 112.9 * end\ terrace\ house\ type + 155.6 * mid\ terrace\ house\ type$
Winter	Living Room	$CO_2 = -2480 + 6.5 * occupancy - 2.8 * advice + 195.8 * orientation\ NE + 78 * orientation\ NO - 84.6 * orientation\ NW + 117.5 * orientation\ SO + 136.7 * orientation\ SW + 100.9 * temperature + 22.34 * humidity - 116.4 * end\ terrace\ house\ type - 82.24 * mid\ terrace\ house\ type$

	Kitchen	$CO_2 = -2225 + 8.6 * occupancy + 34 * advice + 89.8 * orientation\ NE + 4 * orientation\ NO - 38.9 * orientation\ NW + 43.0 * orientation\ SO + 17.7 * orientation\ SW + 80 * temperature + 21.9 * humidity + 90.7 * \ end\ terrace\ house\ type + 78 * mid\ terrace\ house\ type$
	Master Bedroom	$CO_2 = -3628 - 15.8 * occupancy - 51.8 * advice\ + 30.5 * orientation\ NE - 31.6 * orientation\ NO + 64.8 * orientation\ NW + 65.9 * orientation\ SO - 89.9 * orientation\ SW + 116.68 * temperature + 40.24 * humidity + 157.11 * \ end\ terrace\ house\ type + 67.48 * mid\ terrace\ house\ type$
	Second Bedroom	$CO_2 = -1397 + 47.4 * occupancy - 65.6 * advice - 112.6 * orientation\ NE - 14.5 * orientation\ NO + 410.1 * orientation\ NW - 53.1 * orientation\ SO + 127.62 * orientation\ SW + 23.64 * temperature + 28.27 * humidity + 161.7 * \ end\ terrace\ house\ type + 74.2 * mid\ terrace\ house\ type$
Spring	Living Room	$CO_2 = -2349 + 12.4 * occupancy - 39.5 * advice + 100 * orientation\ NE + 70.8 * orientation\ NO + 162.5 * orientation\ NW + 103.8 * orientation\ SO + 76.3 * orientation\ SW + 98.2 * temperature + 22.85 * humidity - 87.3 * \ end\ terrace\ house\ type - 100.1 * mid\ terrace\ house\ type$

	Kitchen	$$\begin{aligned} CO_2 = &-2040 + 19.9 * occupancy + 5.2 * advice\ + 77.8 \\ &* orientation\ NE + 40.1 * orientation\ NO \\ &- 108.7 * orientation\ NW + 13.03 \\ &* orientation\ SO + 24.5 * orientation\ SW \\ &+ 77.7 * temperature + 20.7 * humidity + 70.8 \\ &*\ end\ terrace\ house\ type + 49.9 \\ &* mid\ terrace\ house\ type \end{aligned}$$
	Master Bedroom	$$\begin{aligned} CO_2 = &-4024 + 8.0 * occupancy - 60.2 * advice\ + 96.6 \\ &* orientation\ NE - 47.9 * orientation\ NO \\ &- 43.4 * orientation\ NW + 39.7 \\ &* orientation\ SO + 57.2 * orientation\ SW \\ &+ 116.98 * temperature + 48.48 * humidity \\ &+ 123.6 *\ end\ terrace\ house\ type + 186.9 \\ &* mid\ terrace\ house\ type \end{aligned}$$
	Second Bedroom	$$\begin{aligned} CO_2 = &-2325 + 50 * occupancy - 87.9 * advice - 135.8 \\ &* orientation\ NE + 25.1 * orientation\ NO \\ &+ 279.0 * orientation\ NW - 14.4 \\ &* orientation\ SO - 51.3 * orientation\ SW \\ &+ 71.37 * temperature + 31.10 * humidity \\ &+ 185.53 *\ end\ terrace\ house\ type + 84.93 \\ &* mid\ terrace\ house\ type \end{aligned}$$
Autumn	Living Room	$$\begin{aligned} CO_2 = &-2067 + 12.4 * occupancy + 218 * orientation\ NE \\ &+ 52.2 * orientation\ NO - 204.5 \\ &* orientation\ NW + 102.7 * orientation\ SO \\ &+ 192.7 * orientation\ SW + 87.37 \\ &* temperature + 18.42 * humidity - 172.7 \\ &*\ end\ terrace\ house\ type - 47.8 \\ &* mid\ terrace\ house\ type \end{aligned}$$

	Kitchen	$CO_2 = -1849 + 14.7 * occupancy + 113.6 * orientation\ NE - 8.9 * orientation\ NO - 215.2 * orientation\ NW + 30.5 * orientation\ SO + 121.9 * orientation\ SW + 72.95 * temperature + 18.08 * humidity - 21.2 * end\ terrace\ house\ type + 36.2 * mid\ terrace\ house\ type$
	Master Bedroom	$CO_2 = -3325 - 16.5 * occupancy + 126.3 * orientation\ NE - 51.2 * orientation\ NO - 93.7 * orientation\ NW + 40.1 * orientation\ SO + 162.6 * orientation\ SW + 108.04 * temperature + 36.72 * humidity + 67.8 * end\ terrace\ house\ type + 100.7 * mid\ terrace\ house\ type$
	Second Bedroom	$CO_2 = -3020 + 12.5 * occupancy + 92.1 * orientation\ NE + 55.1 * orientation\ NO - 119.0 * orientation\ NW + 65.3 * orientation\ SO + 457.5 * orientation\ SW + 83.84 * temperature + 36.93 * humidity + 16.5 * end\ terrace\ house\ type + 77.3 * mid\ terrace\ house\ type$

4.4. Overall Findings

On the basis of the above analyses, the findings can be summed up in Tables 4.21-4.23. The overall findings signify the impact of different independent variables (occupancy, advice, orientations, and house types) on each of the three dependent variables (temperature, CO_2 and RH) for different seasons and house zones.

4.4.1. Temperature

The overall findings for temperature are given in Table 4.21. It shows how the temperatures in different seasons and different zones of the house are affected by a number of variables including occupancy, advice (for two out of four seasons), different orientations, CO_2, humidity in the respective zones and the house types. Negatively impacted variables are marked in red in the tables. A number of important findings are highlighted as follows:

- During all four seasons, the temperature is mostly affected by the orientations, which can be due to the solar gains. However, it is observed that the temperature effect is uneven across different zones of the house, as signified by the orientation of the particular room/zone, and the rotation of the sun. Thus, the difference is due to the possibility of some rooms being warmer than others (due to more solar gain), while some take more time to warm (due to less solar gain).

- During Summer and Spring seasons, the temperature for the second bedroom and master bedroom are affected by the house type. Although all the houses are similar in design, except the 4End terrace houses which have a slightly different design, it is observed that the main house type impacting the temperature is a mid-terrace house, which, thereby, calls for further investigation in the reasoning, probably due to they are surrounded by warm houses on two sides.

- It can also be observed that the temperature is affected both positively and negatively by different factors, as indicated by the sign of the regression coefficient. Moreover, the temperature impact for the en suite is not considered, as it is not considered important.

- Another important finding entails that the kitchen, generally, exhibits a higher temperature as compared to the other zones. This may be due to the orientation, as it is in front side of the house, and attracts high solar gain but equally is also impacted by the cooking activities, perhaps prolonged cooking, which calls for further investigation about temperature differences in accordance with the timings of the day.

4.4.2. Relative humidity

Similar to temperature, the highest impact coefficients for RH are compared across different seasons and zones of the house. The maximum coefficient for each of the scenario is presented in Table 4.22.

From Table 4.22, the following findings can be drawn:

- it is found that the RH is mostly affected by the orientations and house types across all the seasons and different house zones. It is majorly due to the fact that the temperature of the house is influenced by orientations and house types, which can be responsible for increasing or decreasing the relative humidity respectively.
- The relevant coefficient factor is highest among the zone of en suite, which is likely due to more moisture build up due to shower in en suite, and it takes some time for the mechanical extract to dissipate that moisture due to wet surfaces.
- It is important to note that the change in advice is not shown to be a major factor in this analysis, but it has impacted the coefficient values, as viewed from the analysis performed in the preceding section. The advice was given to a few houses in November 2019. Data after November is also analysed in terms of any change in behaviour or indoor conditions. Few houses were advised to keep their pattern similar so that their natural behaviour in Winters can be observed, and the rest of the houses were advised to make few changes in their behavioural pattern to have a better indoor environment. Thus, to learn the impact of advice on the RH, further analysis is required which will be performed in a succeeding section.
- Another finding reveals that the movement in RH somewhat corresponds inversely with the changes in temperature, thereby, signifying the impact of temperature on the RH levels in the house zones. Absolute humidity values are also analysed further in the study to see the actual moisture content of the air regardless of temperature.

4.4.3. CO_2 levels

Similar to RH, the highest impact coefficients for CO_2 are compared across different seasons and zones of the house. The maximum coefficient for each of the scenario is presented in Table 4.23, from which the following findings can be drawn:

- It is found that the CO_2 levels are somewhat impacted by the orientation and house types. However, it is also important to note that this variable is mostly impacted by human activity and behaviour and patterns of the use of ventilation and indoor doors in the house. However, one of the possibilities of the high impact of orientations and house type is due to family behaviours of the occupants living in these particular houses, which can be due to ineffective and less use of windows or trickle vents.
- It is also important to note that the highest impact of orientations and house types are observed in the master bedroom and second bedroom, implying that the ventilation is most ineffectively used in those areas.

Table 4.21: Overall findings for impact of different variables on temperature in 44 houses

Season	Area	Occupancy	Advice	Orientation NE	Orientation NO	Orientation NW	Orientation SO	Orientation SW	CO_2	Humidity	End terrace	Mid Terrace
Summer	**Living**	0.27	N/A	0.39	-0.02	0.58	-0.12	0.16	0.002	-0.01	0.21	0.39
	Kitchen	0.27	N/A	0.38	-0.01	0.60	-0.12	0.16	0.002	-0.01	0.21	0.40
	MB	0.14	N/A	0.01	-0.56	-0.49	-0.19	0.11	0.005	-0.00	0.79	1.42
	SB	0.25	N/A	0.46	0.04	-0.07	-0.25	0.27	0.000	0.03	0.54	1.16
Winter	**Living**	0.28	-0.26	-1.61	-1.01	0.62	-1.15	-1.38	0.003	-0.14	1.00	0.32
	Kitchen	0.34	-0.34	-1.03	-0.49	1.26	-1.16	-1.25	0.004	-0.17	0.40	-0.18
	MB	0.32	-0.32	-1.62	-0.71	1.49	-0.82	-1.49	0.002	1.02	0.95	0.48
	SB	0.51	-0.40	-2.04	-0.67	0.21	-0.86	-1.89	0.000	-0.12	0.55	0.13
Spring	**Living**	0.23	0.01	1.50	0.71	0.20	0.86	1.26	0.002	0.13	1.17	0.56
	Kitchen	0.21	0.03	-1.36	-0.64	2.10	-0.70	-1.15	0.003	-0.15	0.65	-0.06
	MB	0.19	-0.17	-2.39	-1.03	1.84	-0.29	-1.15	0.001	-0.17	1.58	0.62
	SB	0.44	-0.02	-1.72	-0.39	0.30	-0.81	-1.44	0.001	-0.11	0.72	0.01
Autumn	**Living**	0.24	N/A	1.45	-0.90	1.43	-1.28	-1.36	0.003	-1.38	1.05	0.35
	Kitchen	0.21	N/A	-1.12	-0.49	3.18	-1.10	-1.30	0.003	-0.15	0.47	-0.07
	MB	0.30	N/A	-1.86	-1.14	3.13	-0.88	-1.30	0.001	-1.56	1.28	0.67
	SB	0.44	N/A	-1.29	-0.63	2.56	-1.26	-1.29	0.001	-1.26	0.21	0.01

Table 4.22 Overall findings for impact of different variables on RH in 44 houses

Season	Zone	Occupancy	Advice	Orientation NE	Orientation NO	Orientation NW	Orientation SO	Orientation SW	Temp.	CO_2	End terrace	Mid Terrace
Summer	Living	-0.59	N/A	1.38	2.12	7.93	0.29	5.21	-0.01	0.006	-4.45	-1.35
	Kitchen	-0.58	N/A	1.38	2.10	7.93	0.29	5.22	-0.02	0.006	-4.46	-1.36
	En suite	-0.13	N/A	2.04	5.55	13.84	0.87	6.58	1.07		-7.93	-8.05
	MB	0.15	N/A	1.10	4.01	3.17	0.79	4.77	-0.32	0.006	-5.35	-4.58
	SB	-0.12	N/A	0.15	2.23	1.40	2.01	5.49	0.18	0.000	-4.95	-3.92
Winter	Living	0.40	-1.09	-1.31	0.29	-7.42	-1.14	3.75	2.17	-0.010	-1.67	1.15
	Kitchen	0.36	-1.57	-0.13	1.13	1.76	-0.30	5.51	-2.13	0.001	-6.92	-3.31
	En suite	0.58	-2.84	5.44	3.57		0.14	6.81	-1.48		-10.96	-7.01
	MB	0.83	-0.44	2.84	2.45	6.00	-0.38	5.03	-1.87	0.007	-5.29	-2.12
	SB	-0.15	-0.44	5.03	1.46	2.69	3.25	8.33	-5.69	0.007	-3.78	0.25
Spring	Living	0.33	-0.53	-0.97	0.33	-7.26	-1.28	5.19	0.04	0.009	-0.73	0.95
	Kitchen	0.19	-1.38	-0.27	0.99	4.33	-0.07	7.08	-1.92	0.011	-6.17	-3.52
	En suite	0.31	-2.41	4.09	4.11	20.87	0.35	10.62	-1.23		-9.86	-6.98
	MB	0.50	-0.37	1.83	2.93	8.59	-0.22	7.00	-1.53	0.053	-4.65	-2.97
	SB	0.19	-0.21	1.87	0.21	3.40	1.21	7.68	-1.32	0.057	-1.28	0.25
Autumn	Living	0.31	N/A	0.04	0.86	-4.67	-0.93	4.14	-1.97	0.009	-1.43	1.57
	Kitchen	0.18	N/A	0.93	1.31	1.80	0.02	6.40	-1.86	0.011	-8.58	-4.18
	En suite	0.61	N/A	7.24	3.40	10.89	-0.70	8.97	-1.22		-11.46	-7.42
	MB	1.11	N/A	4.36	2.22	3.03	-0.47	6.70	-1.37	0.003	-6.25	-3.08
	SB	0.45	N/A	3.20	0.01	4.22	0.56	3.72	-1.36	0.006	-3.14	-0.81

Table 4.23: Overall findings for impact of different variables on CO_2 in 44 houses

Season	Zone	Occupancy	Advice	Orientation NE	Orientation NO	Orientation NW	Orientation SO	Orientation SW	Temp.	Humidity	End terrace	Mid Terrace
Summer	Living	2.08	N/A	-34.82	-11.62	111.15	-14.27	54.75	47.10	6.20	-27.90	11.65
	Kitchen	2.69	N/A	-34.17	-14.03	109.51	-14.56	54.71	47.00	6.11	-28.80	10.02
	MB	6.69	N/A	-43.77	-60.09	-0.52	-5.13	-28.68	50.80	28.07	95.17	96.70
	SB	54.81	N/A	114.12	-41.79	832.29	33.49	584.21	9.36	29.70	112.88	115.61
Winter	Living	6.49	-2.81	195.80	77.97	-84.60	117.50	136.70	100.90	22.34	-116.40	-82.24
	Kitchen	8.56	34.00	89.76	3.96	-38.90	43.03	17.69	80.00	21.90	90.65	77.99
	MB	-15.80	-51.85	30.52	-31.62	64.81	65.92	-89.94	116.68	40.24	157.11	67.48
	SB	47.38	-65.60	-112.60	-14.45	410.12	-53.05	127.62	23.64	28.27	161.74	74.17
Spring	Living	12.41	-39.46	100.00	70.76	162.50	103.80	76.31	98.21	22.85	-87.29	-100.10
	Kitchen	19.88	5.22	77.84	40.13	-108.70	130.30	24.47	77.65	20.68	70.79	49.90
	MB	8.02	-60.18	96.55	-47.93	-43.42	39.72	57.19	116.99	48.48	123.62	186.89
	SB	49.91	-87.95	-135.77	25.14	279.06	-14.44	-51.29	71.37	31.10	185.53	84.93
Autumn	Living	12.24	N/A	218.00	52.24	-204.50	102.70	192.70	87.37	18.42	-172.70	47.84
	Kitchen	14.67	N/A	113.60	-8.93	-215.20	30.45	121.90	72.95	18.08	-21.52	36.24
	MB	-16.49	N/A	126.27	-51.17	-93.66	40.09	162.65	108.04	36.73	67.78	100.71
	SB	12.55	N/A	92.14	55.09	-119.04	65.26	457.50	83.84	36.93	16.47	77.28

4.4.4. Summary

The chapter studied the impact of different variables - CO_2, temperature and RH - for different seasonal and zonal variables. However, there are a number of discrepancies found in the analysis, which encourage the researcher to undertake further analysis. For instance, occupancy is an important factor for CO_2, since a greater number of occupants implies a higher emissions of CO_2. But this is not always the case as it depends on the use of ventilation, of course. There are few examples of houses with a similar number of occupants but different CO_2 conditions. Moreover, while regressing the variables, occupancy has not evolved as the most important variable, thus, it calls for further investigation to understand the implication of occupancy on CO_2 levels. This factor is considered to examine of the extent to which occupancy affects CO_2 levels in general. There are several other conditions which can affect this variable such as closed trickle vents, not opening the bedroom door in the morning or turning off the central ventilation system.

Similarly, humidity and CO_2 are not affected significantly by house type or orientation. But as the coefficients for both the RH and CO_2 are higher for these variables, it implies that there are a few houses that are affected at these levels. For example, if one of the house type coefficients Is higher for either CO_2 or humidity, then there can be a few houses in that category which are affecting these results, but there is no direct correlation between them. There are also other conditions that can generate moisture and affect inside humidity, for example, showering, cooking and breathing, which are not discussed in this section. Hence, it is necessary to undertake further analysis of these factors for individual categories of houses.

5. Family Behaviour and IAQ

5.1. Introduction

In the previous section, it was observed that the variables of temperature, RH and CO_2 were significantly impacted by differences in seasons and time of the day. To understand the impact of different zones of the house, the influence on these variables is further analysed in this chapter. As an extension to the last chapter, this chapter will thoroughly discuss the impacts of all these factors individually. Moreover, the chapter will highlight the impact of different family and occupant behaviours on the indoor air quality of these selected houses in Location 1.

5.2. Orientation and its Impact on Thermal Environment

Orientation has evolved as an important factor that impacts all three variables, temperature, CO_2 and RH, as observed in the last chapter. In this study, a total of six orientations are considered, namely NE, NO, NW, SO, EO and SW. There is a strong relationship between any given house/room orientation and the thermal conditions inside, particularly the effect of solar gain on temperature and, subsequently, RH, the latter of which will be higher in summers but will pose an impact all year round.

Since the sun rises in the east and sets in the west, the houses/rooms that are facing the south will have the highest solar gain. That is, when the longer dimension of a house faces south, the relevant vertical surface area of the house will absorb the sun's energy. The role of windows is also important in such houses because they directly impact the penetration of solar rays inside the house, which can be absorbed to influence the temperature, humidity levels and, indirectly, the CO_2 levels. People tend to open doors/windows if a room is too warm which impacts the ventilation and hence the overall CO_2 levels.

Figure 5.1 signifies the proportion of time in two seasons, namely Winter and Summer, where the temperature (T) of different zones of the houses in different orientations shows deviations from the acceptable range of 18 to 25°C. A high temperature is considered to be T > 25°C, while a low temperature is considered to be T < 18°C. Overall, it can be observed from the graph that the incidences (in the percentage of total time) of low-temperature exceedances almost always occur in Winter, not surprisingly, owing to low external temperatures.

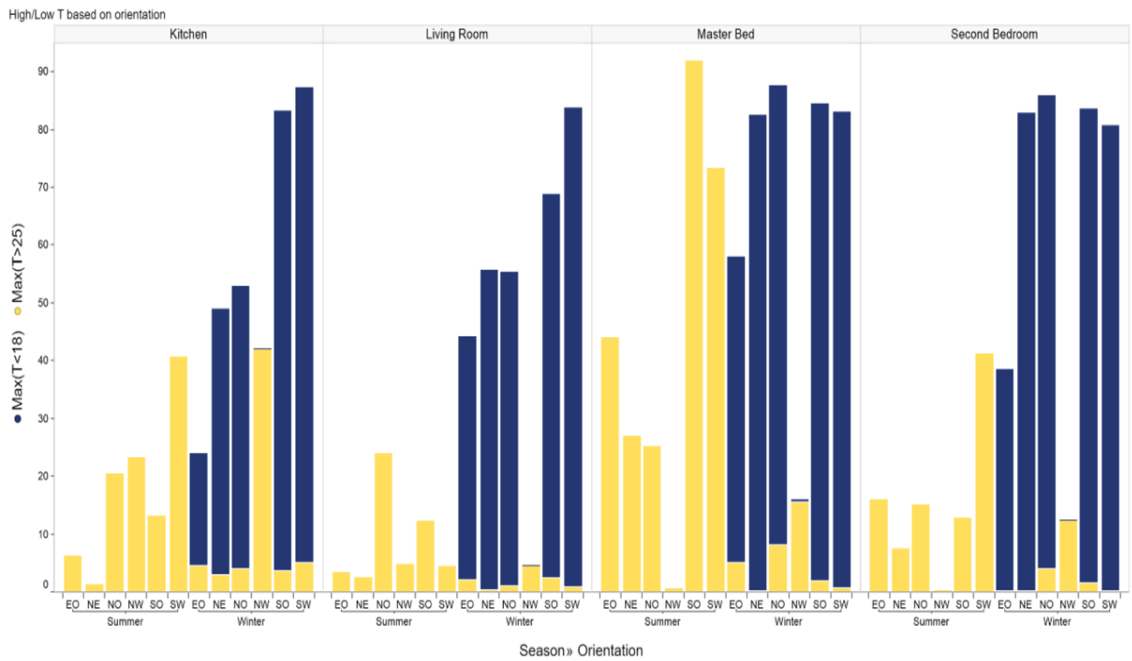


Figure 5.1 Exceedance of temperature in Summer versus Winter for four house zones

Conversely, it is not the case that high-temperature exceedances are confined to the Summer. For a house to maintain a comfortable indoor temperature, occupants can use their heating systems wisely, along with the use of other occupant-related behaviours, such as trapping heat by closing the door after switching off the heating system.

Further findings are given as under:

- In kitchens, the exceedances are more evident in SW and NW oriented houses in Summer, while the NW oriented kitchen areas are more vulnerable to high temperatures in Winter. Moreover, during the Winter, the houses with

SW and SO orientations are most likely to experience higher incidences of low temperature.

- In living rooms, high temperatures during Summer are evident in NO oriented houses, while during Winter, low temperatures are experienced in SO and SW oriented houses, which is due to the fact that all houses have their living room in the back, so the living room will face the opposite orientation to the front of the house.

- The master bedrooms in Summer exhibit a higher exceedance in the SW and SO oriented houses. Since these two zones of the house are located in the front, they can also utilise solar gain in Winter and Autumn more effectively to manage their indoor environment quality. It is also interesting to note that out of all four zones in these houses, the master bedroom represents the highest proportion of exceedances in both seasons and, thereby, the reasons for these exceedances and the measures to reduce them can be provided to the occupants. In Winter, the NW oriented house exhibits the highest incidences of exceedances. Also, the houses in the NE, SW and SO orientations reflect the maximum times of low temperature in the master bedroom. This is due to the fact that there is only one house facing NW, and the master bedroom in this house is occupied for lengthy periods, and the heating is mostly on in that room, which is the reason for its higher average temperature, in comparison with other rooms. Exceedances are higher in Winters due to the switching on of the heating system for most houses.

- In the second bedrooms, the exceedances of temperature are predominantly lower in summers, as compared to the master bedroom. This may be attributed to the layout of the house, such that the second bedroom is usually on the rear side of the house, which affects the solar gain. In both Summer and Winter, the maximum incidences of high temperature and lower temperature are evident in the SW orientation, which can be due to the use of the heating in Winter, and solar gain in Summer.

Figure 5.2 signifies the proportion of time in Autumn and Spring when the temperature of different zones of the houses in different orientations have deviations from the range of 18 to 25°C. Overall, it can be observed that the incidences of low temperature are more evident in Spring as compared to the Autumn. There is no particular reason for this difference as the average outside temperatures in both seasons were similar.

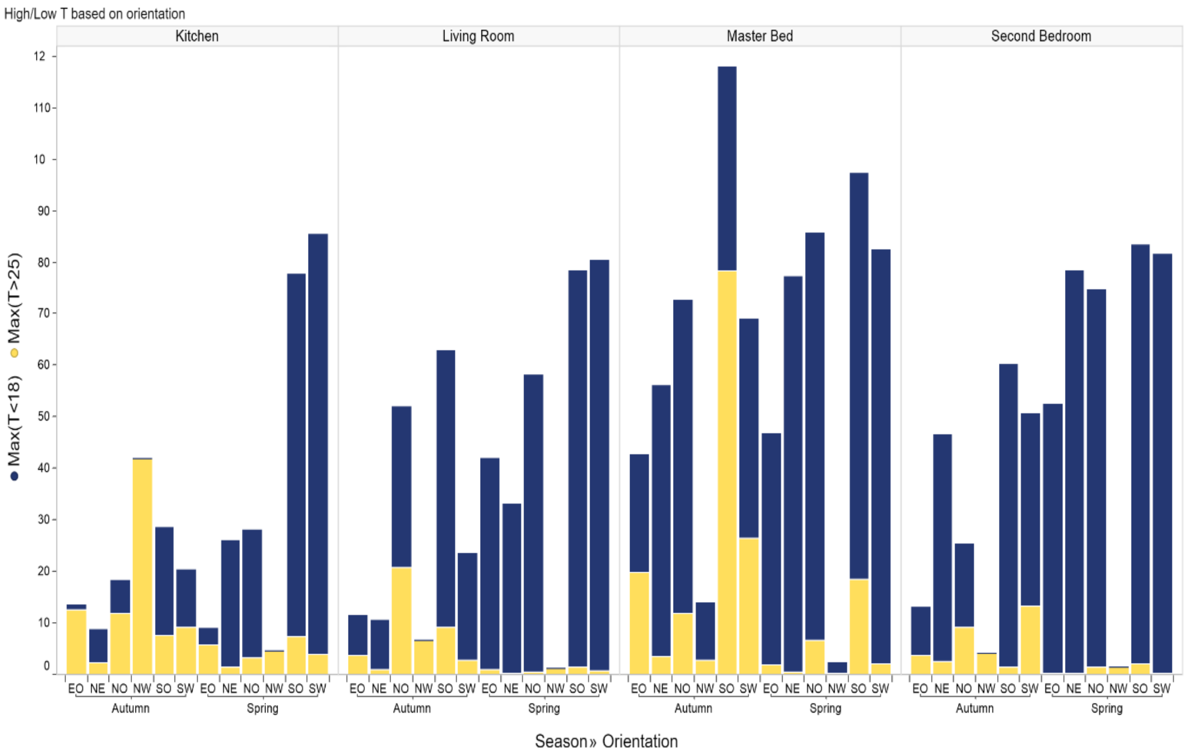


Figure 5.2 Exceedance of temperature in Spring versus Autumn for four house zones

Further findings are given as follows:

- In the kitchen, during Autumn, the exceedances of temperature are more evident in NW and NO oriented houses, while in Spring, all houses have nearly similar incidences of high temperature, which is less than 5% of cases. However, during Spring, the houses with SW and SO orientations are more likely to experience higher incidences of low temperature in the kitchen.
- In living rooms, the overall proportions of low temperature are higher than that of the master bedroom and kitchen. People tend to spend more time in bedrooms and the kitchen's temperature is influenced by cooking activities.

During Autumn, the high temperatures are evident in NO oriented houses. During Spring, low temperatures are experienced in SO and SW oriented houses.

- The master bedrooms in Autumn exhibit a higher exceedance in the SW and SO oriented houses. It is also interesting to note that of the zones considered, the master bedroom represents the highest proportion of exceedance in both seasons. Also, the houses in the NE, SW and SO orientations reflect the highest periods of low temperature in the master bedroom.

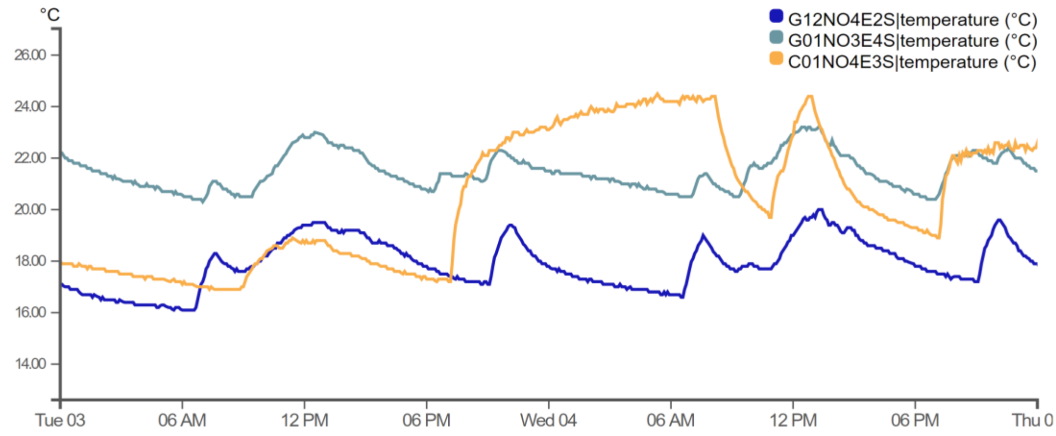
- In the second bedrooms, the high exceedances of temperature (more than 25°C) are predominantly lower as compared to the master bedroom. This could be due to the master bedroom being used in most of the houses regardless of the occupancy while the second bedroom is used in houses with more than 2 occupants. In Autumn, the maximum incidences of high temperature are evident in the SW orientation, while in Spring, the maximum exceedances are observed in NW, NO and SO oriented houses. Although the orientations are not that important since the layout of the house shows that this zone lies towards the back side of the house, the temperature difference can be due to the seasonal impact, or the usage. The houses with children are more likely to use that room, and those houses will show lesser exceedances.

- Out of the four zones, the master bedroom shows the highest number of incidences of high temperature, which can be due to the fact that it is the most used zone regardless of the occupancy.

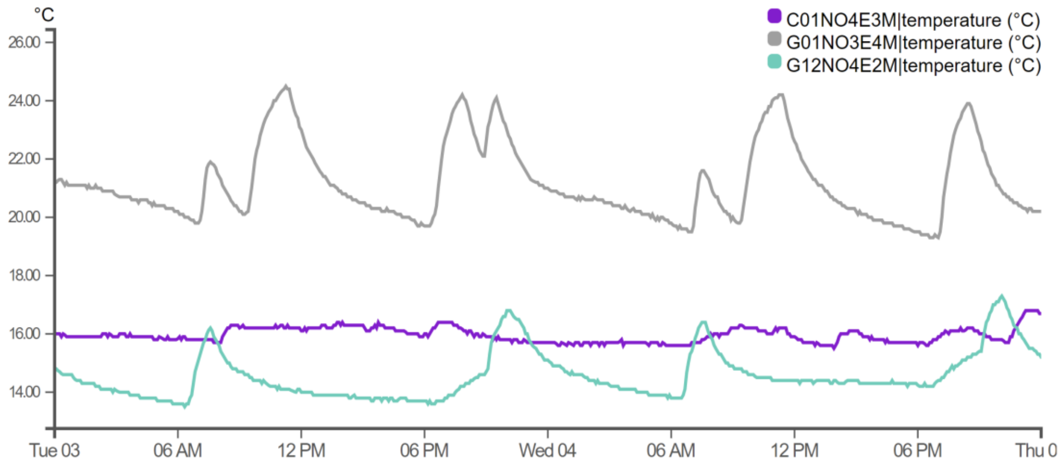
However, it is important to note that the above patterns and findings may not be significant for all the houses in the same orientation. After undertaking the analysis, it was interesting to note that many houses in the same orientation exhibit a wide variation in the temperature, probably due to occupancy factors. It may be majorly attributed to their personal living behaviour and use of the heating and ventilation systems, door-window openings, as well as the use of Trickle vents.

5.2.1. Variations of solar gain in different houses

So far, the average values of the main parameters of all the 44 houses have been studied. However, it is important to note that the houses with the same orientation (and in the same season) can experience a wide variation in the measured elements of IAQ, such as shown in Figure 5.3.



(a)



(b)

Figure 5.3 Effect of solar gain on different house examples, with the same orientations - End terrace bedrooms (a) Second bedroom, S (South orientation) and (b) Master bedroom, M (North orientation)

Figure 5.3(a) shows three houses, namely, C01, G01 and G12, that have the same orientation (of NO), but which exhibit a large variation in the temperature in the same day in Autumn in the same house zone, the second bedroom. It is observed that house G12 shows the least temperature range of 17 to 20°C throughout the day. In contrast, house C01 showed a range of temperature between 18 to 24.6°C between 6 am and 12 pm. It is evident that on two consecutive days, around 9 am on day 1 and 12 pm on day 2, there is a gradual rise in temperature in the three houses at the same time and in similar proportion, which is probably due to solar gain, these room being South facing. It raised the temperature by nearly 2°C in these areas and kept them warmer for a longer period. However, in house C01, it is evident that the heating is on throughout the night (from 6 pm to 6 am next morning) and, thereafter, it dropped suddenly probably due to leaving the bedroom door completely open for a lengthy period. It results in a higher peak temperature for the bedroom, decreasing drastically in the morning. This demonstrates the extent to which opening doors in heated rooms contributes to rapid heat loss. That is, when the doors are kept open after running a heating system, the heat is not trapped inside and rather migrates out by convection, inferring that the heating system must be switched on for a higher time, leading to poor IAQ and energy inefficient use.

Finally, house G01 exhibits a range of temperatures that remain between 20.5°C and 23°C, with no highly significant steep falls or rises in the temperature, in contrast with G12. However, it can be observed that the heating system in house G01, with four occupants, is switched on for a longer duration than in house G12, with two occupants. It appears that there is no heating used in house C01 on these two days. So, it can be concluded that for houses with similar construction and orientation, the temperature environment depends more on heating controls than on occupancy levels, which means the inefficient use of the openings and heating system can lead to a loss of trapped heat, which can be saved by improving the usage patterns (this will be addressed in the subsequent sections).

Similarly, the differences in the temperatures for these three houses are investigated for the master bedroom, as shown in Figure 5.3(b), all with a Northern aspect. House G12 exhibits a similar pattern as in the second bedroom, where the average temperature throughout the day remained between 15 and 16.6°C approximately. The reason for the lower temperature in the master bedroom as compared to the second bedroom may be due to the full opening of the Trickle vent (100%), or a lower setpoint or the heating system being used for a shorter duration.

The best performing house was G01, which particularly showed a temperature range within the normal comfort zone, that is, between 19 and 24.2°C. The comparatively wider fluctuations in the temperature in this house may be attributed to a greater number of occupants, their presence for a greater number of hours and the evidently higher use of the heating throughout the day. Also, house G12 exhibited a more efficient use of their heating system, since they seem to use it only twice a day, once in the morning and once in the evening, on both days. Hence, it can be inferred that the impact of the orientation on a house's temperature is observable, but it is not the sole factor that influences the temperature of different zones in a house. Hence, the role of the internal environmental actions is highly important, such as the use of heating systems, setting of Trickle vents, occupancy patterns and the pattern of use of different devices in the house.

5.3. House Types and Impact on Temperature

In this section, the impact of house types, namely, end terrace or mid terrace, on the average temperature is studied. It is generally assumed that the houses have identical construction details and if they have similar orientations must have similar exposure to solar gain, and thus, must have a similar range of temperatures, notwithstanding occupant behaviour. Firstly, the average temperature for different sets of house types over six months is assessed, as given in Figure 5.4, where the labels for the various months are given in Table 5.1.

Table 5.1 Reference letters used for different months

Month	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Ref.	a	b	c	d	e	f	g	h	i	j	k	l

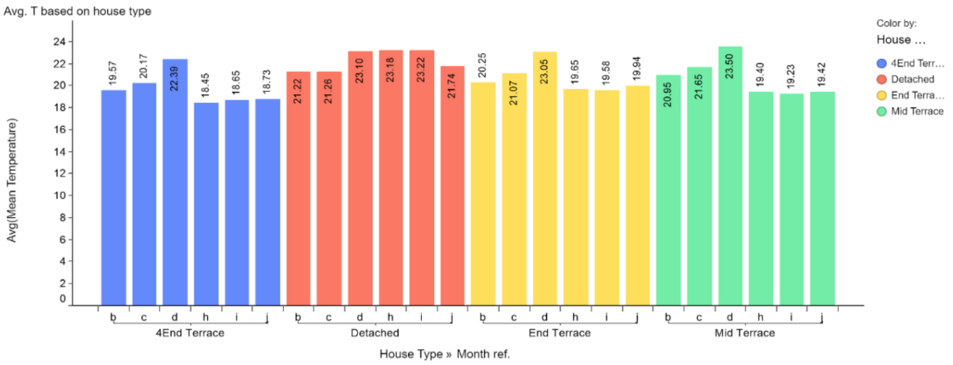


Figure 5.4 Average temperature of different house types during different seasons

This figure shows the average temperature for the months of May to October, thereby covering two seasons, Summer and Autumn, for all four house types, namely 4-bedroom end terrace, detached, 3-bedroom end terrace and mid terrace. From this graph, the following findings can be deduced:

- The average temperature in 4-end terrace houses is generally slightly lower than in other house types but less so than might have been anticipated due to the high level of insulation used in all house types.
- Other than the detached houses, all other house types experienced a lower temperature is Autumn, and higher in Summer, thereby, signifying the impact of exterior environmental conditions.
- Another impact of the external environment is that July was the hottest month externally (from the weather station data), leading to the highest temperature in all the house types, while no such difference is visible in the months during Autumn. The primary conclusion is that external temperatures are influential in determining the indoor characteristics of the houses when the heating is not on, despite the high level on insulation provided in every house type.

To study the role of indoor features of houses with similar house types, further analysis is required. For this, the two main house types, end-terrace and mid-terrace, are more closely analysed with respect to trends in temperature (Figure 5.5).

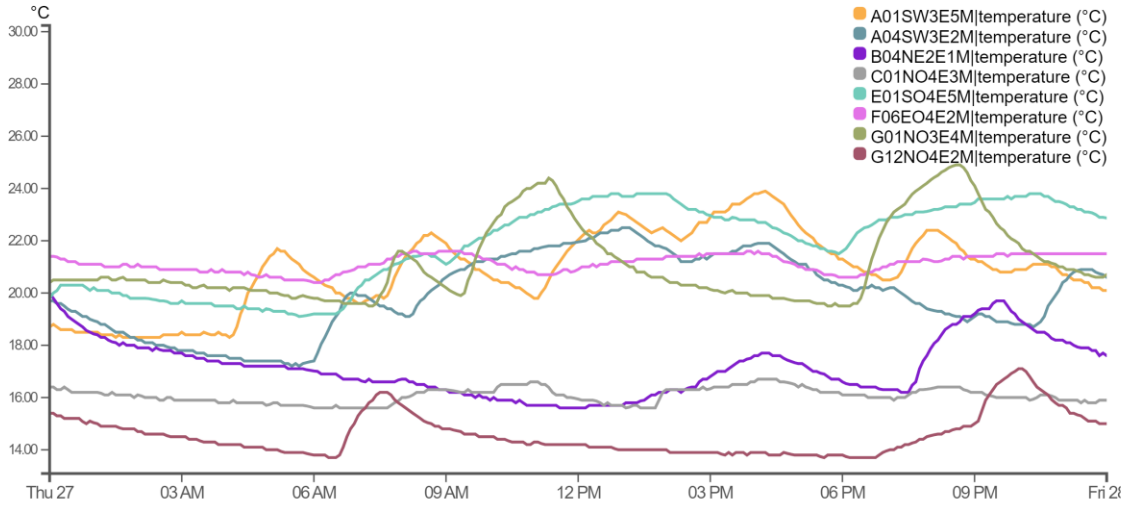


Figure 5.5 One-day (Winter) temperature profile in the master bedroom of all ten 4-end terrace houses

In Figure 5.5 the houses, with house references, A1, A4, B4, C1, E1, F6, G1 and G12, all belong to the same house types (end terrace and 4-end terrace). Despite the similarity between houses (and the data is all from the master bedrooms), they do not all exhibit similar temperature gain, although the range of temperatures in these houses is between, for example, 16.9 to 20.4 °C for houses G12 and F6. From this graph, it is noted that the same house types exhibit a wide range of temperatures in one day, but also that these grouped trends can be explained – heating on or not, solar gain or not, etc. For example, house E1, which experienced a temperature of 20 °C at 9 am, increasing to 24 °C by noon, the same trend was witnessed in the evening between 6 pm and 9pm, caused by the use of the heating system only twice in the day. Similarly, most of the houses exhibited a rise in temperature just twice in a day, demonstrating the use of the heating system in morning and evening time. However, it can be noted that house G12 showed a much lower temperature range, even after switching on the heating system, with the temperature range of 15.5 and 17 °C during the day. This may be due to the fact that the house's Trickle vents are always 100% open, or a window is slightly open, and thus, neither the solar gain, nor the heating is in place for long enough compared to others.

To further understand the impact of the indoor environmental characteristics of same house type, a more refined analysis is performed (Figure 5.6). In this figure, the minimum and maximum ranges of temperature for all the end terrace houses for the same house zone (master bedroom) is presented for three days from 12th to 14th February. One of the findings of this graph is that some of the houses exhibit a higher difference in the temperature range on a specific day, and over the three-day period. For instance, houses A01 and C01 showed a similar range of minimum temperature on each day, of about 6 °C, while other houses, such as F06 and G12, consistently showed a much smaller range of about 2 °C. In contrast, house A04 showed a higher range of temperature at day 2, and lower on day 1 and day 3. This confirms that the external temperature is not the only function which affects internal temperature patterns, but other indoor factors such as the living patterns, use of indoor appliances and devices, like trickle vents, heating and cooling devices, considerably impact the house temperature. From Figure 5.6, it may be noted that house G01 always experienced the highest temperature, exceeding 25 °C, while its lowest temperature was 18 °C, which was also at the higher end. In contrast, house G12 had a minimum temperature of between 12 and 16 °C, at all times. Such a low temperature was a feature of complaints made by the occupants of that house, who always felt that their house was overly cold most of the time which can be due to some issue with their Trickle vent settings (as checked by site team).

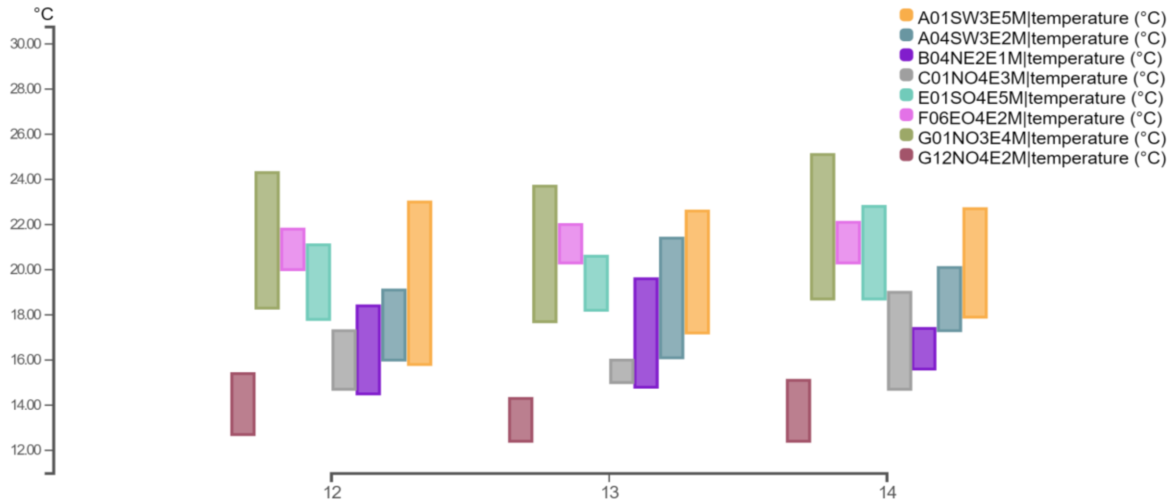


Figure 5.6 Min/Max range of temperature on 3 consecutive days in February (12^{th}, 13^{th} and 14^{th})

5.4. Family Behaviour and its Impact on Indoor Environment

5.4.1. Occupancy (working/stay-at-home)

Figure 5.7 shows the average CO_2 levels for all 44 houses, colour coded on the basis of occupancy in each house. Different colours show different occupancy levels as per the accompanying legend, ranging between 1 and 5; their ages are not defined. The figure shows that the average CO_2 levels ranges between 542 and 1238 ppm, without considering the presence (working or staying at home) of the occupants. It can be observed that generally the CO_2 levels are lower for houses with lower number of occupants: for example, the houses with one occupant (B3, B4, E1, G1 and E2 in blue) have a much lower CO_2 levels (between 567 ppm (for house B3) and 636 ppm (for house E2)); On the other hand, the average CO_2 level for houses with 5 occupants (in pink) ranges between 701 ppm (house F3) to 1056 ppm (house D1). However, some contrasting findings are also made, since the average CO_2 levels of houses with 4 occupants range between 769 ppm (for house F1) to 1238 ppm (house A3), which is much higher than the range for houses with 5 occupants. Similarly, the lowest average CO_2 level exists in house G6 (542ppm), which houses 3 occupants. In fact, the majority of houses with an occupancy of 5 is mid-range in this scale showing it is possible to have high occupancy medium CO_2 levels in a house design of this type. The ones with particularly high levels (E3 and D1) merit particular attention. Therefore, while the occupancy number is relevant to the CO_2 level, it is not the sole determinant related to occupancy of course. This calls for further analysis to understand the impact of working outside the home status or staying at home in the context of occupancy levels.

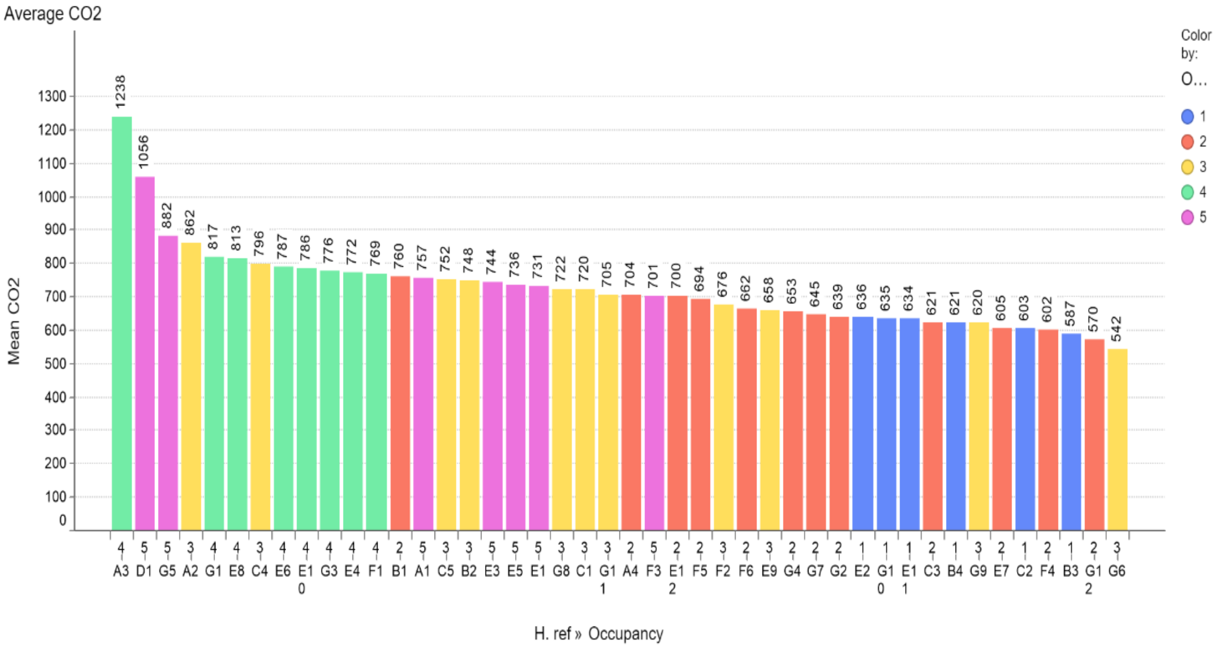


Figure 5.7 Effect of occupancy on average carbon dioxide levels in 44 houses

Figure 5.8 shows the maximum average CO_2 levels of all non-working/stay-at-home families in the three months of Winter, for the four zones. It can be enumerated that the maximum CO_2 levels for the kitchen is lowest over the three months, while it is significantly higher in the second bedroom. This may be due to use of ventilation during cooking activities in the kitchen area, but it is likely to be due to the fact that people stay in the second bedroom for a longer duration. The high CO_2 levels in the second bedroom may also be because its door is generally closed during occupation, potentially accompanied by closed trickle vents. It is also notable that the CO_2 levels in this zone are generally higher than in the master bedroom which will be explained later.

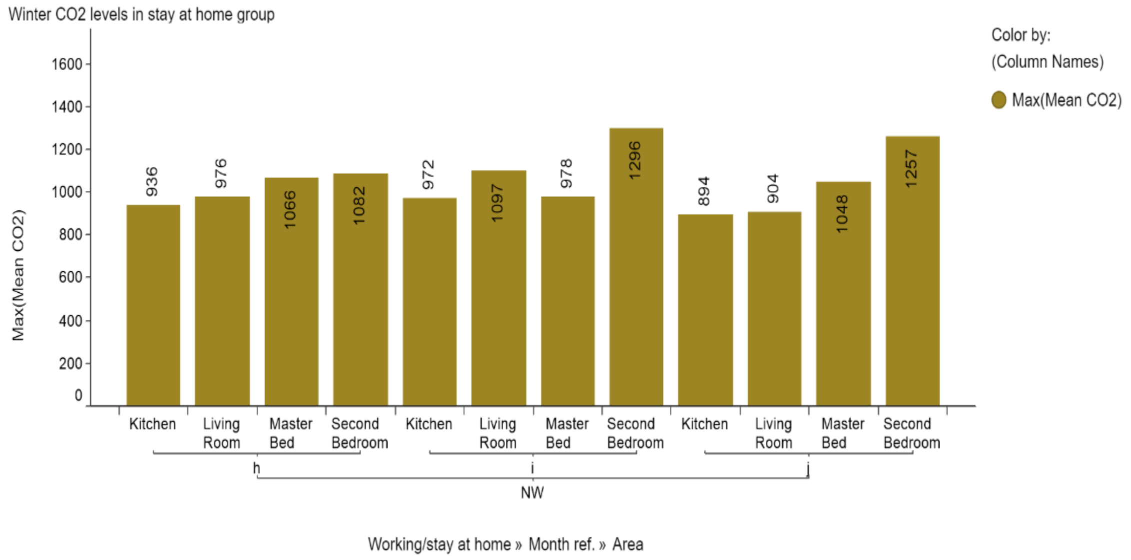


Figure 5.8 Average maximum monthly CO_2 levels in different zones of non-working families in Winter

In contrast to Figure 5.8, Figure 5.9 shows the maximum average CO_2 levels of the working (outside the home) family houses in the three months of the Winter season for the four house zones. Similar to the non-working families, the lower CO_2 levels are observed in the kitchen and highest in the second bedroom for two months out of three, the other high value being in the master bedroom. It is important to note that the highest average CO_2 values in the living room, master bedroom and second bedroom are much higher for working families, as compared to the non-working families. Applying the rationale of higher occupancy rates being positively related to the higher CO_2 levels, this seems to be contradictory. The rationale for extremely high CO_2 levels in working family houses may be due to the fact that the Trickle vents are not opened, and similarly, doors of the respective rooms are also shut throughout the day and night, leading to higher average accumulation of CO_2 in different zones of the house even if the houses are occupied for a lesser time. Moreover, the higher CO_2 may also be due to improper use of the ventilation system, which calls for further interventions to investigate further, which was done by a site team. In addition, despite the fact that the family members are working, there is still the possibility that not all the members in the house are working, and some of them appear to stay in the house most of the day as evidenced by the CO_2

levels. It may be the inefficient use of ventilation by those occupants during occupied hours which resulted in higher average CO_2 accumulations.

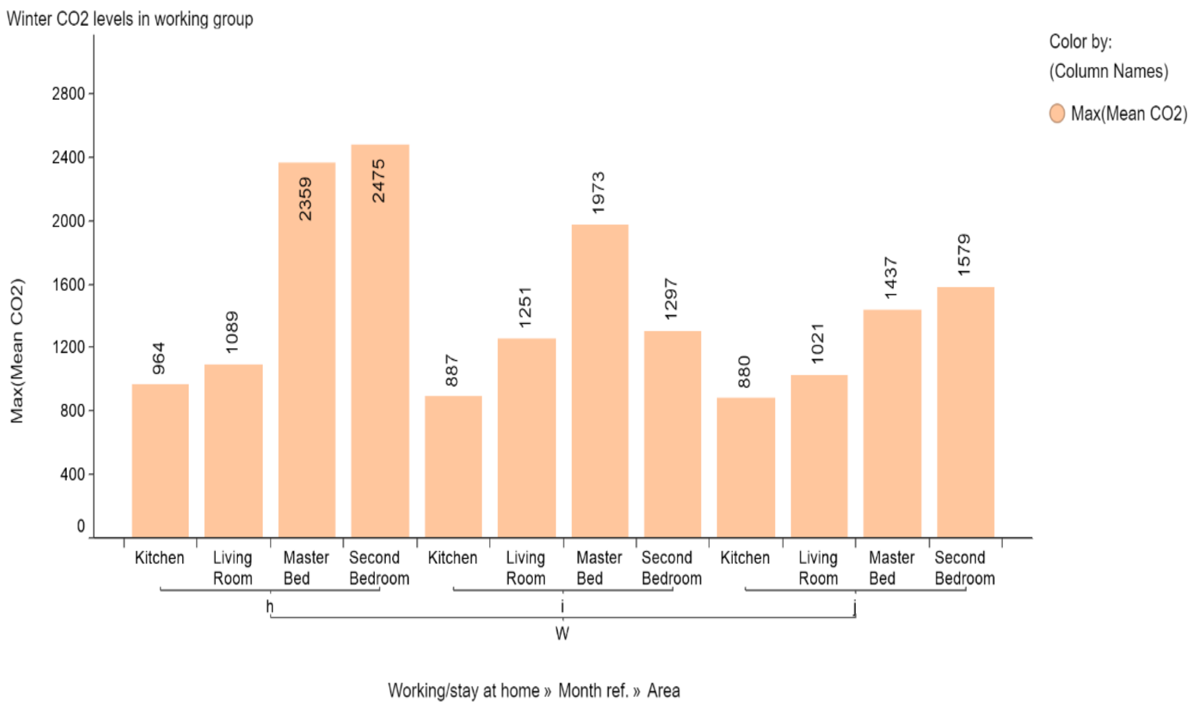


Figure 5.9 Average maximum monthly CO_2 levels in different zones of working families in Winter

When investigated in detail, it is found that there are specifically only 2-3 houses in the working group that have extremely high CO_2 values. These houses have high humidity levels in both bedrooms. There is also some evidence of mould growth in these houses. During investigation on site, it was found that these houses had completely blocked their Trickle vents and the family admitted that they never opened their windows throughout the entire season. Even their HVAC filters were blocked. In the worst case (House A03), CO_2 levels peaked at 5900 ppm in the master bedroom and 4300 ppm in the second bedroom. It is also observed that CO_2 levels stayed higher throughout the night (Figure 5.10). Although this is just one-night's example, it happened relatively frequently in these houses. At the same time, CO_2 levels in the second bedroom of E06 reached as high as 3300 ppm at night (Figure 5.10). Both have an occupancy of a family of 4, but the CO_2 levels differ. This difference may be due to the behaviour in using ventilation, as the house with closed Trickle vents will experience an accumulated CO_2, compared to the other house with open Trickle vents or open doors/windows at night. Thus, higher CO_2

levels in these houses were a combination of many factors, including turning off their central ventilation system frequently, closing their Trickle vents completely, not opening their windows, and not cleaning their HVAC filters. These families were not cooperative in taking advice from the research or site teams, which resulted in more than 1500 ppm CO_2 levels for 50% of the time in a month.

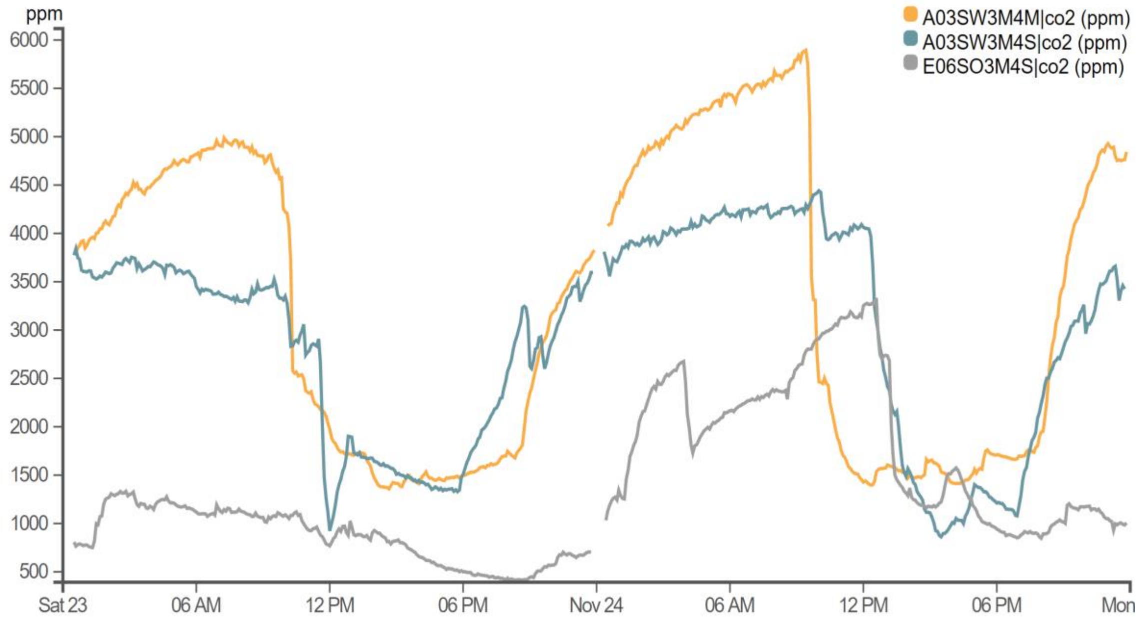


Figure 5.10 Night CO_2 trend in the bedroom with higher levels

The analysis, therefore, shows that occupancy is not always an important variable in influencing the CO_2 concentrations in different houses. But it is often the situation in extreme cases that their living behaviour and use of different heating/ventilation systems significantly impact the CO_2 levels.

5.4.2. Analysis based on pre and post pandemic working (Jan 2020 vs April 2020) between 10 am to 5 pm

Previously, the impact of occupancy on the house CO_2 levels for the external working and stay-at-home families in normal circumstances was computed. In the monitoring time period, all families suffered from the pandemic effects, which impacted the working from home effects. To analyse this, t-tests are performed on the average CO_2 levels for all houses in a pre-restriction period (January 2020) and a strict lock-down restricted period (April 2020), for the working hours of 10 am to 5 pm. The findings of the Welch two sample t-test are given in Tables 5.2 and 5.3 for both the working and non-working groups of families:

Working

Table 5.2 T-test based on the sample data of working group

```
        Welch Two Sample t-test

data:  aprilco2w and janco2w
t = -22.16, df = 272134, p-value < 2.2e-16
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -22.55689 -18.89104
sample estimates:
mean of x mean of y
 618.0356  638.7596
```

The null hypothesis, applicable in Table 5.2, is to test the similarity of the two means, related to CO_2 levels in houses of working groups for January 2020 versus April 2020. The alternative hypothesis states that the two means are different. The table shows that the t-statistics is t=-22.2, with the degree of freedom (df) of 272134. The p-value is 0.000, which is less than the significance value of 0.05, indicating strong statistical significance to reject the null hypothesis. Hence, it is concluded that the mean CO_2 for the working group is significantly different between January 2020 and April 2020, not surprisingly.

This result may be attributed to the fact that in January 2020, occupants occupied the house premises for a much lesser time than in April 2020, when they stayed at home as instructed by government. As such, common sense dictates that the mean CO_2 should be higher in April (stay-at-home), due to more occupied hours, but it is the opposite. The January 2020 signified a higher CO_2 level as compared to April 2020, but this may be due to closing of Trickle vents in cold weather, not opening internal doors, nor ventilating different zones, thereby accumulating a higher CO_2. The rationale for this difference in the CO_2 levels in the two months under study may be due to a difference in external temperature, thereby, encouraging different behaviour by the occupants. That is, as compared to the CO_2 in the month of January, the April CO_2 might be expected to be higher, but no such evidence exists.

Simply put, occupants may be opening their windows in the daytime due to the warmth in April 2020, thereby, keeping the CO_2 levels low.

It is also observed from the previous analysis that some families who are tampering with the ventilation system whose houses are worse performing in terms of IAQ, come under the working group. Therefore, their indoor CO_2 levels are always higher regardless of the month, their working status or pandemic lockdown.

Not working

Next, the average CO_2 levels of the stay-at-home group are compared for the January and April 2020 months using the Welch two sample t-test.

Table 5.3 T-test based on the sample data of non-working group

```
        Welch Two Sample t-test

data:  aprilco2nw and janco2nw
t = 62.587, df = 74856, p-value < 2.2e-16
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 110.2282 117.3553
sample estimates:
mean of x mean of y
 742.8019  629.0101
```

The null hypothesis for Table 5.3 is that the two means are similar, related to CO_2 levels in stay-at-home groups for January 2020 versus April 2020, while the alternative hypothesis states that the two means are different. The table shows that the t-statistic is t=62.6, with the degree of freedom of df = 74856. The p-value is 0.000, which is less than the significance value of 0.05, signifying strong statistical significance to reject the null hypothesis. Hence, it is concluded that the mean CO_2 for the stay home group is significantly different between January 2020 and April 2020.

The April 2020 CO_2 average value (742 ppm) signified a higher CO_2 level as compared to Jan 2020 (629 ppm). Generally, as the occupancy levels are similar for the families in both months, the average CO_2 levels are not expected to be significantly different. Thus, this difference may be attributed to a difference in living patterns of the occupants, the use of windows/vents and, most importantly, the children are at home all the time as schools were closed, where the use of devices due to online schooling is evident. It is also important to note that April is a Spring month, which had a higher CO_2 level, despite the warmer temperature (see Figure 5.11) this month which could be due to higher actual occupancy levels during the COVID lockdown.

Furthermore, Figure 5.11 compares the external temperatures for the months of January (circled blue) and April (circled orange). It can be observed that, unsurprisingly, the temperature is higher in April compared to January. It may be a possibility that during April, to reap the benefit of warmer temperatures, some occupants may be opening windows, thereby, causing the levels of CO_2 to be lowered.

5.4.3. Typical behaviour/activities

This section analyses the humidity levels in the en suite, as a derived variable of the RH level in the master bedroom, over the time period of 24 hours in a single day. It is distinguished by the fact that the master bedroom humidity is positively and significantly related to the humidity in the en suite.

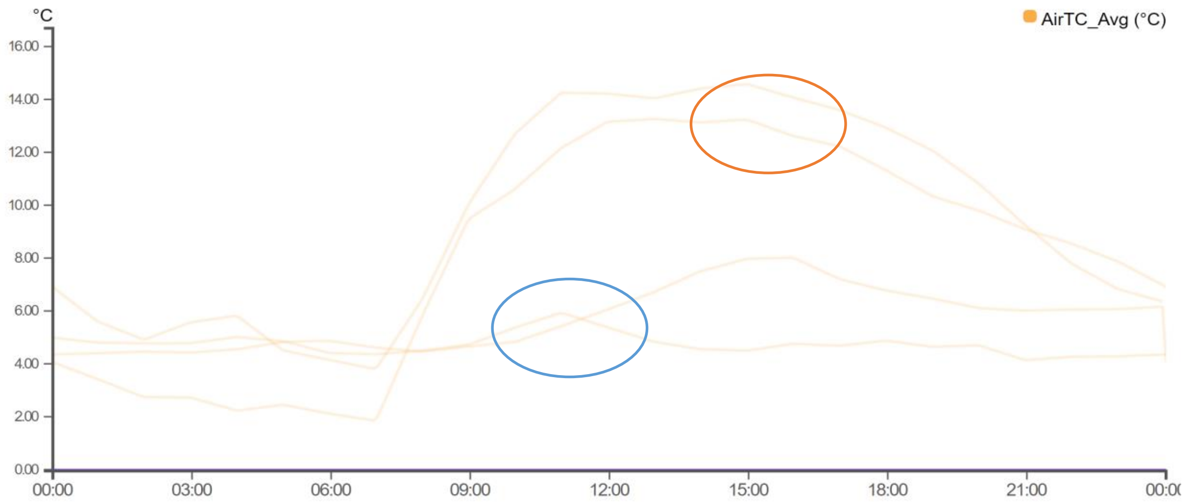


Figure 5.11 Outside temperature for 2 days in January (Blue circle) and April (orange circle)

Figure 5.12 shows the humidity levels in the master bedroom and en suite for house E08. It can be observed that the RH levels in the en suite and master bedroom changed in a similar fashion, especially at around 6pm on Tuesday. This is most likely due to the fact that the humidity was high in the en suite due to moisture generation during a shower and the door to the bedroom was not closed, leading to rapid transfer of humidity to the master bedroom. In contrast, just after 6am on the Wednesday, the high RH in the en suite did not affect the RH in the master bedroom, probably due to the closing of the door of the en suite, leading to very little dissipation of RH to the adjacent room.

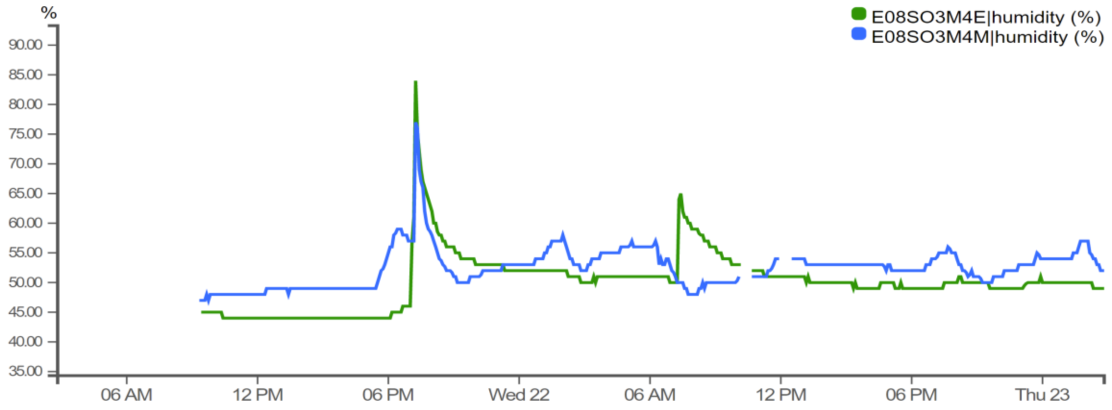


Figure 5.12 RH in master bedroom caused by en suite during shower

Another example of the relationship between RH levels in the master bedroom and en suite may be observed in house C03 (Figure 5.13). At several times during the day, the change in RH in the en suite caused a similar effect on the RH levels in the master bedroom. This may again be attributed to the rationale that the door between the en suite and master bedroom was always open, leading to similar accumulation of RH.

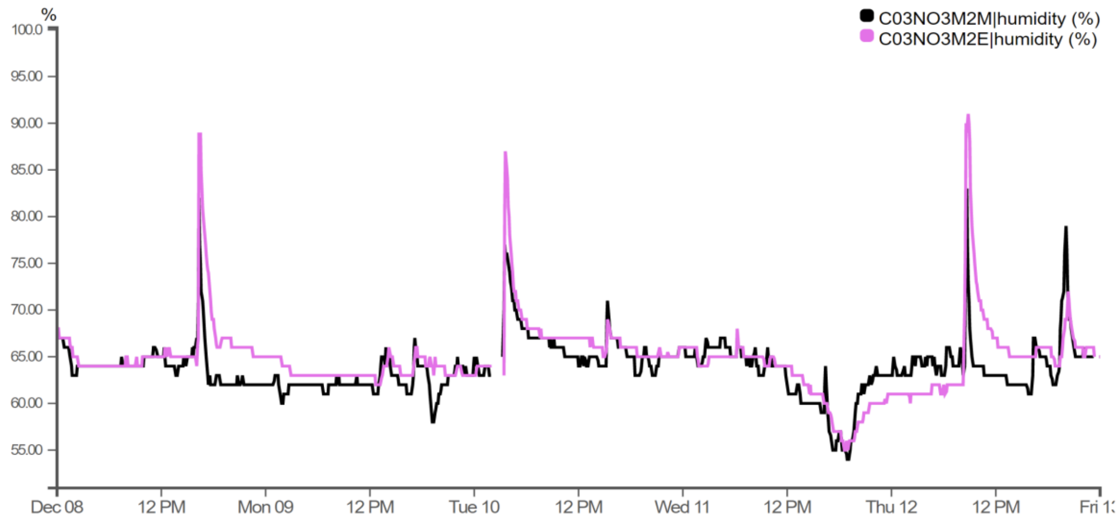


Figure 5.13 An example of master bedroom and en suite RH relation

The relationship between the RH of the master bedroom and en suite is studied by categorising the houses containing one occupant, and houses with more than one occupant. The results are given in the scatter diagram in Figure 5.14 and the regression output in Table 5.4.

To understand the impact of humidity between the en suite and master bedroom, linear regression analysis of Figure 5.14 data was undertaken, keeping the RH master bedroom as the dependent variable, and the RH for the en suite as the independent variable.

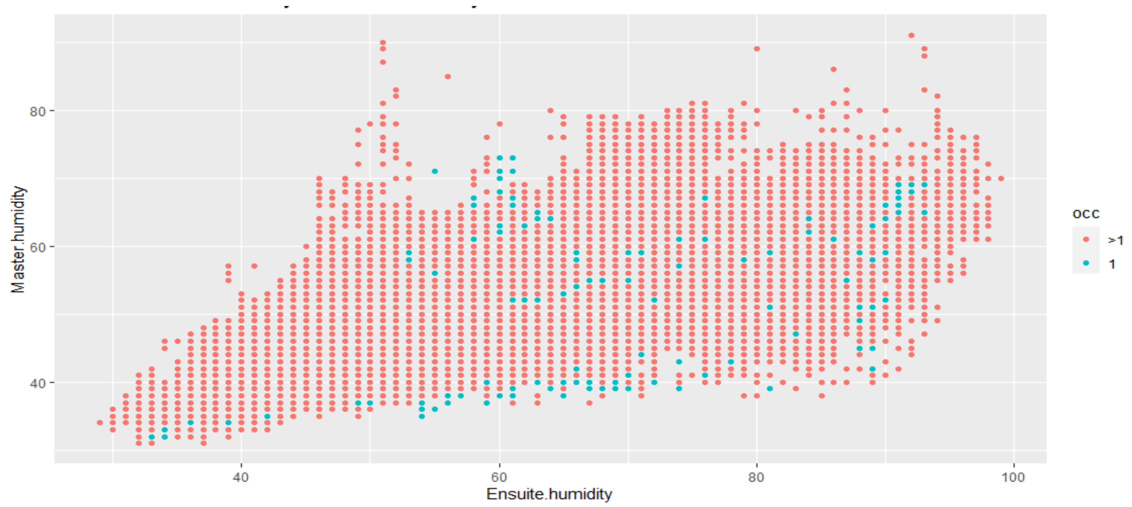


Figure 5.14 Relation between master bed and en suite humidity in houses with single and more occupancy

Table 5.4 Master bed and en suite RH with single occupancy

```
Call:
lm(formula = dm1$Master.humidity ~ dm1$Ensuite.humidity)

Residuals:
    Min      1Q  Median      3Q     Max
-34.371  -2.160   0.328   2.874  18.746

Coefficients:
                      Estimate Std. Error t value Pr(>|t|)
(Intercept)          1.324e+01  1.599e-02   827.9   <2e-16 ***
dm1$Ensuite.humidity 7.093e-01  3.104e-04  2284.9   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 3.933 on 2203258 degrees of freedom
Multiple R-squared:  0.7032,    Adjusted R-squared:  0.7032
F-statistic: 5.221e+06 on 1 and 2203258 DF,  p-value: < 2.2e-16
```

For single occupancy, from Table 5.4, it can be observed that the p-value of the whole model is less than 0.05 and, hence the model is significant in predicting the master bedroom RH. It can be viewed that the coefficient of the en suite humidity is positive, described using the following regression equation (Eq. 5.1):

$Master\ bed\ room\ Humidity = 13.24 + 0.71 * en\ suite\ humidity$ Eq. (5.1)

The coefficient suggests the relative humidity in the master bedroom increases by a factor of 0.7 due to the RH in the en suite.

The R-squared value of 0.70 suggest that 70% of the variation in RH in the master bedroom can be explained by the independent variable and a strong positive correlation. The overall F statistic's value and p value of the model suggests the model to be significant for estimating the RH for given values of independent variable.

For more than one occupancy, from Table 5.5, it can be observed that the p-value of the whole model is less than 0.05. Hence the model is significant in predicting the master bedroom RH. It can be viewed that the coefficient of en suite humidity is positive, and the relationship is represented by the following regression equation (Eq. 5.2):

$Master\ bedroom\ Humidity = 22.22 + 0.5677 * en\ suite\ humidity$ Eq. (5.2)

Table 5.5 Master bed and en suite RH with more than one occupancy

```
Call:
lm(formula = dm2$Master.humidity ~ dm2$Ensuite.humidity)

Residuals:
    Min      1Q  Median      3Q     Max
-32.739  -2.573   0.104   2.750  38.833

Coefficients:
                      Estimate Std. Error t value Pr(>|t|)
(Intercept)          2.222e+01  6.991e-03    3178   <2e-16 ***
dm2$Ensuite.humidity 5.677e-01  1.278e-04    4441   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 4.595 on 12614278 degrees of freedom
Multiple R-squared:  0.6099,    Adjusted R-squared:  0.6099
F-statistic: 1.972e+07 on 1 and 12614278 DF,  p-value: < 2.2e-16
```

The coefficient suggests the RH in the master bedroom increases by a factor of 0.56 due to RH in en suite. The $R^2 = 0.61$ suggest that 61% of variation of RH can be explained by the regression equation with the independent variable. The overall F statistic's value and p value of the model suggests the model to be significant for estimating the relative humidity for given values of independent variable.

It is recommended that one leaves the door to the bathrooms open after taking a shower/bath to help reduce the concentration of the moisture in that and adjacent rooms. It is not recommended to leave the en suite door open during a shower because, as seen in Figures 5.12 and 5.13, this will raise the humidity levels of the master bedroom substantially. However, if one leaves both the en suite and master bedroom door open immediately after a shower it only affects the master bedroom humidity by about 5% (as observed in the gathered data) which is not a condition that is likely to lead to condensation or mould growth (Appendix G), however it can help in dissipating much of the moisture from the en suite to the surrounding area at a faster rate.

Similarly, Figure 5.15 shows the variation in RH levels of two houses. It is observed that the RH levels in the kitchen of A03 were much higher than A01, both during cooking activity and thereafter. It is observed that most of the houses do not experience high levels of RH in the kitchen during cooking, but in some houses, there were very high peaks which could be due to a cultural aspect/cooking style or the absence of ventilation by occupier choice. There is a ceiling vent in the kitchen of every house to extract extra moisture, in addition to the cooker hood extractor to remove the immediate build-up of moisture due to the various cooking activities involving steam. It was found that the extractor fan in the kitchen was not that strong for all types of cooking. For example, cooking with water boiling on a cooker or kettle causes a higher RH level than simple baking in a microwave.

However, if occupiers do open their windows for a short interval after cooking, the extra moisture build-up can be dissipated immediately which can prevent the problem of condensation.

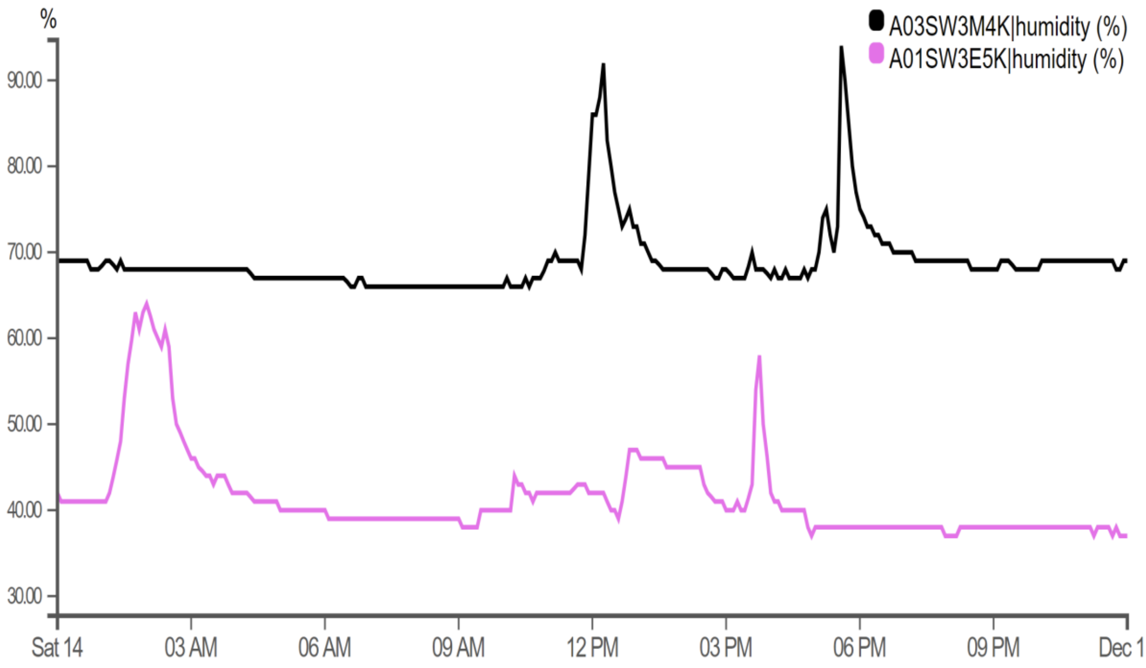


Figure 5.15 RH levels in the kitchen in two different houses

5.4.4. Family interventions

In this section, the impacts of family interventions on the CO_2 levels of houses are assessed.

Figure 5.16 shows the degree of CO_2 levels in the master bedroom in three comparative situations, such that the first and second situation caters to the CO_2 levels when the Trickle vents were opened on one day in the months of August and December, while the third situation shows the CO_2 levels for one day in March, when the Trickle vents were closed. It can be noted from the graph that generally, for the first half of the day, the CO_2 in March surpassed that in August and December. This indicates that the opening of the Trickle vents is vital in keeping the CO_2 levels low and, thereby, a better indoor environmental quality of the house zone in question.

Moreover, the sudden fall in the CO_2 levels for the latter half of the day in the March case may have been due to an alteration in the ventilation patterns, with the bedroom door being left open to quickly dissipate the CO_2 around the house.

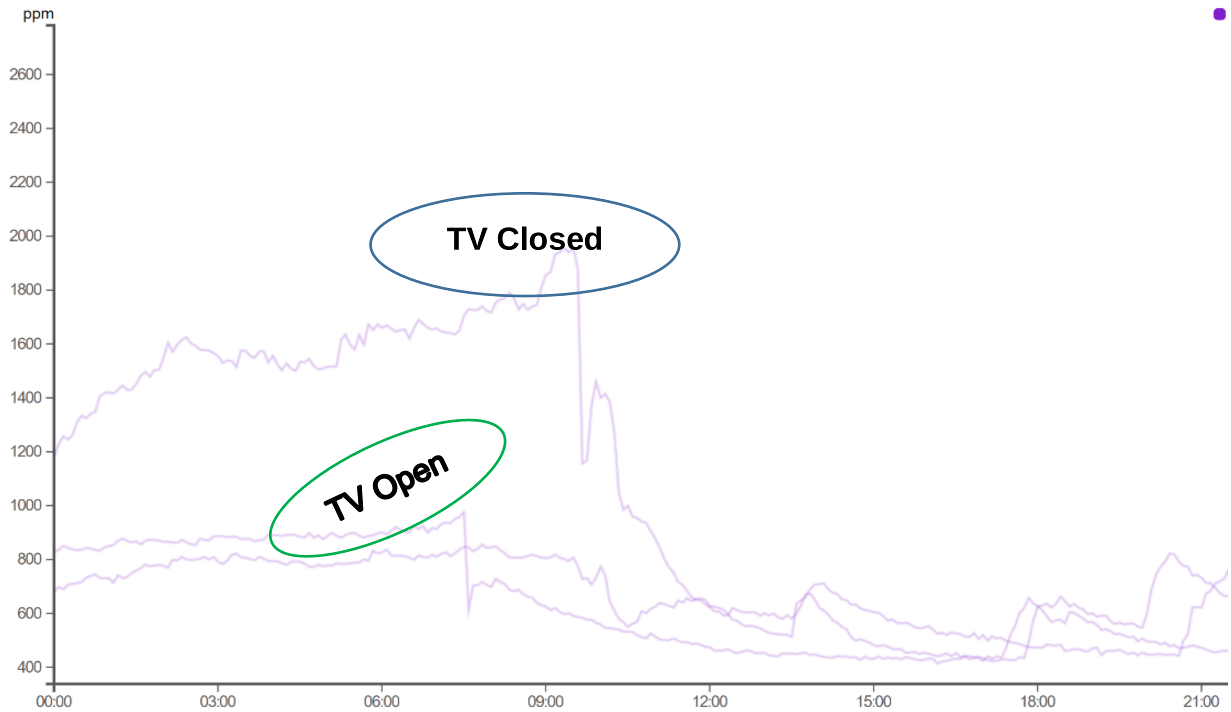


Figure 5.16 One day in August, December (Trickle vent open) and March (Trickle vent closed)- effect of Trickle vents on CO_2 levels of bedrooms

5.5. Impact of Researcher Advice on IAQ

This section will give examples of the improvement in IAQ of houses whose occupants have changed their behaviour after selective advice was given by the author to the occupants on the more efficient use of heating, adjusting the room thermostats and proper use of ventilation systems (Appendix H). It is also important to note that this advice was given to a selected 32 houses (which were identified as performing poorly based on their excessive CO_2 and RH levels) in the month of November 2020. The impact of the advice given, and subsequent sustainability of their actions is assessed in this section.

Figure 5.17 shows the average maximum CO_2 and RH levels in the houses to which the advice was given. It can be observed that the maximum average CO_2 level observed in this set of houses was 2475 ppm in the month of November as the advice (Appendix H) was issued in November (h), its impact can be observed in the notable drop in CO_2 levels highlighted in red in the figure. The average of the maximum CO_2 levels in these houses, before change, showed a continuous increment from August to November (from 1572 to 2475 ppm), which fell continuously from 2475 ppm to 1498 ppm in the subsequent months. This signifies that the occupants in these houses have changed their behaviour with respect to the use of the ventilation systems. In contrast, there is no improvement in the RH levels of these houses even after receiving the advice. In fact, the RH levels in these houses remained as high as 77% (same as November) in December, and further increased to 79% in January. However, these values of RH levels are strongly influenced by the temperature environment.

However, it may be observed that not all the houses demonstrate the same behaviour when acting (or not acting) on the advice made to these occupants which can be deduced from the histogram in Figure 5.18. Only 50% of the houses took the advice

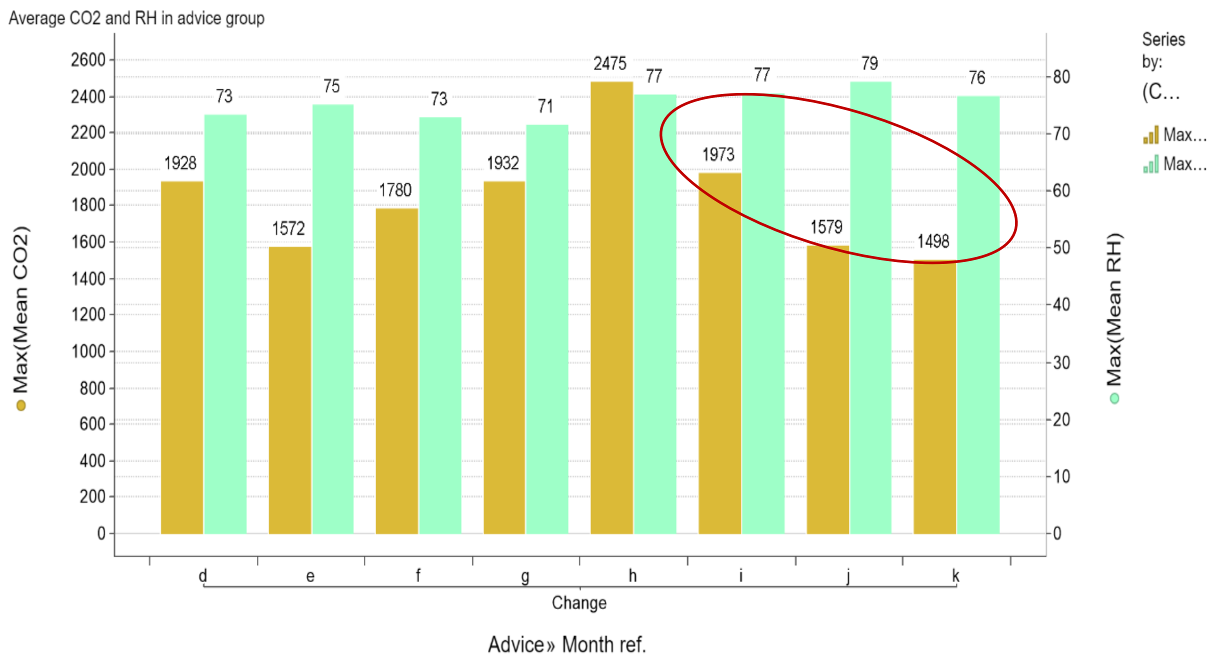


Figure 5.17 Change in IAQ after advice given in November (month h)

and changed their behaviour and that too was not sustained for a long period. They changed their behaviour back after 2.5 to 3 months.

Figure 5.18 illustrates the average CO_2 levels of three houses, namely A3, A4 and G5, to whom change advice was given. It can be observed that all three houses showed an increase in the average CO_2 levels from August (e) to November (h), which may be due to changes in the external environment inducing the occupants to use the ventilation systems less efficiently. For instance, to keep the houses warmer due to changing external weather conditions, the houses may be opening their windows less often or blocking the vents in these months.

However, it is interesting to note the differences in the CO_2 levels after November. For example, for the occupiers of house A3, which had always experienced very high CO_2 levels, much better adherence was given to the advice, which caused the decrease in CO_2 levels from 2475 ppm to 1498 ppm from November to February respectively. However, it seems that this house failed to maintain the implemented advice in the long-term, as evident by a significant rise in CO_2 to 2508 ppm in the month of March (l). Similarly, the graph shows another house, A4, with an average CO_2 level at 1476 ppm in November, which experienced a less

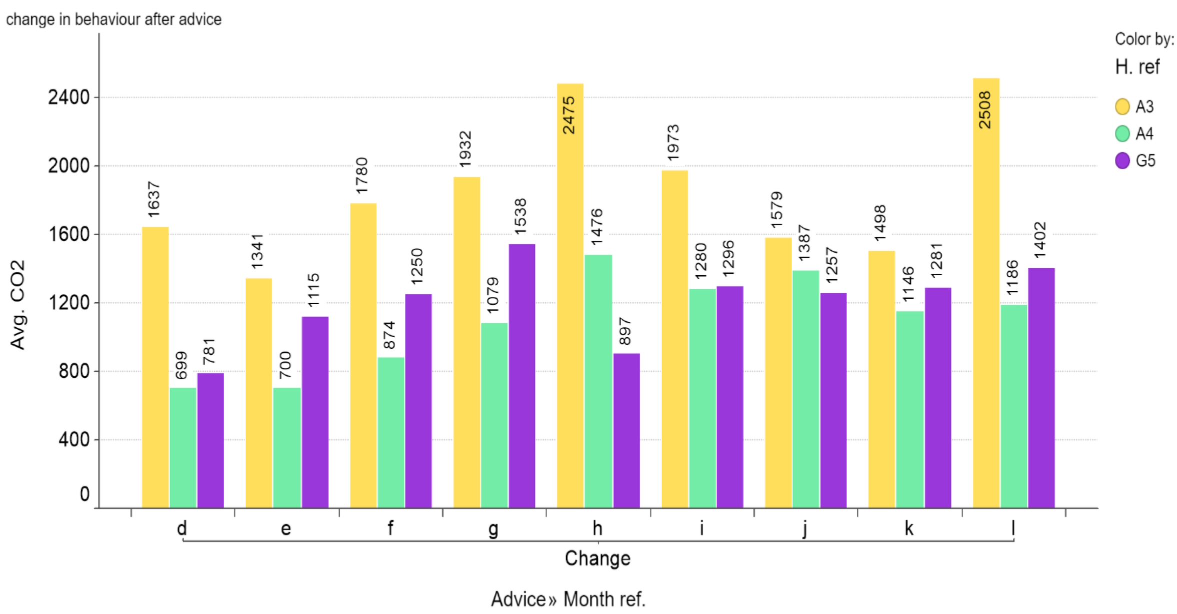


Figure 5.18 Change in behaviour after advice, comparing 3 different houses

pronounced improvement in the IAQ, as the CO_2 dropped to 1280 ppm in December and fluctuated about this broadly improved value in the months thereafter. Another house, G5, showed different behaviour of the occupants. whereby it experienced a continuous rise in CO_2 to 1538 ppm, and then reduced drastically to 897 ppm in November after the advice was given but failed to maintain low CO_2 level, thereafter, signifying that the occupants did not continue to implement the advice given to them.

It is possible that the occupants may not have believed in the advice or failed to understand/experience the effects of the advice.

To show one actual impact of the advice, Figure 5.19 shows the CO_2 levels in house B3 as a consequence of closing and opening of the door of the second bedroom. This shows that the level of CO_2, after advice, for the open and closed door of the second bedroom to the landing, declined at similar rates throughout the day. However, it is important to note that, throughout the night, the CO_2 level when the door is kept slightly open is much lower than when the door of the room is kept closed.

Thus, these examples signify that the advice given to the occupants are not difficult to implement and it inculcates small behavioural changes when occupying different rooms in the house. The advice is impactful in maintaining better internal environmental quality but only if the advice continues to be followed. On similar lines, the impact of imparting advice on a couple of houses' IAQ are further illustrated by Tables 5.6 to 5.9 where the peak values are highlighted; the red highlights indicate the highest levels, while the yellow highlights indicate the 'needs attention' cases.

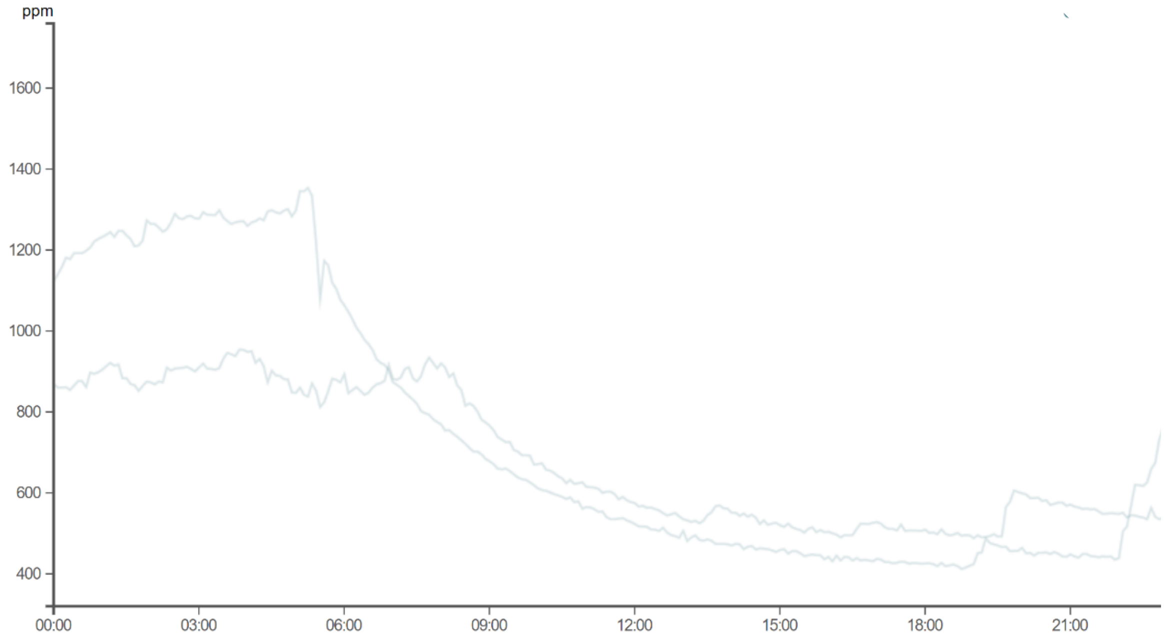


Figure 5.19 Reduced CO_2 in second bedroom after following the advice

The data in Table 5.6 show the different parameters of temperature, RH and CO_2 for house A1 before advice. It can be observed that minor exceedances are in yellow, principally occurring in the kitchen and master bedroom, while the predominantly high exceedances (in red) were for CO_2 levels in the master bedroom and second bedroom. Subsequently, the impact of advice on these parameters for this house is given in Table 5.7.

Table 5.6 IAQ before advice

	TEMPERATURE			**RELATIVE HUMIDITY**				**CARBON DIOXIDE**			
Room	**Avg. Temp**	**Max Temp**	**%> 25°C**	**Avg. RH**	**Max RH**	**>60% RH**	**> 80% RH**	**Avg. CO_2**	**Max CO_2**	**>1000**	**>1500**
Living	21.9	26.7	4%	51.4	68%	13%	0%	658	2506	17%	1%
Kitchen	23	29.9	41%	49.1	83%	3%	0%	645	3202	17%	1%
Master Bed	22.2	28.2	17%	51.6	77%	9%	0%	772	2574	34%	14%
En suite	22.2	26.8	4%	53.6	91%	19%	1%	-	-	-	-
2nd Bed	22	25.8	6%	52.2	66%	13%	0%	852	2931	65%	25%

Table 5.7 IAQ after advice

	TEMPERATURE				**RELATIVE HUMIDITY**				**CARBON DIOXIDE**			
Area	**Mean Temp**	**Max Temp**	**T<18 °C**	**T> 25 °C**	**Mean RH%**	**Max RH%**	**RH> 60%**	**RH> 80%**	**Mean CO_2**	**Max CO_2**	**CO_2> 1000< 1500**	**CO_2> 1500**
Living	20.6	24.6	0.97	0	45.4	68	0.1	0%	744	2652	11%	2.50%
Kitchen	22	30.7	0	2.8	43.1	73	1.1	0%	723	3547	8%	2.10%
Master Bed	19.3	25.1	15.5	0.05	49	69	1	0%	771	2982	6.40%	8%
En suite	21.1	25.8	1	0.24	47.8	90	2.4	0.5				
2nd Bed	19	22.3	15	0	48.1	68	0.3	0%	634	2173	2.45%	1.15%

Now it may be observed that exceedances for temperature and CO_2 levels were significantly reduced, such that most of the values for temperature and CO_2 attained normalcy, while those marked in yellow still need attention post advice.

On similar lines, another example signifying improvement in the IAQ is shown by the pre- advice and post-advice figures for house A2. The average figures for the pre-advice period, from April to September, are given in Table 5.6.

Table 5.8 IAQ before advice

	TEMPERATURE			RELATIVE HUMIDITY				CARBON DIOXIDE			
Room	**Avg. Temp**	**Max Temp**	**%> 25°C**	**Avg. RH**	**Max RH**	**>60% RH**	**> 80% RH**	**Avg. CO_2**	**Max CO_2**	**>1000**	**>1500**
Living	21.4	25.1	0.04%	57.9	76	71.3%	0%	726	2968	16%	6.6%
Kitchen	21.9	29.2	9.6%	60.4	82	58.6%	0.02%	823	3056	52.3%	9.2%
Master Bed	21.9	28.7	18.5%	57.0	77	47.9%	0%	789	1899	49%	7.7%
En Suite	21.7	26.8	8.4%	61.6	95	87.5%	2.1%	-	-	-	-
2nd Bed	21.7	26.3	11.7%	58.7	73	55.9%	0%	1001	4954	31.9%	36.3%

After studying the possible reasons for these higher values, a range of advice was given to the occupants of this house for improving the ventilation, internal temperature and different activities and behaviour, such as using the thermostat, when to open and close windows and doors etc. The impacts of these pieces of advice are given in Table 5.9.

Table 5.9 IAQ after advice

	TEMPERATURE				RELATIVE HUMIDITY				CARBON DIOXIDE			
Area	**Mean Temp.**	**Max Temp**	**T<18 ºC**	**T>25 ºC**	**Mean RH%**	**Max RH%**	**RH> 60%**	**RH> 80%**	**Mean CO_2**	**Max CO_2**	**CO_2> 1000< 1500**	**CO_2> 1500**
Living Room	18.4	24.2	33.3	0	63.2	77	63.5		953	3181	22.1	8.8
Kitchen	18.4	23.5	36.5	0	64.5	92	71.6	0.54	887	3363	16.7	8.4
Master Bed	15.9	20.6	81.7	0	67.5	80	79.7		746	1502	18.4	0.01
en suite	16.8	23	70.8	0	70.8	95	81.6	6				
Second Bedroom	16.8	23.5	68.1	0	64.7	80	75.3		859	2022	26.6	1.3

This table signifies that the IAQ for the house improved measurably after adopting the advice. Though the change wasn't as prominent as was found for the previous house, the number of red cells reduced, and the overall exceedances for all five zones for all three variables showed improvement. There were also some instances when a few houses, like houses A03 and D01, did not show much improvement in the IAQ following the receipt of advice. Thus, the magnitude of adoption of the advice by the houses caused considerable variations in the extent of post-advice improvements in the temperature, RH and CO_2 levels.

5.6. Different Indoor Environments in both Bedrooms

In this section, the indoor environment quality of two bedrooms, specifically the variations in the CO_2 levels, are studied. Furthermore, the results from different houses with the same number of occupants in both the rooms are also analysed to develop an understanding of the influences of CO_2 in both these house zones. Consider the example of average CO_2 levels for the master bedroom and second bedroom for house G3, which has 4 occupants. Occupancy data is collected from all 57 houses by preparing a questionnaire (Appendix I). Figure 5.20 shows one-day CO_2 variations in the master and second bedrooms. It is observed that most of the master bedrooms have low average CO_2 compared to the second bedroom under similar conditions and timings and this is a good example of that. Some more examples are presented in Appendix J. This difference may be attributed to the internal layout of the houses, such that the master bedroom is attached to the en suite with its own mechanical ventilation which operates for 24 hours a day. When the door between the master bedroom and en suite is left slightly or fully open, the accumulated CO_2 levels in the master bedroom are released by the mechanical extract, which is permanently operating in the en suite.

The second bedroom has no such adjunct mechanical extract. This point will be further confirmed by modelling in the next chapter.

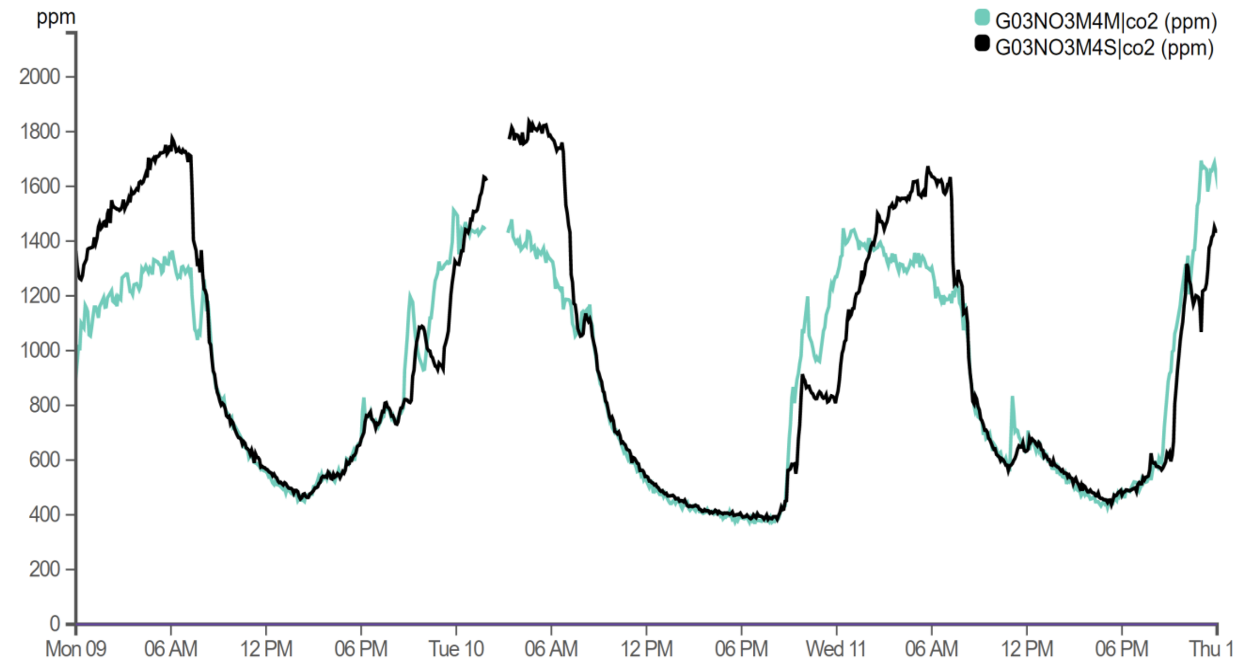


Figure 5.20 One-day CO_2 variations in master and second bedroom with 2 occupants

The variations in the level of CO_2 in the master bedroom and second bedroom for house E7 with single occupancy in each room, is exhibited in Figure 5.21. This figure matches the findings for houses with 2 occupants. The CO_2 levels in the master bedroom are much lower than that of the second bedroom despite the assumption of being used in a similar manner with similar occupancy. This suggests that the door between the en suite and master bedroom is kept open for a longer time during the day. The same more rapid trend is replicated consistently over succeeding days as may be observed.

Similarly, the trend of CO_2 levels in these rooms over a week for a house (E4) with 2 occupants in each room, is presented in Figure 5.22. That is, the CO_2 levels for the master bedroom are consistently lower than the second bedroom.

Thus, it can be concluded that although the number of occupants is one of the key factors affecting negatively on CO_2 levels, the differences in the CO_2 levels between different house zones depend on occupant behaviour as much as the designed air-tightness aspect.

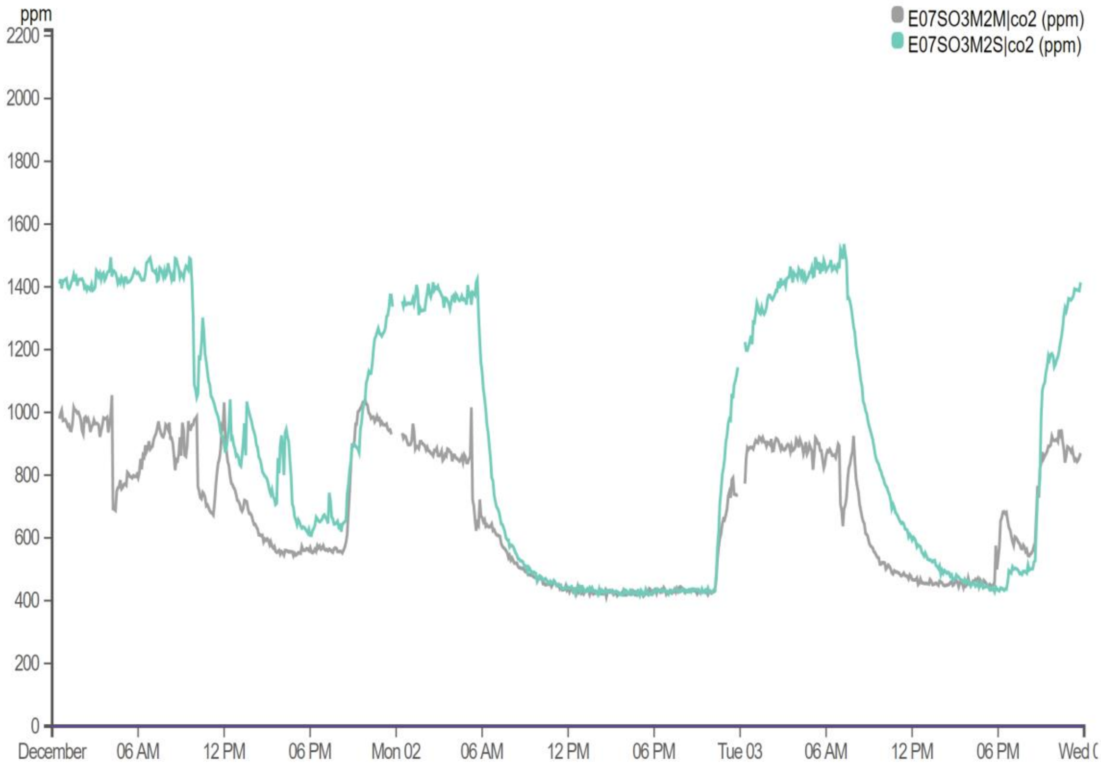


Figure 5.21 One-day CO_2 variations in master and second bedroom with a single occupant in both rooms

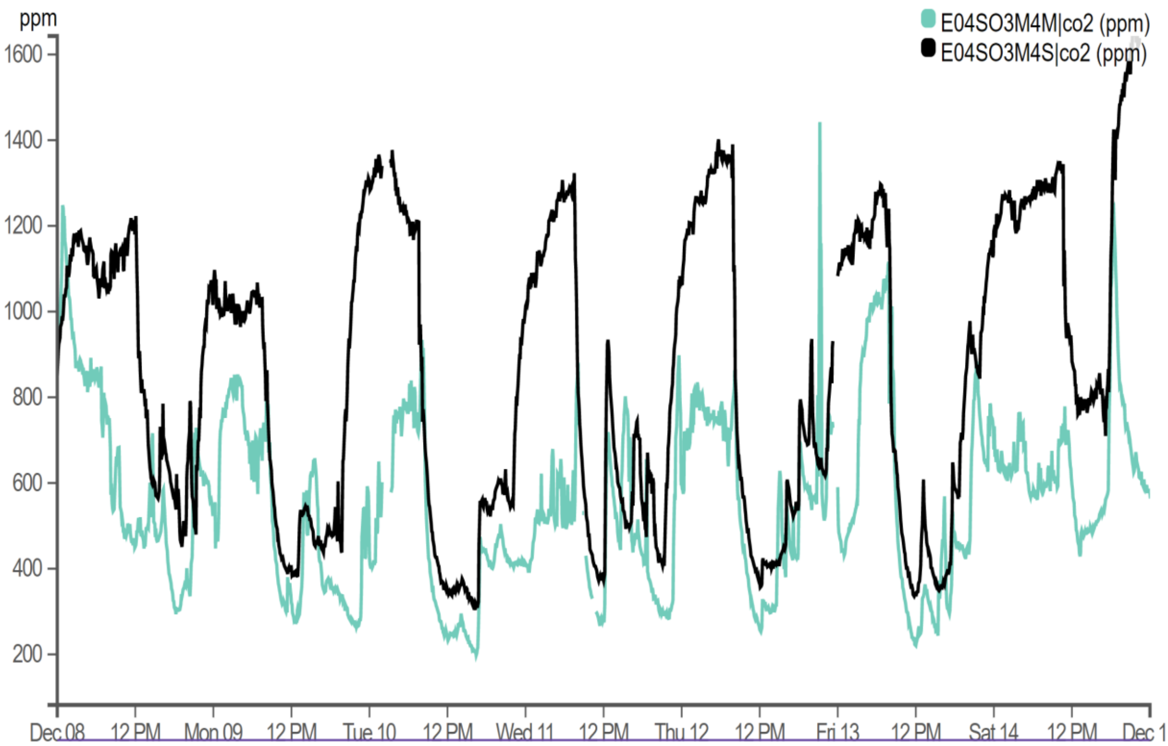


Figure 5.22 One-day CO_2 variations in master and second bedroom with 2 occupants in each room

5.7. Overall Analysis of IAQ of all Houses

In this section, the comparative analysis of all 44 houses is undertaken by calculating the exceedances for each of the three parameters, with the aim of recognising the houses with acceptable and unacceptable IAQ.

5.7.1. CO_2 levels

In Figure 5.23, houses are analysed over each month of the year of study. The red and yellow bars show the proportion of times when the CO_2 levels for the respective houses in a particular month are greater than 1000 ppm and 1500 ppm respectively.

The houses exhibit a diverse range of exceedances that differ between months and seasons. Some of the houses that show lower exceedances are C3, E7, G2, G4 and G12 and are categorised as houses with good IAQ. In contrast, the houses that regularly showed much higher CO_2 levels and higher proportions of exceedances are A2, A3, D1, E2, E10, E11 and F1. All these houses constantly showed exceedance over 1500 ppm, thereby, reflecting very poor IAQ. As high CO_2 levels is one of the reasons for health concerns, especially many respiratory disorders, the IAQ of these houses should be of concern. Some of the houses, such as A1, F2, F6 etc., show fluctuations in these exceedances, where some months they have high exceedances while others do not. These variations are probably due to different occupant behaviour inside the houses.

The exceedances in CO_2 for different seasons for these houses are presented in Figure 5.24 to understand the seasonal impact on CO_2. The grey areas of the bars signify CO_2 levels above 1000 ppm, while the red areas signify the CO_2 to be higher than 1500 ppm.

Figures 5.24 (a to d) show that houses exhibit broadly similar quantities of CO_2 exceedances despite the difference in the seasons, while most of the houses show a variation in the CO_2 levels across the seasons. The maximum exceedances in CO_2 are observed in the seasons of Winter and Spring.

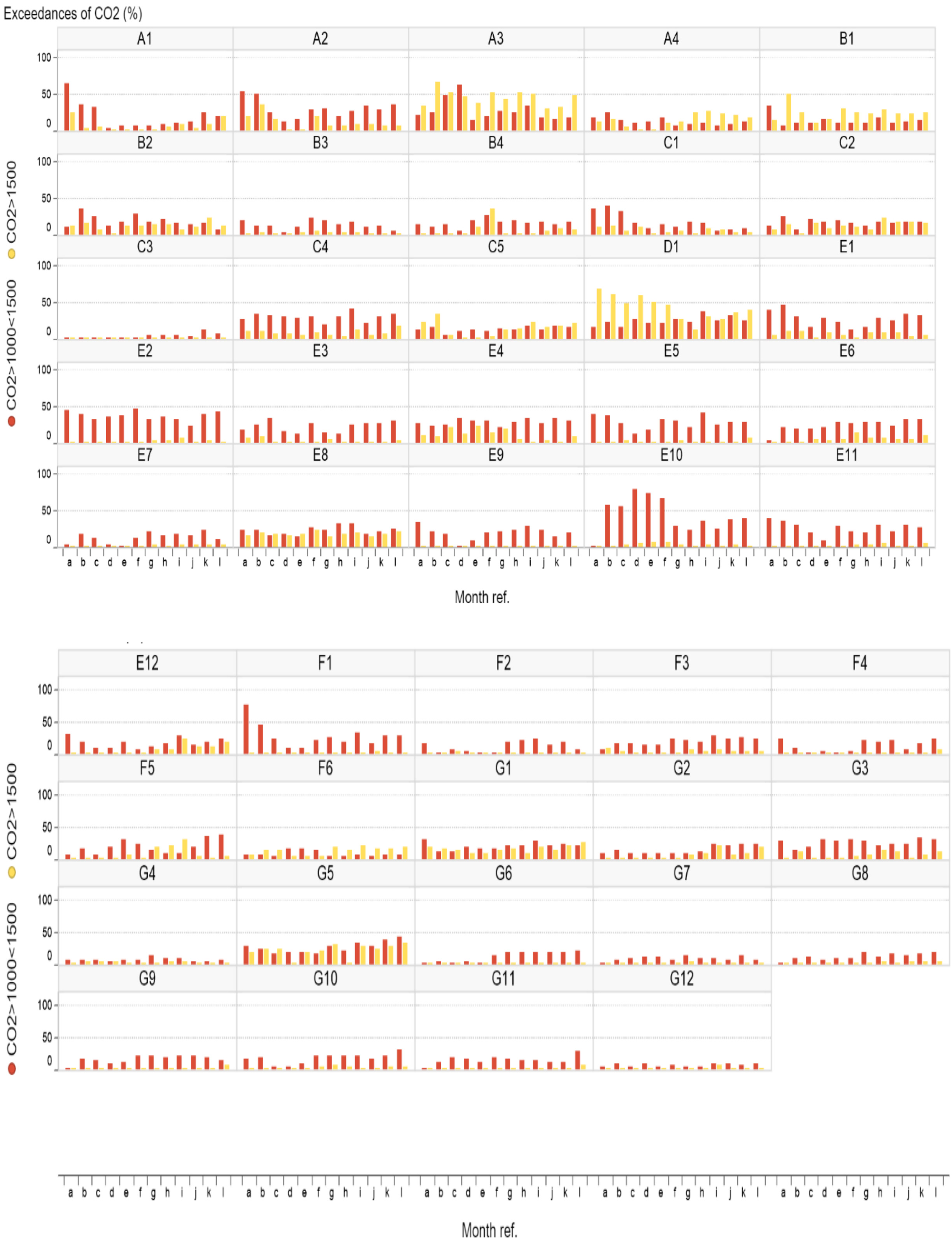
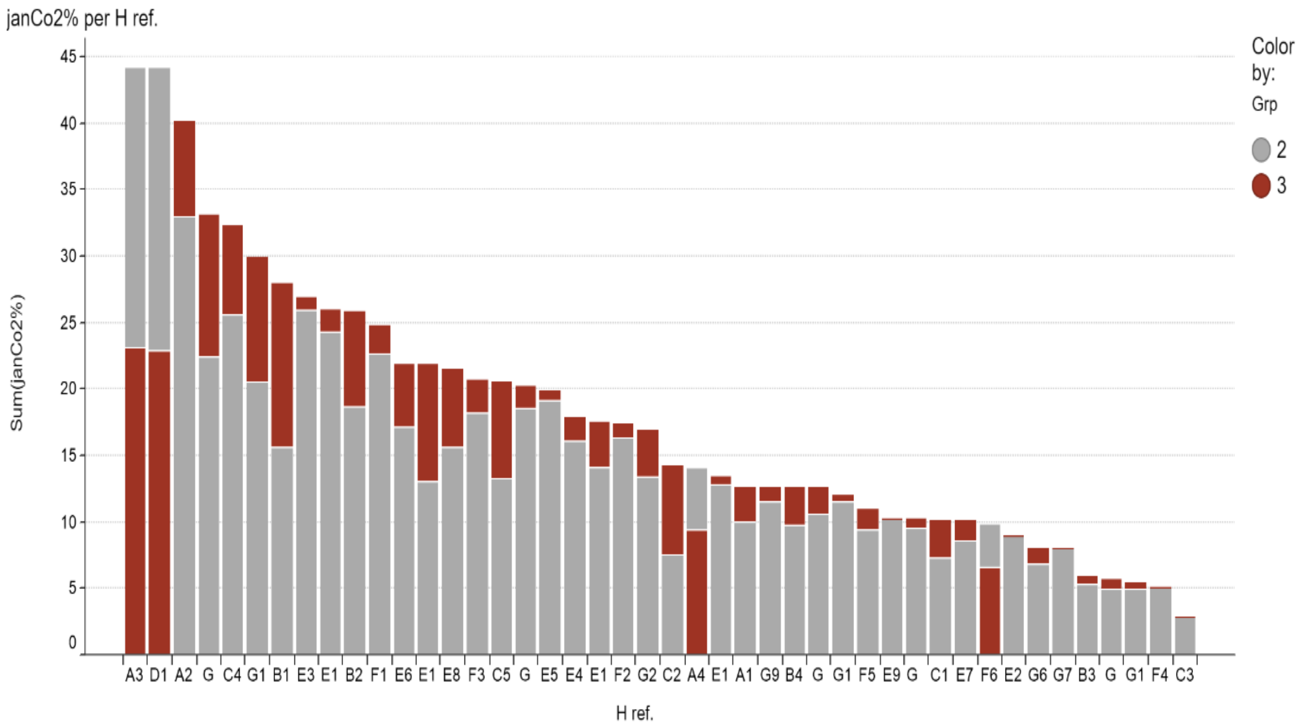


Figure 5.23 Proportion of times when the CO_2 levels are greater than 1000 ppm (in red) and 1500 ppm (in yellow)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Sum(janCo2%)
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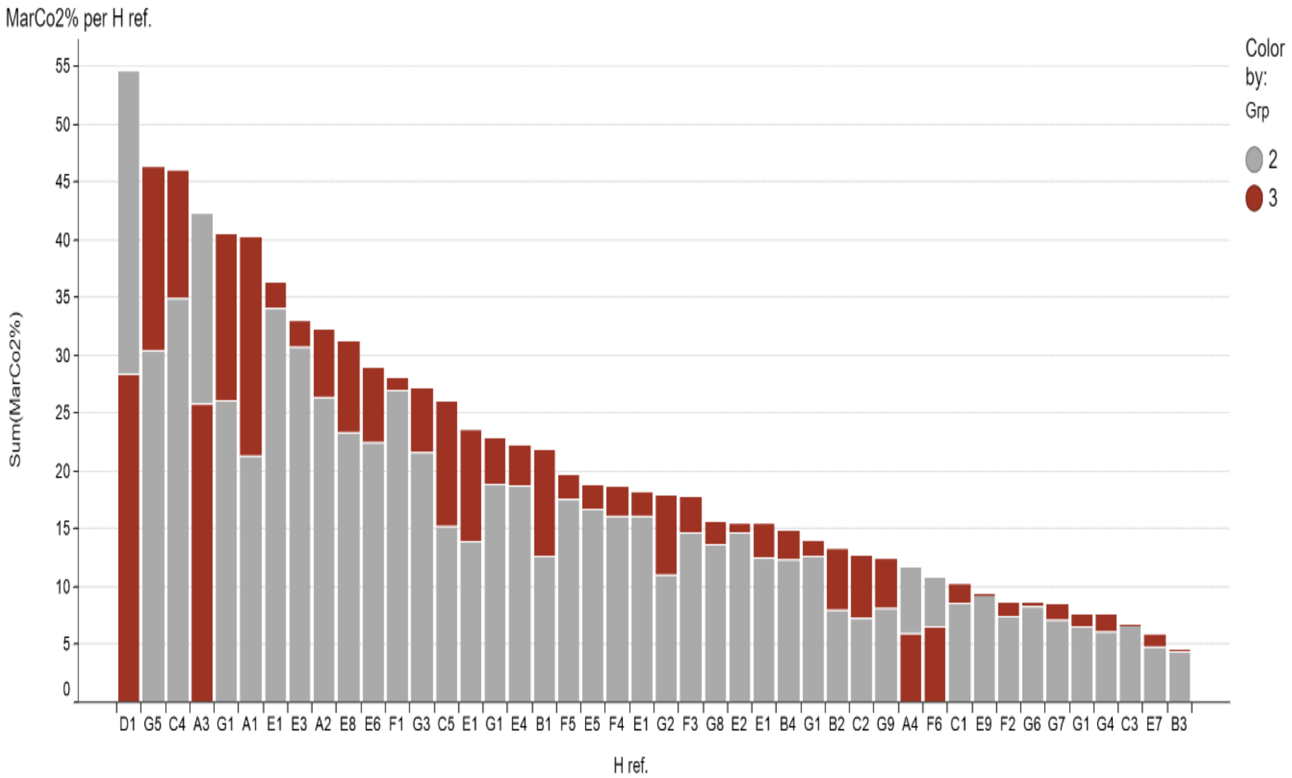
5
10
15
20
25
30
35
40
45
A3 D1 A2 G C4 G1 B1 E3 E1 B2 F1 E6 E1 E8 F3 C5 G E5 E4 E1 F2 G2 C2 A4 E1 A1 G9 B4 G G1 F5 E9 G C1 E7 F6 E2 G6 G7 B3 G G1 F4 C3
H ref.
Color by:
Grp
2
3

(a)


MarCo2% per H ref.
Sum(MarCo2%)
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5
10
15
20
25
30
35
40
45
50
55
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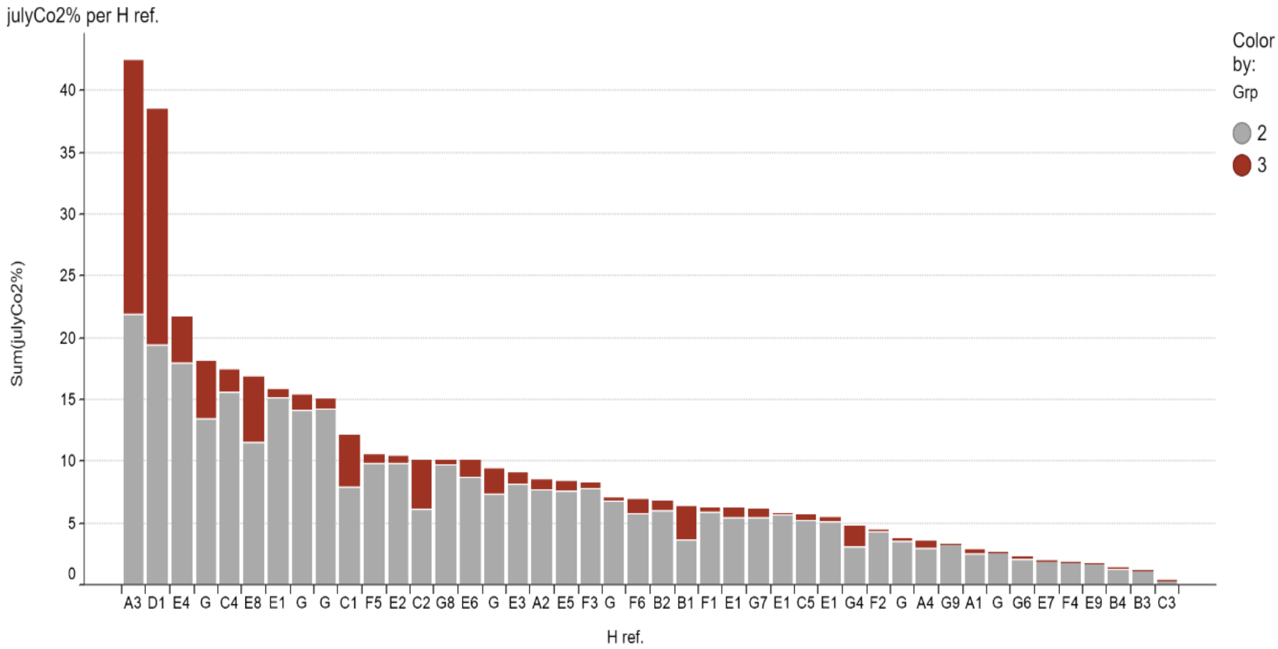
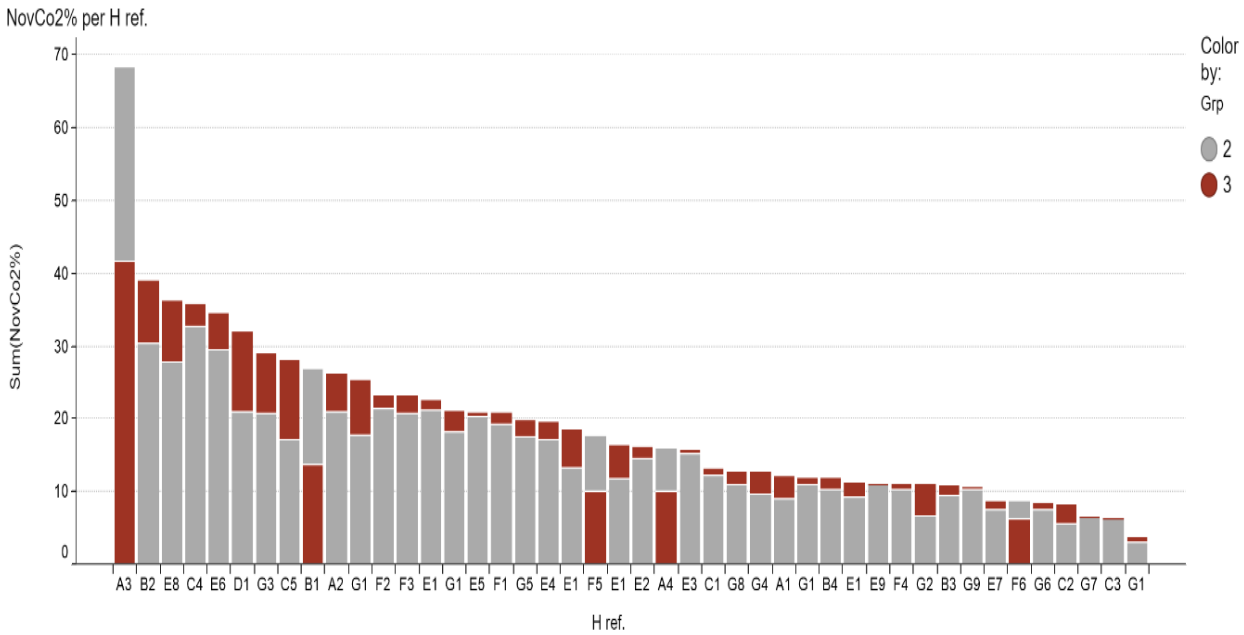
H ref.
Color by:
Grp
2
3

(b)



(c)



(d)

Figure 5.24 CO_2 exceedances in different seasons, greater than 1000 ppm (in grey) and 1500 ppm (in red)

In **Autumn**, only 7 out of 44 houses showed CO_2 exceedances lower than 10%, while 17 out of 44 houses showed CO_2 exceedances higher than 20%. Only 6 houses showed exceedances for more than 30% of the time, and only one house, A3, exhibits CO_2 exceedance for more than 40% of the time and is as high as 68%, signifying hazardous conditions. It can be observed that the CO_2 exceedances were comparatively higher during the **Spring**. Only 9 houses showed CO_2 exceedances to be lower than 10%, while 18 houses exhibited a CO_2 exceedance higher than 20%. As high as 10 houses show CO_2 exceedance higher than 30%, and 6 houses had high exceedances more than 40% of the time. The worst performing house was D1 with CO_2 exceedance as high as 54%.

In the **Summer** season, the CO_2 exceedances were comparatively low. Only 15 houses out of 44 had exceedances more than 10% of the time, and 14 houses had exceedances below 5%. Only 3 houses experienced exceedances over 20%, and the worst performing house was A3, with exceedances for about 44% of the time. Manual interventions in ventilation may be the explanation for these trends.

Finally, the **Winter** season also witnessed higher exceedances, in which only 9 houses had CO_2 exceedances lower than 10%. 18 houses had exceedances more than 20%, and 11 had exceedances more than 25% of the time. 3 houses experienced exceedances of 40% or more. The worst performing house was A3, followed by D1 and A2.

On the basis of the above data, given these are A-rated houses, there should be concern about how the houses are functioning, influenced undoubtedly by human behaviour (some perform well despite identical construction). The best and worst performing houses can be identified- for instance, two of the houses, A3 and D1, exhibited the highest exceedances in three out of four seasons.

In all, across all the four seasons, the worst performing houses in terms of CO_2 were A1, A3, B2, C4, D1, E1, E3, E4, E8 and G1. In contrast, some of the good performing houses noted were B3, B4, C3, E7, E9, F4, G1, G4, G6 and G7.

5.7.2. Temperature

The temperature exceedances of all 44 houses were analysed over each month of the year of study. The blue and red bar graphs in Figure 5.25 show the proportion of times when the temperature for the respective house in a particular month is less than 18°C and greater than 25°C respectively.

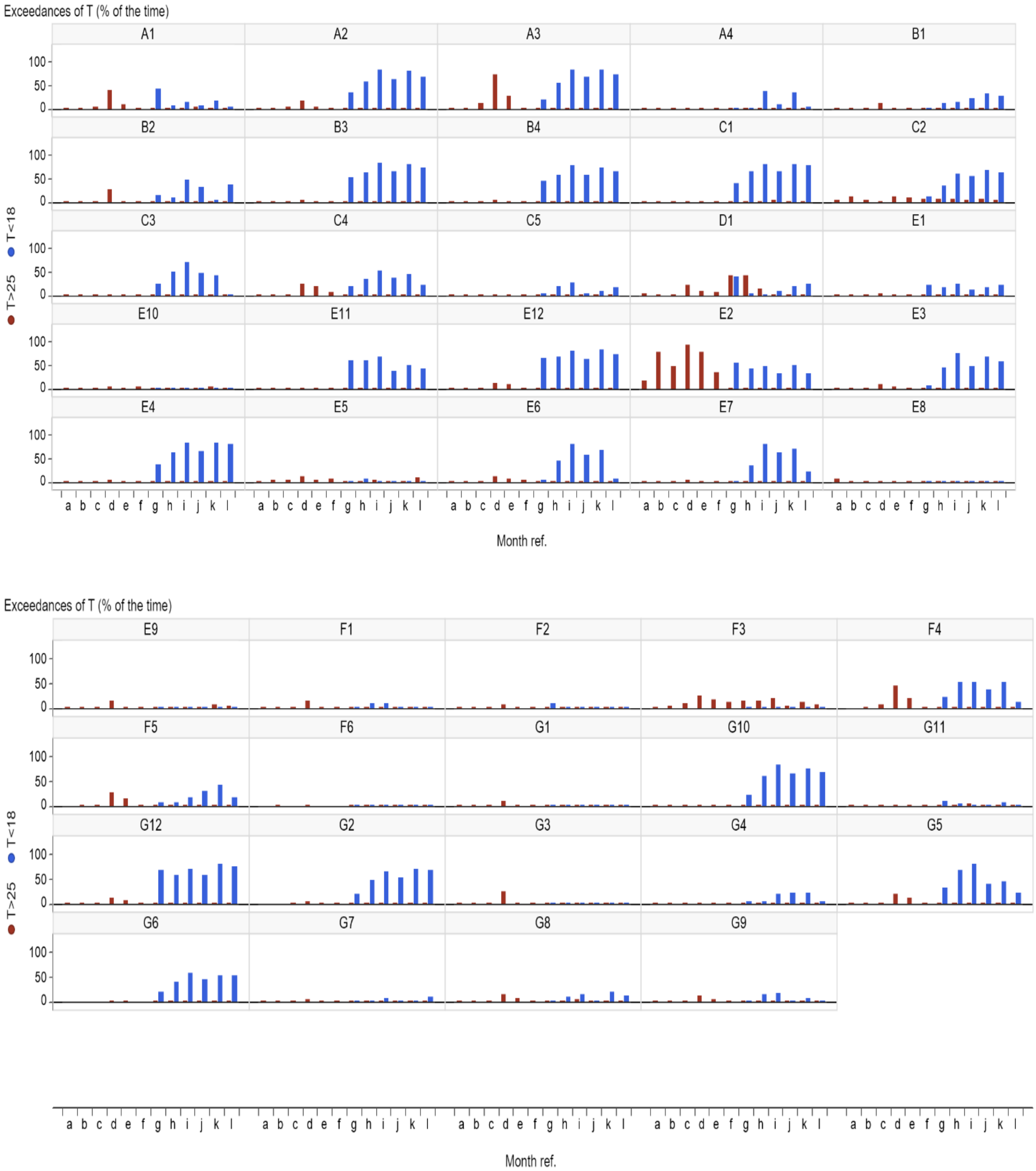


Figure 5.25 Proportion of times when the temperature is less than 18°C (in blue) or more than 25°C (in red)

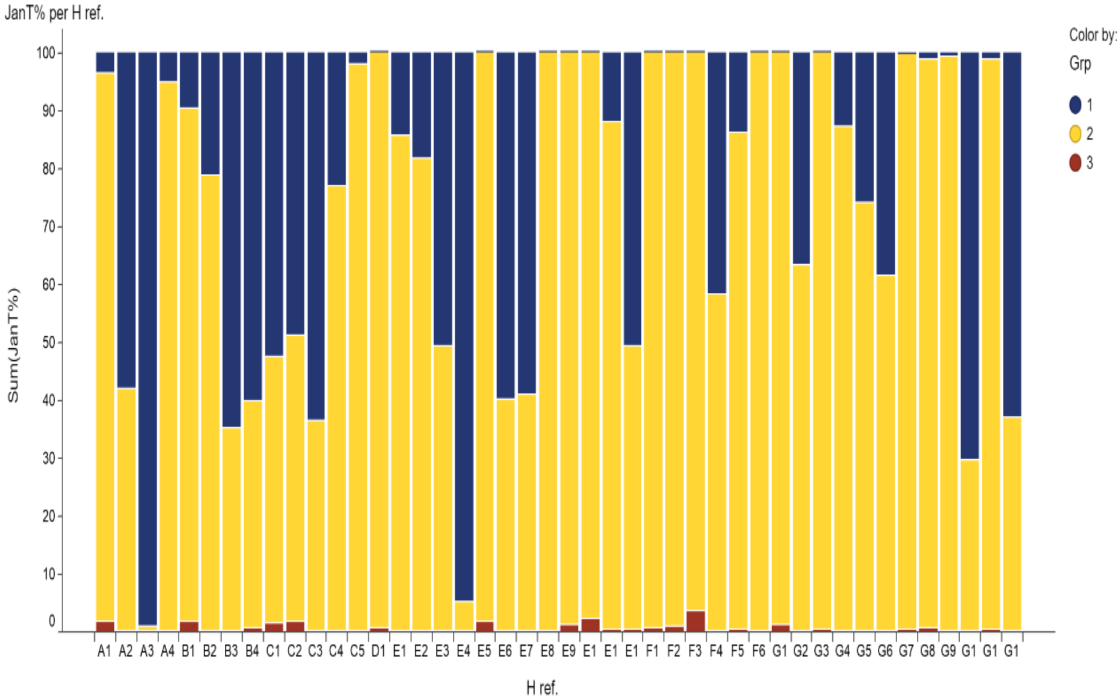
Figure 5.25 shows a wide variation in the 44 houses, with some houses exhibiting an overall low exceedance for all the 12 months, while others signify a diverse range of exceedances that differ between the months and seasons. Some of the houses that show lower exceedances are B1, C5, E5, E8, E9, E10, F1, F2, F6, G1, G3, G4, G7, G8, G9 and G11 and are categorised as houses with good thermal IAQ. In contrast, the houses that constantly showed much higher quantities of exceedances are A2, A3, E2, E4, E7, G5 and G6. Many of these houses regularly had temperature ranges either below 18°C or above 25°C, therefore, reflecting a poor thermal environment. Most of these latter houses show that for a significant proportion of time the temperature was below 18°C, which implies that they are unoccupied, or are not able to maintain a reasonable temperature or are not utilising the energy efficient houses optimally.

The exceedances in temperature for different seasons for these houses are also studied (Figure 5.26 (a to d) over the four seasons) to better understand the seasonal impact on temperature. Blue represents the temperature incidences less than 18°C, yellow represents 18-25°C and red represents more than 25°C. It may be noted that the proportion of incidences in terms of temperature lower than 18°C is more prominent in all the seasons except Summer, in which clear evidence of exceedances of more than 25°C is observed.

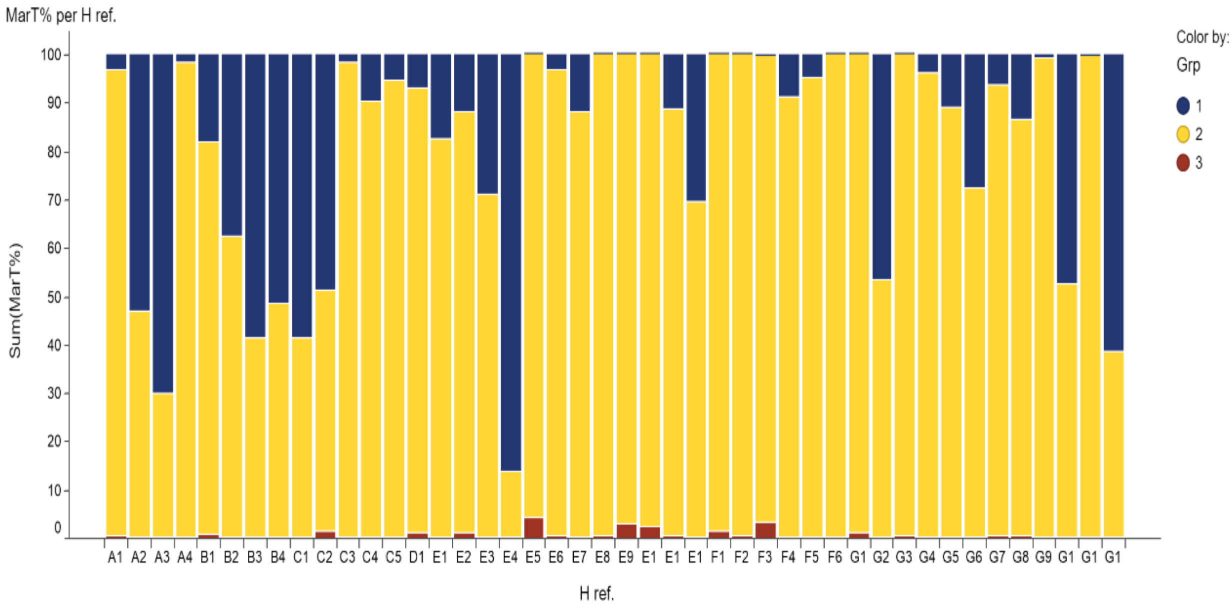
During **Autumn**, 14 houses showed temperature exceedances of more than 25°C, while all the houses, at some time, exhibited temperature less than 18°C. 20 houses experienced temperatures of less than 18°C for less than 20% of the time. Similarly, 16 houses showed lower temperature for more than 30% of the time.

In the **Spring**, 18 houses experience a temperature exceedance of more than 25°C, although all of those were so for about only 5% or less time. With respect of temperature less than 18°C, 23 houses observed this for less than 10% of the time, and 14 houses showed this for more than 20% of the time. Lastly, 7 houses showed low temperature for over 50% of the times and the worst performing house was E4, with lower temperature about 85% of the time.

During the **Summer** season, all the houses experienced temperature exceedances higher than 25°C. About 10 houses showed the temperature exceedances to be higher than 10%, and 3 houses showed exceedances to be about 20% of the time. The worst performing house was A3 with a high exceedance for more than 35% of the time. The exceedances in Summers were mostly due to higher ambient temperatures, solar gain and not opening windows, while in other seasons, the main factor of causing higher temperature exceedance may be attributed to the inefficient use of the heating system.



(a)



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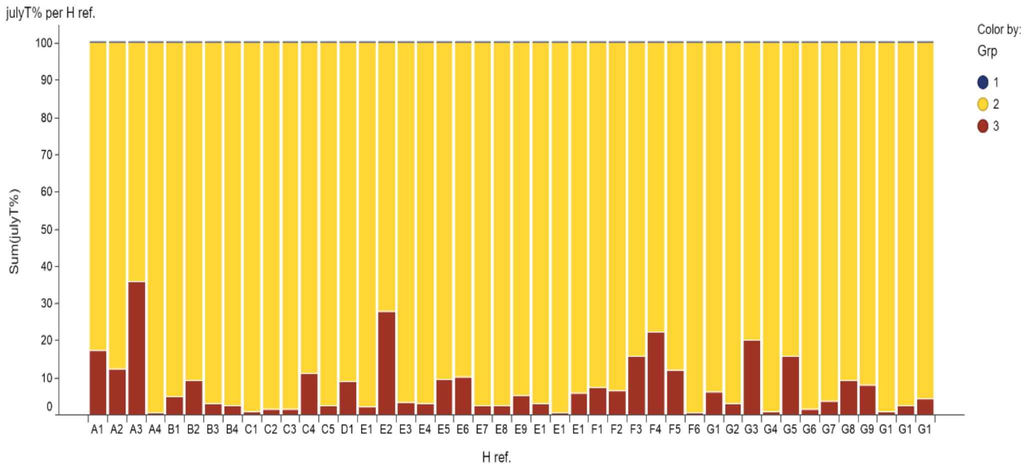
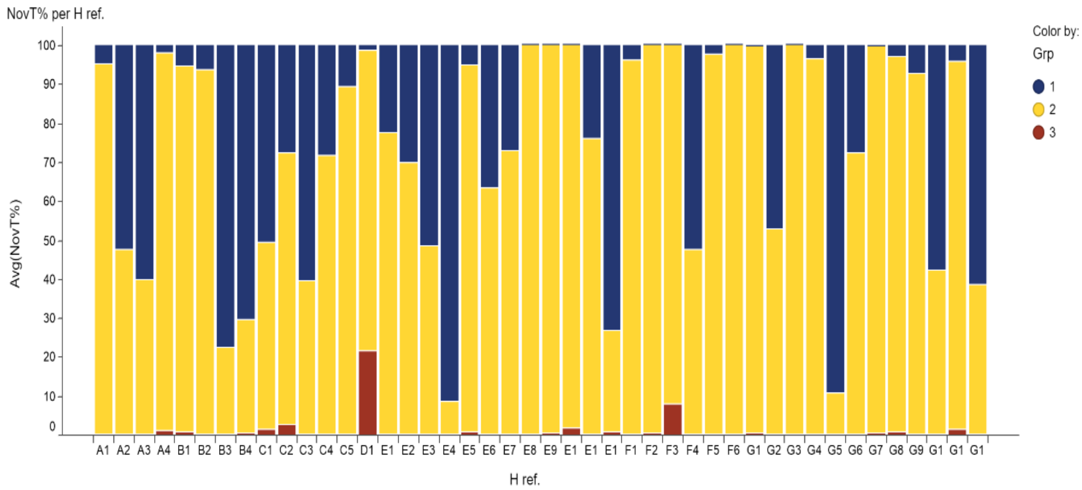


(c)



(d)

Figure 5.26 Temperature exceedances in different seasons (a) Winter (b) Spring (c) Summer (d) Autumn (blue is low, yellow medium and red is high)

In **Winter**, the incidences of temperature lower than 18°C was more prevalent than the temperature higher than 25°C. Only 20 houses had temperature exceedances of higher than 25°C, and all of these exceeded for only about 1-2% of the total time. The temperature lower than 1°C had high variations among the houses. Only 19 houses experienced the lower temperature for less than 20% of the time, and as many as 17 houses showed the lower range of temperature more than 70% of the time. The highest incidences of lower temperature were witnessed by houses A3 and E4, accounting for over 98% and 95% of the total time respectively.

The worst performing houses in terms of thermal comfort noted were A2, A3, C3, E2, E4, F3, F4, G1 and G5, while some of the better performing houses observed were E8, E9, F1, F2, F6, G3, G7 and G9. It is, therefore, concluded that the efficient utilisation of the ventilation, Trickle vents and heating system is needed to improve the IAQ during the different seasons, noting that all houses were similarly insulated.

5.7.3. Relative Humidity

In this section, the RH exceedances of all 44 houses were analysed over each month of the year of study. The orange and black bar graphs in Figure 5.27 show the proportion of times when the RH levels for the respective house in a particular month were greater than 60% and 80% respectively.

Figure 5.27 shows a wide variation in the 44 houses, with some houses showing an overall low exceedance for all 12 months, while other houses signify a diverse range of exceedances that differ between months and seasons. Some of the houses that showed the lower exceedances were A1, E7, E8, F3, F4, G8 and G9 and are categorised as houses with good IAQ. In contrast, the houses that regularly showed much higher exceedances were A2, A3, C1, D1, E4, E12, G4, G5 and G12, reflecting very poor IAQ where most of these houses showed the proportion of time the RH levels were higher than 60%.

An exception was house D1, which showed much higher exceedances for RH higher than 80% over many months. These may possibility be caused by Trickle vents that were not open, inadequate use of ventilation systems, or closed doors/windows, which may lead to much higher instances of higher RH levels.

The exceedances in RH for different seasons were also studied (Figure 5.28) to better understand the seasonal impact on RH. In the figure, grey represents the RH > 60% and red represents when RH > 80%.

Figures 5.28 (a to d) show the exceedances in RH in these houses for the four seasons. It is important to note that the proportion of exceedances in terms of RH more than 60% and lesser than 80% was most prominent in all the seasons.

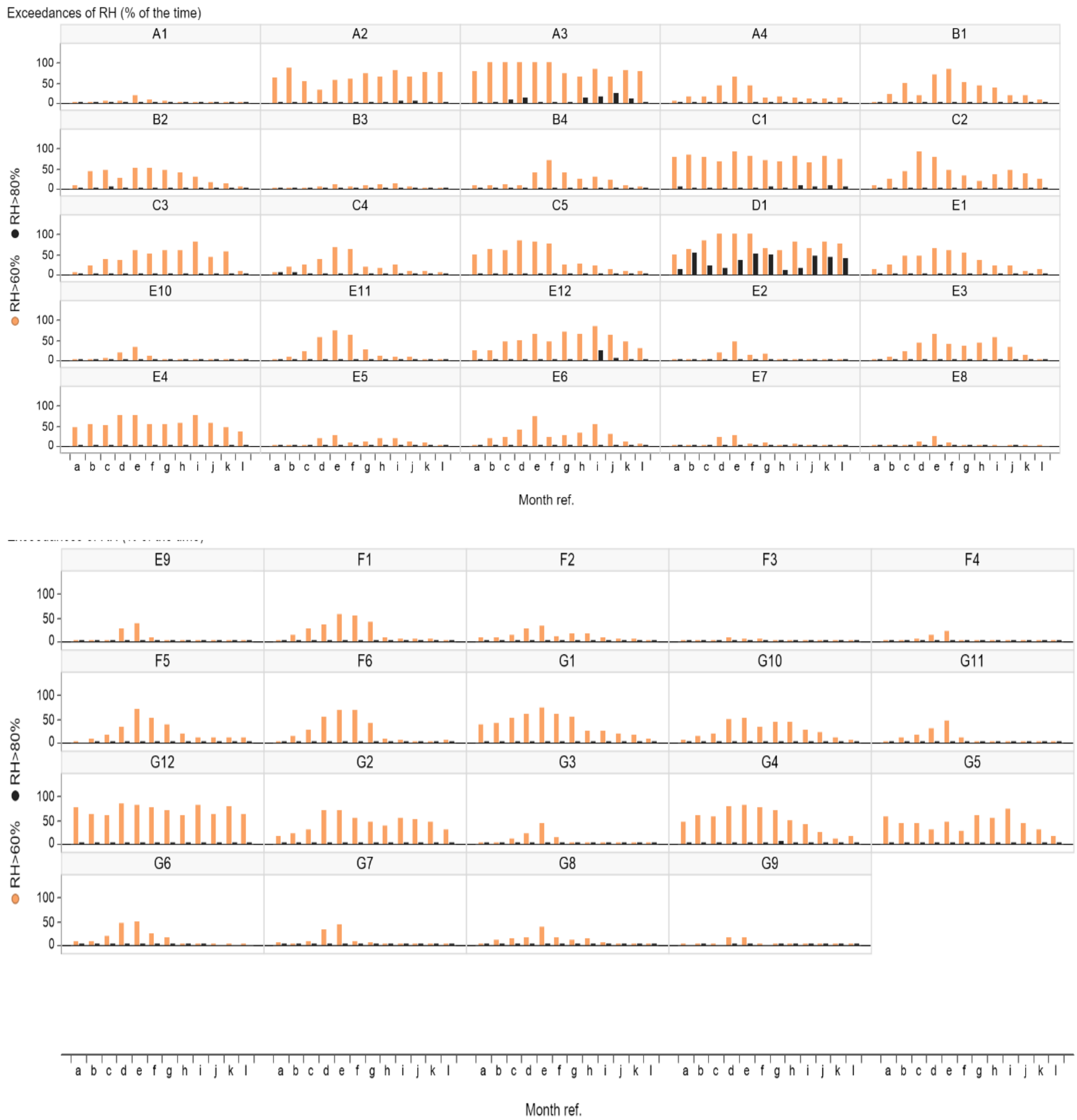
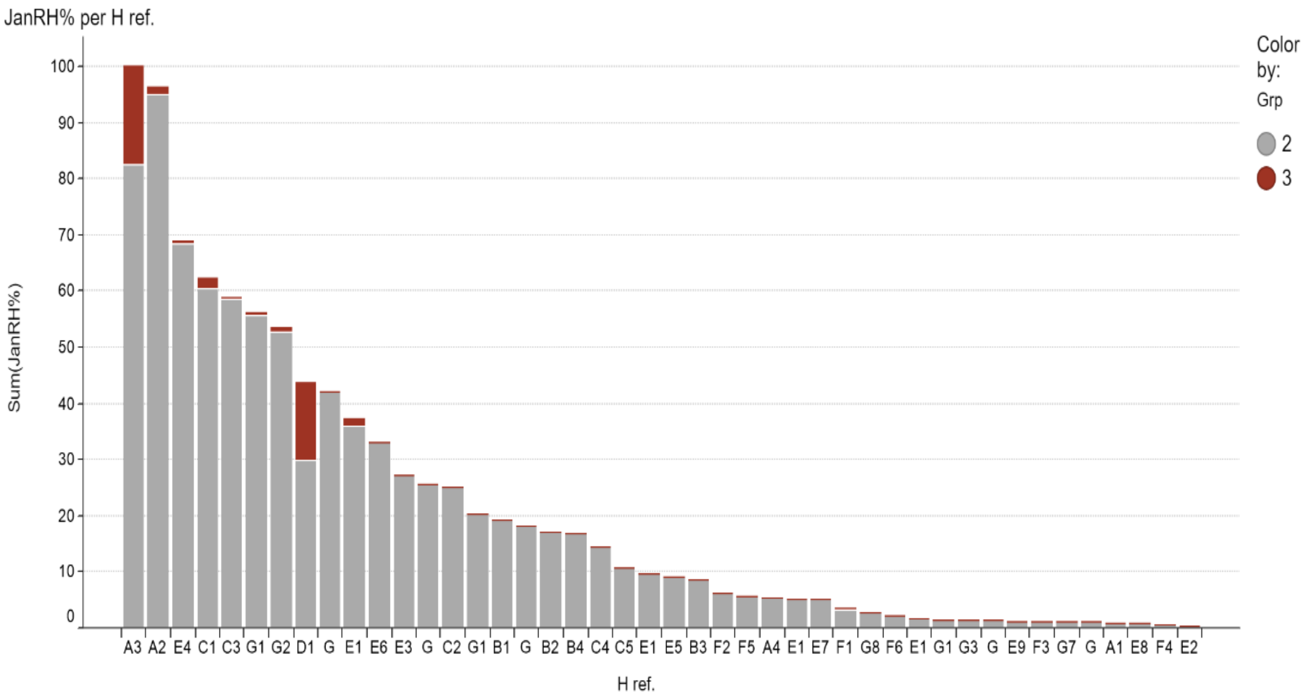


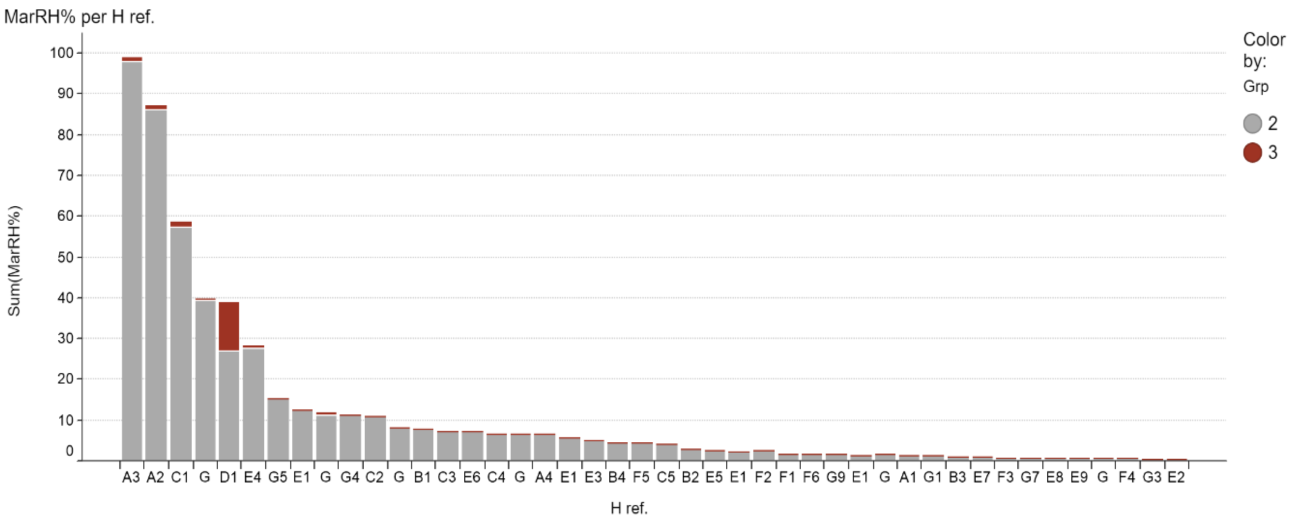
Figure 5.27 Proportion of times when RH is more than 60% (in orange) or 80% (in black)

In **Autumn**, 19 houses out of 44 had exceedances in RH for lower than 10% of the time. 21 houses showed the RH exceedances for more than 20%, and 9 houses showed exceedances over 50% of the time. The worst performing house was A3, which accounted for high moisture levels all the time during this season. Moreover, the exceedance in RH of more than 60% accounted for 81% of the time, while 29% of the time the RH was as high as 80% in house A3.

In **Spring**, the RH exceedances reported were much lower, such that only 11 houses showed RH exceedances for more than 10%, and 6 houses exhibited RH exceedances over 20% of the times. 3 houses experienced RH exceedances for more than 50% of the time. The worst performing house continued to be A3, followed by A2, with the exceedances reported for 98% and 88% of the time respectively during the season.



(a)



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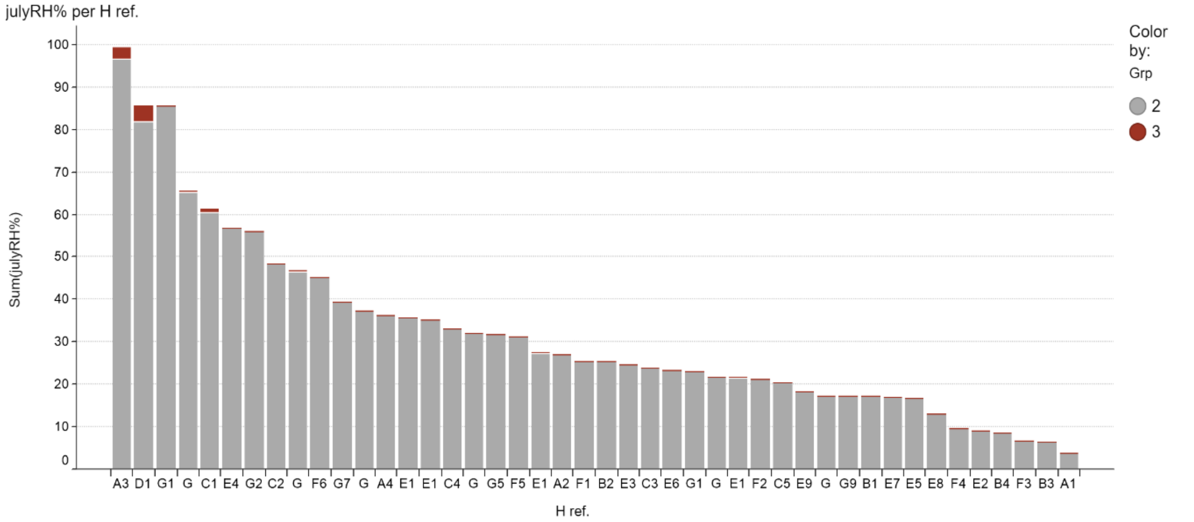

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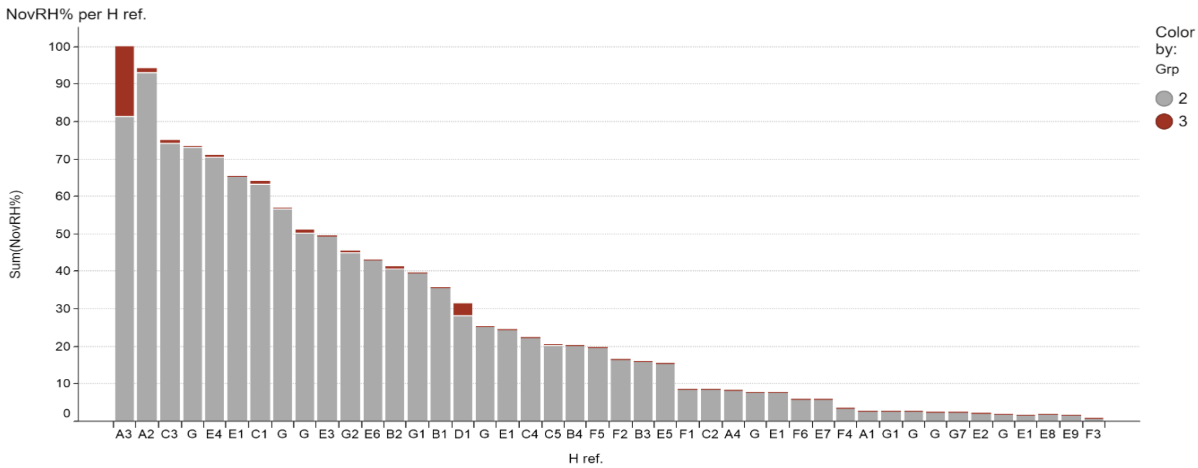


(d)

Figure 5.28 RH exceedances in different seasons (grey when RH>60%, red when RH>80%)

Summer again showed higher incidences of RH exceedances. Only 5 houses experienced RH exceedance less than 10%, and 13 houses reported RH exceedances to be less than 20%. 11 houses had exceedances for more than 40% of the time, and 3 houses reported RH exceedances for more than 80% of the time. Finally, the worst performing house was A3 with high moisture all the time during the Summer season.

Finally, **Winter** also recorded lower RH exceedance incidences. 23 houses out of 44 experienced RH exceedances for lesser than 10% of the time, and 14 houses reported RH exceedance to be more than 20%. 7 houses had exceedance for more than 50% of the times during Winter, with the worst performing house being A3, followed by A2, with RH exceedance occurring at 100% and 98% of the times respectively. The worst performing houses noted were A2, A3, C1, C3, D1, E4, G1 and G2, while some of the better performing houses observed were B3, B4, E2, E8, F3, F4, F9, G3, G7 and G8. The houses with high RH exceedance signify that the moisture content in the houses' atmosphere is high, which has the potential to cause mould and form damp and condensation issues in the building.

In conclusion, while the three variables are not independent, some houses perform well in all three, such as house G08, which appears to well ventilated while others perform poorly in all three, such as A03, which appears to be poorly ventilated, despite both houses having identical construction and systems in place. This confirms that human behaviour is one of the key characteristics in determining the IAQ in houses.

5.8. Comparison between a House with Acceptable versus Unacceptable IAQ

Thus far, the IAQ of the 44 houses at Location 1 have been analysed on the basis of different factors such as orientation, type of house, differences in family behavior and the impact of advice. Moreover, the rationale for differences in the IAQ values in different houses, as well the differences in the CO_2 levels for different zones (master bedroom and second bedroom) for the same house have been discussed. On the basis of the overall analysis, considering all these factors, a number of houses with acceptable and unacceptable IAQs have been identified. From the above analysis, two houses, A03 and G08, are now extracted, as they exhibit contrasting quality in their IAQs, and are now compared based on a number of parameters.

Figure 5.29 shows that the pattern of RH for both these houses exhibited similar trends for the week under consideration. However, comparing the RH movements between these two houses, house A03 showed high levels of RH, reaching the peak levels of 80% on several occasions. This demonstrates sustained high moisture in the master bedroom of house A03 each day which may be due to not just poor use of the ventilation system but by completely blocking the ventilation outlets and/or tampering with the central ventilation system as humidity is continuously high in this house for the entire week.

In contrast, house G08, with similar construction, experienced some fluctuations in the level of RH in a day, but the fluctuations were not high. The range of RH exhibited by the master bedroom of this house lay between 52% and 60%. Moreover, the RH changes were never rapid, but exhibited gradual change throughout the day. It is, therefore, inferred that these house occupants make much better utilization of their heating and ventilation systems, and cautiously utilize the opening and closing of the room door/Trickle vents, so that the change in room temperature and resultant RH are restored for the maximum time. As shall be seen, the CO_2 levels demonstrate high occupancy in both cases.

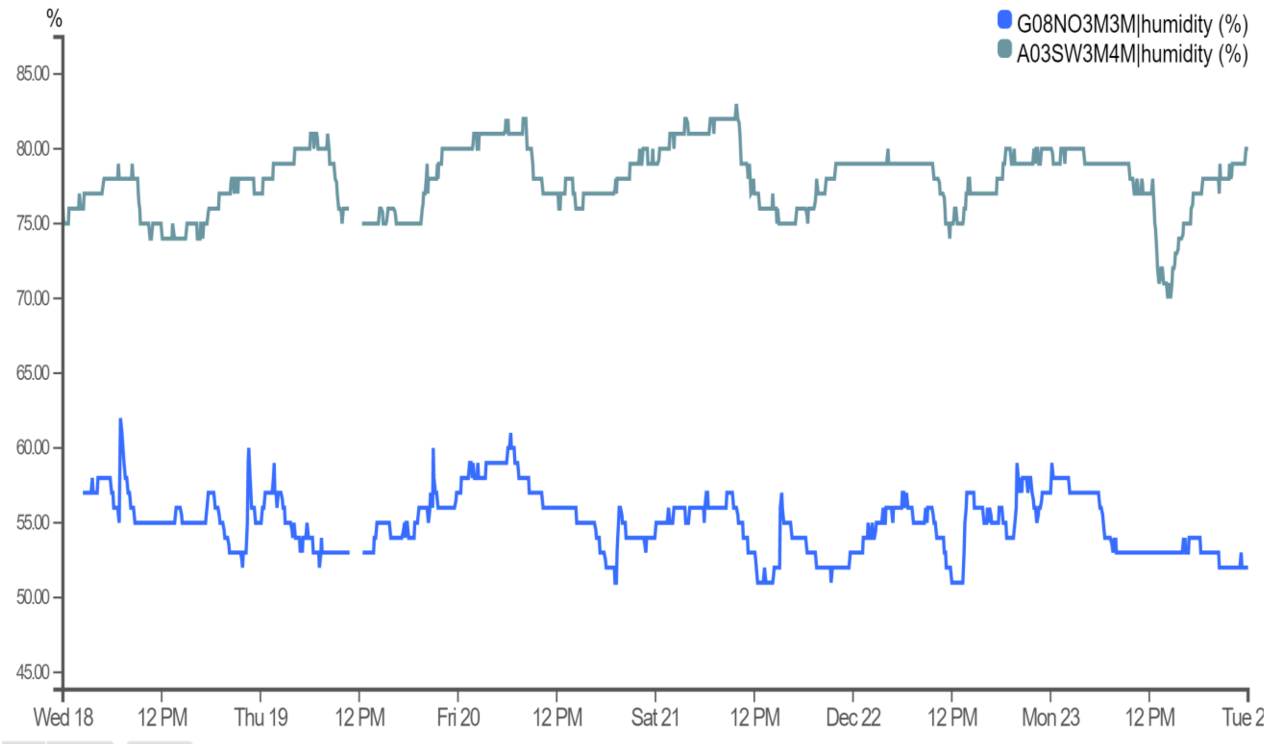


Figure 5.29 RH contrasting examples on the same day in the master bedroom

To understand the implications of RH on the IAQ for both these houses, the absolute humidities are computed for these two houses (which is a measure of moisture content in grams/m^3, regardless of temperature), A03 and G08, as given in Figure 5.30.

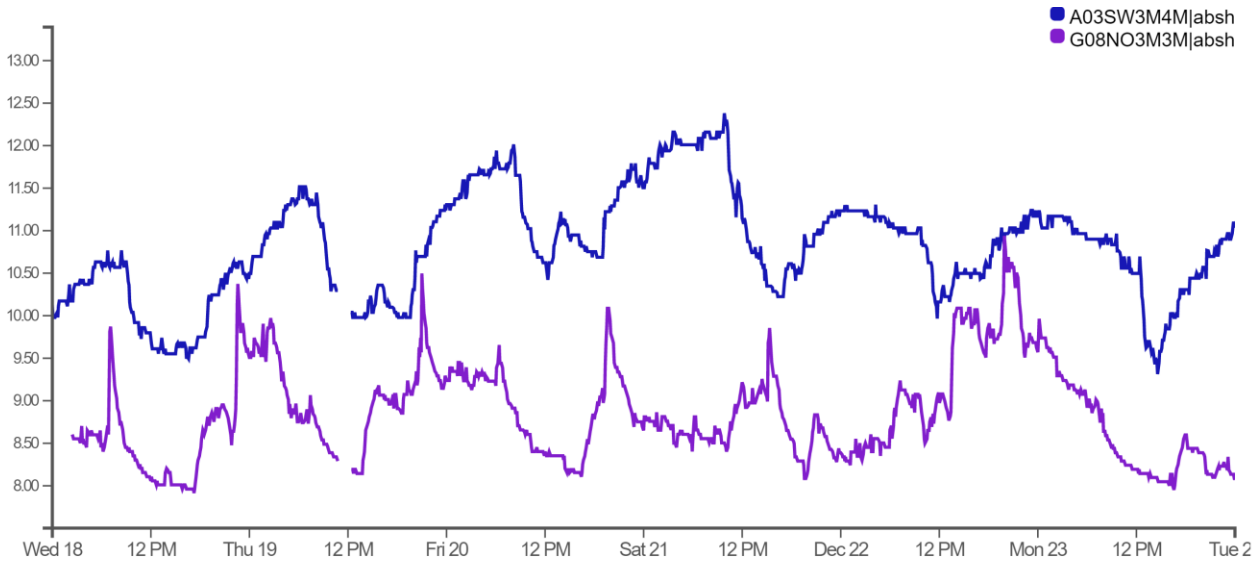


Figure 5.30 Absolute humidity – contrasting examples on the same day in the master bedroom

The weekly range of absolute humidity in each house showed similar movements over the week. However, the overall level of absolute humidity remained much higher in A03, ranging between 9.5 g/m^3 to 12.5 g/m^3, while the absolute humidity for G08 remained between 8 g/m^3 to 10 g/m^3, with an outlier of 11 at only one time in the week. However, the mean absolute humidity for the G08 was calculated to be around 9.0, which showed good control of air moisture. The rationale for considering absolute humidity is due to the fact it is not affected by change in temperature. Thus, this is a good example where it is informative to learn the actual moisture in the air without temperature dependency.

Therefore, the better performing house, G08, seems to be using the heating and ventilation systems more efficiently. However, the poor IAQ house, A03, is allowing the absolute humidity to move beyond 10g/m^3, signifying potential future high incidences of mould formations, dampness, condensation, and other high moisture related problems. Apart from humidity, the other variable that showed the IAQ of houses is the accumulation of CO_2 levels within the house. For the two houses, A03 and G8, the CO_2 levels in the master bedroom, over that same week are assessed using Figure 5.31.

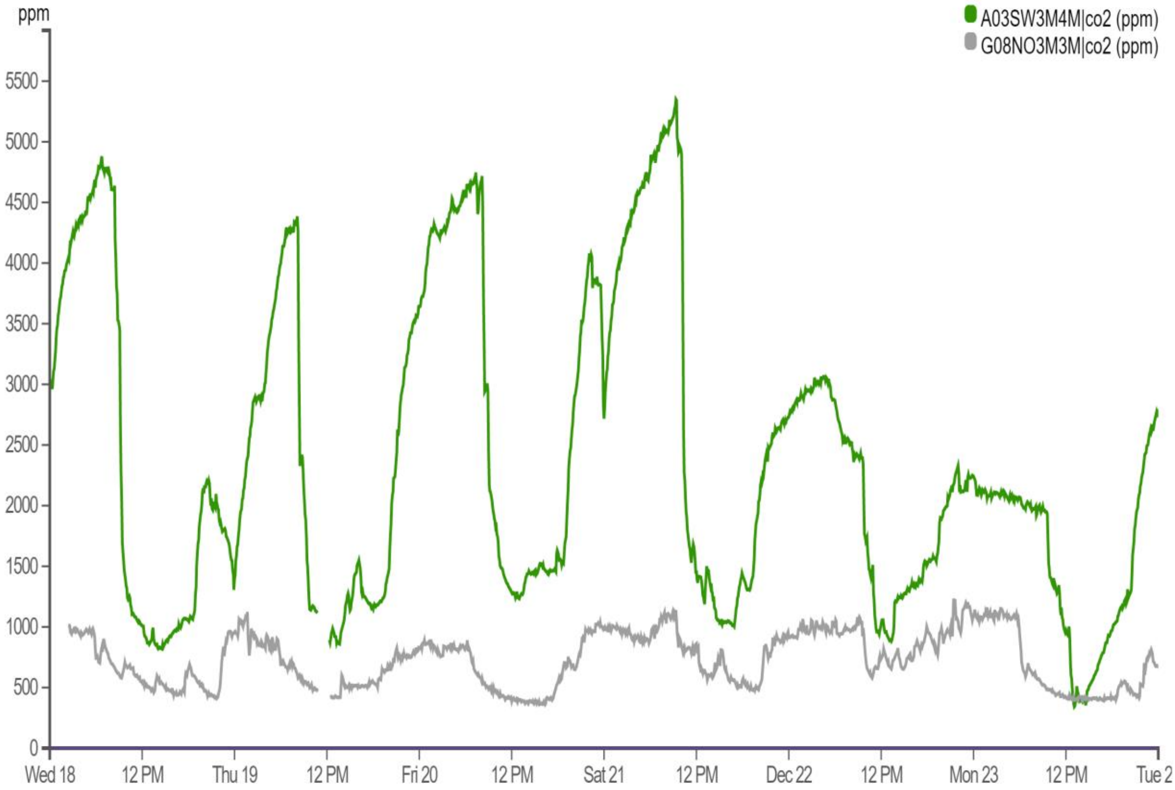


Figure 5.31 Contrasting examples of master bedroom CO_2 in the same week

This graph shows a remarkable difference in the CO_2 levels between the houses over the same time period. G08 had been successful in keeping the overall CO_2 levels low (with obvious daily occupancy) and ranged between 400 ppm and 1000 ppm, with one outlier of 1200 ppm.

Moreover, the transition between every change in the CO_2 levels in G08 was also not rapid, which showed efficient management of the ventilation system in the house. In contrast, house A03 showed much higher CO_2 levels, ranging between 1000 ppm and 5000 ppm. The change in CO_2 levels were very large and rapid and showed a continuous pattern of high CO_2 during occupied hours. This implied that the occupant behaviour is not optimum and may be caused by the fact that the occupants kept the Trickle vents of the master bedroom closed, with the doors between the en-suite and landing and master bedroom also remaining shut for most of the time, which led to an accumulation of CO_2 within the room.

5.9. Summary

Based on the overall analysis, some of the key findings relating to these houses are:

1. Although the houses under study were fundamentally similar in construction, there were many factors that influenced their IAQ.
2. Some of the factors, like orientation and house types, initially provided some reasons for the variations in temperature of these houses in different seasons, however, it was also noted that many houses experienced differences in their IAQ factors despite having the same orientation and house type.
3. Further analysis indicated that some of the crucial factors that impact the IAQ factors, namely temperature, RH and CO_2 levels, are strongly affected by family behaviour, such as occupancy, working status and family interventions with the heating and ventilation systems. Though these factors influenced the IAQ factors, still wide variations were noted between different houses. These differences were attributed to the living and activity behaviour of the occupants residing in each house.
4. To investigate the implication of this behaviour of the occupants, the consequences of delivering professional advice to selected occupiers were examined on a set of houses in the month of November. It was found that the IAQ factors show significant improvement following adherence to that advice. Once again, some contrasting findings were made, wherein the post-advice improvements in the IAQ factors were either small, negligible, or not long lasting. Thus, further investigation is required to learn the effectiveness of providing advice which will have more permanent benefits.
5. The CO_2 level for closed internal door versus open internal door (one of the suggestions for improvement given) were assessed. It was concluded that when the door of the second bedroom was left slightly open, the CO_2 levels were measurably lower as compared to when the door was closed during sleeping hours. This, therefore, showed that the advice provided to the houses was effective and of significant benefit to the occupants, but where

they failed to follow or sustain that advice, no sustainable improvements in the IAQ factors resulted.

6. Another important finding of the study is that when the houses kept the door between the en suite and master bedroom partially open during sleeping, the accumulation of CO_2 (one of the IAQ factors) was reduced measurably, because the excess CO_2 was removed by the mechanical extract in the en suite. This feature is of some importance and helped to significantly lower the CO_2 levels in a double occupancy master bedroom, to levels lower than a single occupancy second bedroom.
7. In some houses, like G12, though the house was maintaining a good IAQ profile, often complaints were received of cold temperatures, even after switching on the heating system. This called for checking that the Trickle vents were operational, since it may be possible that the Trickle vents were open fully (100%) throughout the year.
8. It is found that different zones of the house, due to their design, are suffering from poor IAQ. For instance, the second bedroom, often being at the North side of the house, is not able to benefit from any solar gain and its air changes relies on the Trickle vent. It thus suffers from very high CO_2 levels when vents are blocked, and doors are kept closed at night. However, it is proposed here that by making slight changes to the design, such as installing an extra extract in the landing area and inserting a vent grill above the door of the second bedroom, such houses could experience much reduced CO_2 and humidity levels in the second bedroom.

6. Simulating Family Behaviour

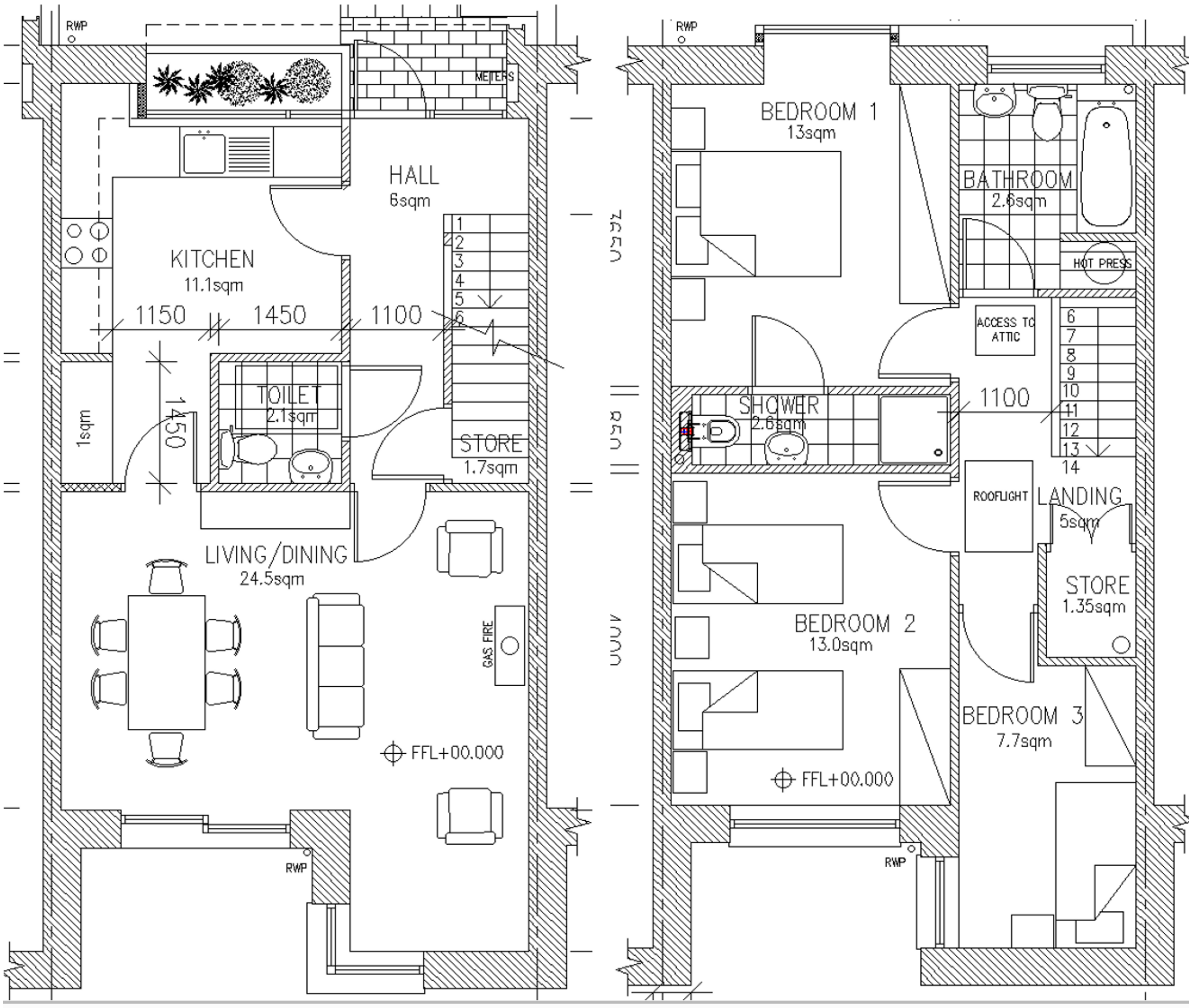
6.1. IESVE Model

The researcher utilised “virtual environment by Integrated Environmental Solutions” (IESVE) software for data modelling, including calibrating and simulating the results. IESVE is a software package that contains several integrated tools for analysis, which can efficiently facilitate thermal and moisture condition modelling in buildings, as well as having the potential to perform value engineering, cost planning, lighting assessment and lifecycle analysis (IES, 2012; 2015). IESVE comprises a suite of integrated environmental analysis tools capable of modelling environmental conditions in a building, particularly temperature and RH variations. A full description of the software and the theoretical models it uses for analysis can be found in Chapter 3.

6.2. Model Creation

The model created in the IESVE entailed a number of steps, namely, defining the geometry of the house, the orientation and house type, solar parameters, material and elemental properties and various loading scenario inputs. In the first stage, the model is created by specifying the geometry of the houses. Floor plans of a typical house, drawn using AutoCad, were obtained from Project Architect, as shown in Figure 6.1. Floor plans were then converted into *‘dwf’* format. This allowed them to be imported directly into the software and used to virtually build the geometry of the house.

The internal parameters of the typical 3-bedroom house were utilised to construct the envelope including the walls, roofs and partitions. Then, the “draw extruded shape” function was used to create each floor height to build the external perimeter of the house (floor height was obtained from elevation drawings). Later the partitions and openings (including doors and windows) were added to the model (Figure 6.2). It is a mid-terrace house so external left and right-side walls are specified as adiabatic walls (with no heat transfer).



(a) (b)

Figure 6.1 Floor plans of house (a) ground floor and (b) first floor

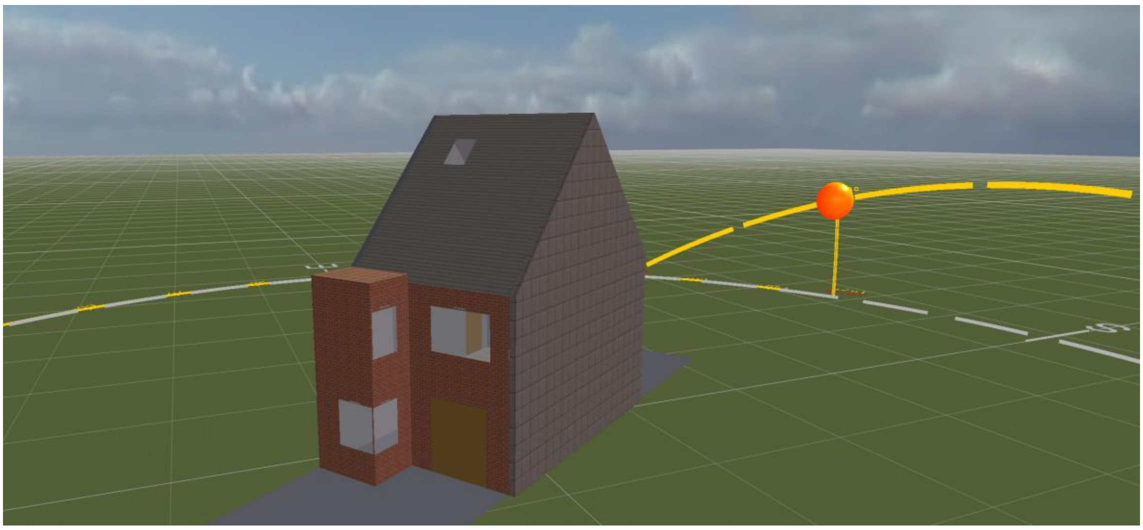


Figure 6.2 Axonometric view of a typical house constructed using ModelIT in VE

Next, the constructed windows and walls were defined using the thermal properties of the individual building elements. Once the u-values, wall type and thicknesses were defined in project construction window of ModelIT (as obtained from Part L document), IESVE specified the rest of the details based on the input data. This process was completed using the Apache package and building template manager within the IESVE software. The programme requires the density, thermal conductivity and specific heat capacity of each material and its thickness within the particular element being constructed. The software has a large database of materials and their relevant thermal properties inbuilt in Apache.

Similarly, for windows, the thermal properties involving thicknesses, u-values and G-values (from BER and Part-L document) were inserted. For example, the specifying of an external wall and window in the building template manager window is illustrated in Figures 6.3 and 6.4 respectively. Once the geometry was constructed, the location and orientation were defined using the APlocate function in the software, with the relevant weather file.

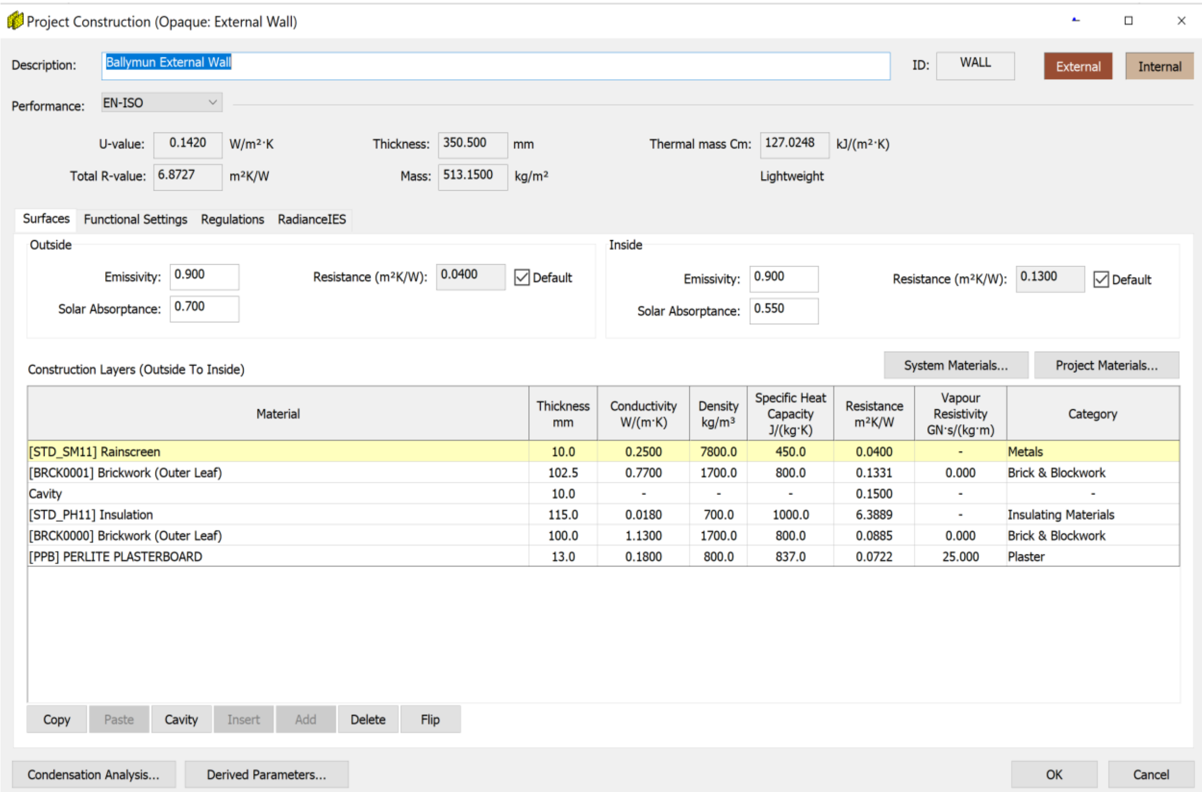


Figure 6.3 The construction window used to input structural element properties of wall to IESVE

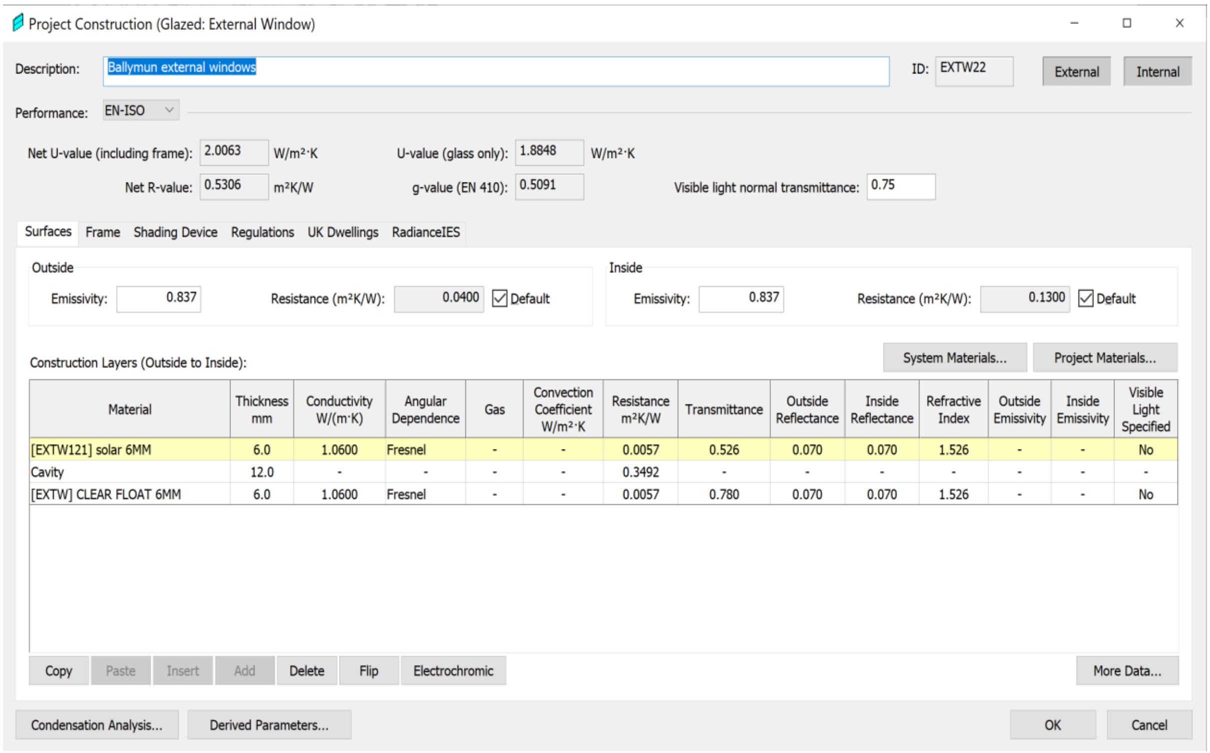


Figure 6.4 The construction window used to input structural element properties of window to IESVE

To assess the impact of the external environment, the weather data for the simulated year and months were extracted from the weather station, as given in Figure 6.5. The weather file was downloaded in Excel format from the weather station data. The iScan feature of IES was used to convert the weather file from an Excel format to a *'fwt'* format with the help of IES project team. iScan feature of IESVE automatically created the necessary channels for this format which allowed the weather file to be imported directly into the IESVE model.

The operational profile was also created for different house zones, along with the heating operating profile and heating setpoints, as given in Figure 6.6. For instance, the figure shows that in different zones, the heating operating profile was kept continuously on, based on the profile created for heating setpoints, except flat roof and roof areas, for which it was shown as off continuously. This feature is called ApPro profile in the software. These profiles were constructed in two stages. First, the daily profiles were specified using time and value variables. After creating the daily profile, weekly profiles were created for heating, occupancy and equipment gains.

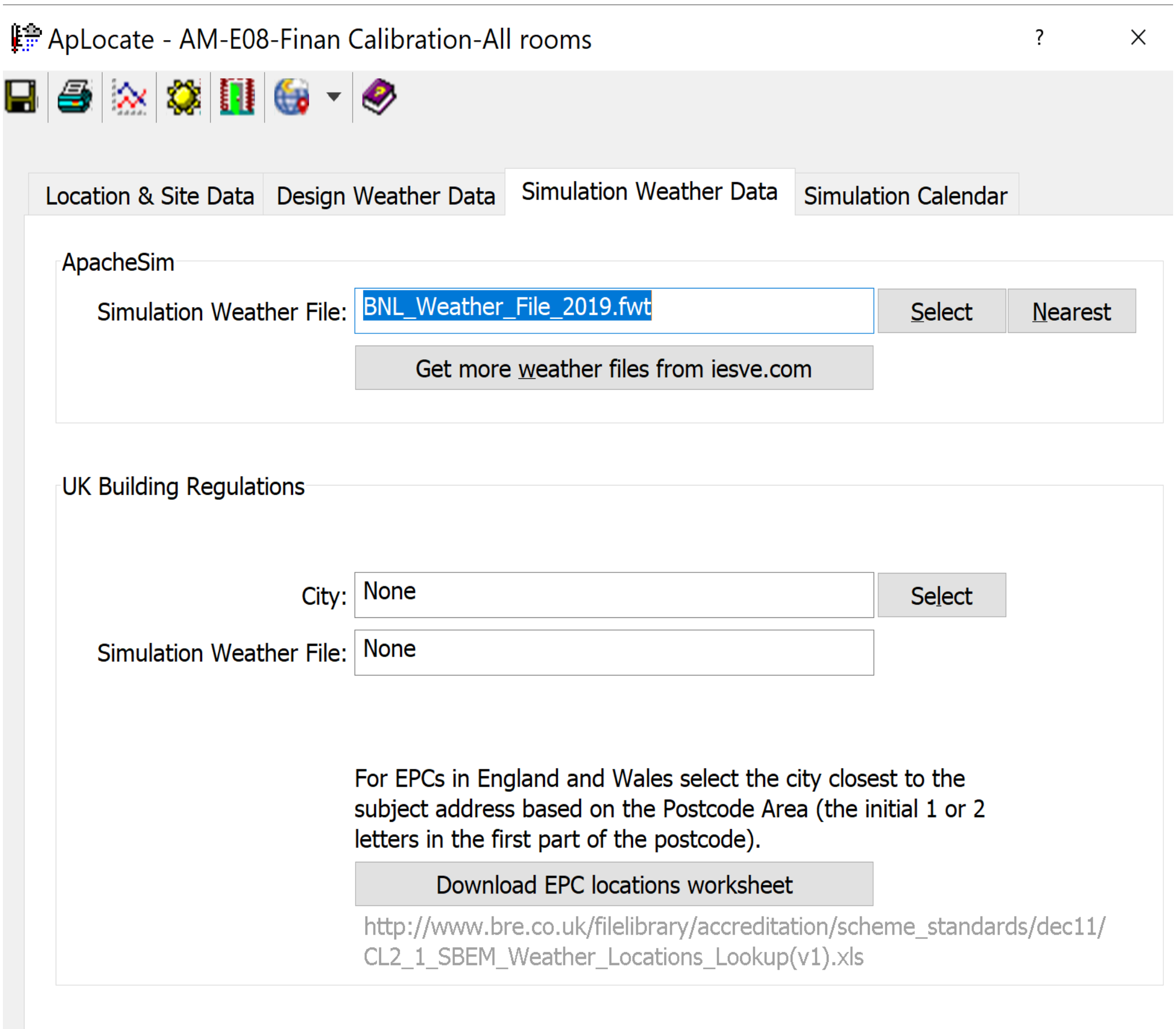


Figure 6.5 Weather data extracted from weather file for the simulated year

Space ID	Space Name	Heating operation profile	Heating Setpoint (°C)
BT000000	bathroom	on continuously	Profile: E08SO3M4K|temperature_predict...
BD000000	bedroom 1	on continuously	Profile: E08SO3M4M|temperature_predict...
BD000001	bedroom 2	AM-bed2-heating-Weekly	Profile: E08SO3M4S|temperature_predict...
BD000005	bedroom 3	on continuously	Profile: E08SO3M4S|temperature_predict...
NT000001	Ent. Foyer/Stairs GF	on continuously	Profile: E08SO3M4K|temperature_predict...
FL000001	Flat roof	off continuously	19.0
HT000001	hotpress	on continuously	Profile: E08SO3M4K|temperature_predict...
KT000000	Kitchen	on continuously	Profile: E08SO3M4K|temperature_predict...
LV000000	Living/Dining	AM-Living-Heating-1-Weekly	Profile: E08SO3M4L|temperature_predicte...
NS000001	on-suite	on continuously	Profile: E08SO3M4E|temperature_predict...
PW000000	Powder Room	on continuously	Profile: E08SO3M4K|temperature_predict...
RF000000	roof	off continuously	19.0
ST000000	store	off continuously	Profile: E08SO3M4K|temperature_predict...

Figure 6.6 Thermal profile of different house zones

Also, the opening profile of windows was projected using the 'Macroflow' feature by providing a description of all the openings, as given in Figure 6.7. The figure provides the Macroflo opening types for different windows and door openings in the entire residential unit. It states the openable area percentage, the fixed coefficient discharge of 0.60, crack flow coefficient, crack length as a percent of the opening perimeter and opening threshold temperature. After specifying the openable area, category, exposure type and degree of opening by creating an openable profile, other features were calculated by the software from the inbuilt standard files.

Next, the profiles for ventilation, door opening and window opening profiling were created in Apache profiles. For this, the profile for heating and ventilation for the master bedroom were plotted for different values across different times of the day. Figure 6.8 provides the graphical representation for the modulating values across the specified time intervals.

Similarly, the profile for the master bedroom occupancy for a day (Figure 6.9) was created using the modulating values as per occupancy over different time points during the day. A simulation was carried out to ensure that the model was performing without any error. The ApacheSim (Dynamic Simulation) option was used and the required time period, reporting interval and preconditioning period were specified. Once simulations had been completed, the software automatically switched to the Vista programme and the relevant data, in this case the temperature (T), relative humidity (RH) and carbon dioxide emissions (CO_2), were extracted and inserted into Excel for interpretation.

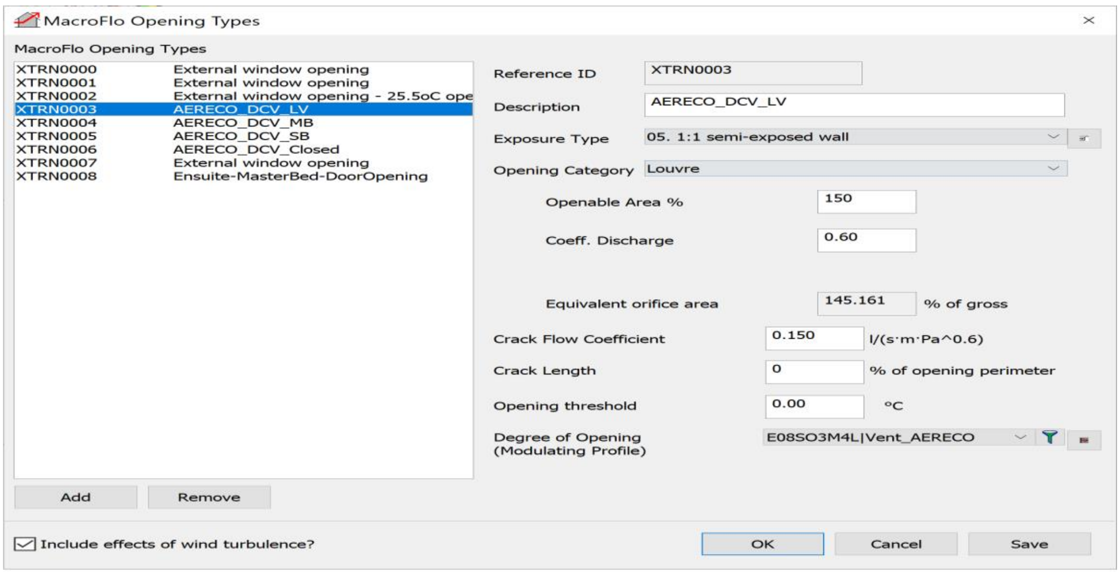


Figure 6.7 Macroflow opening types

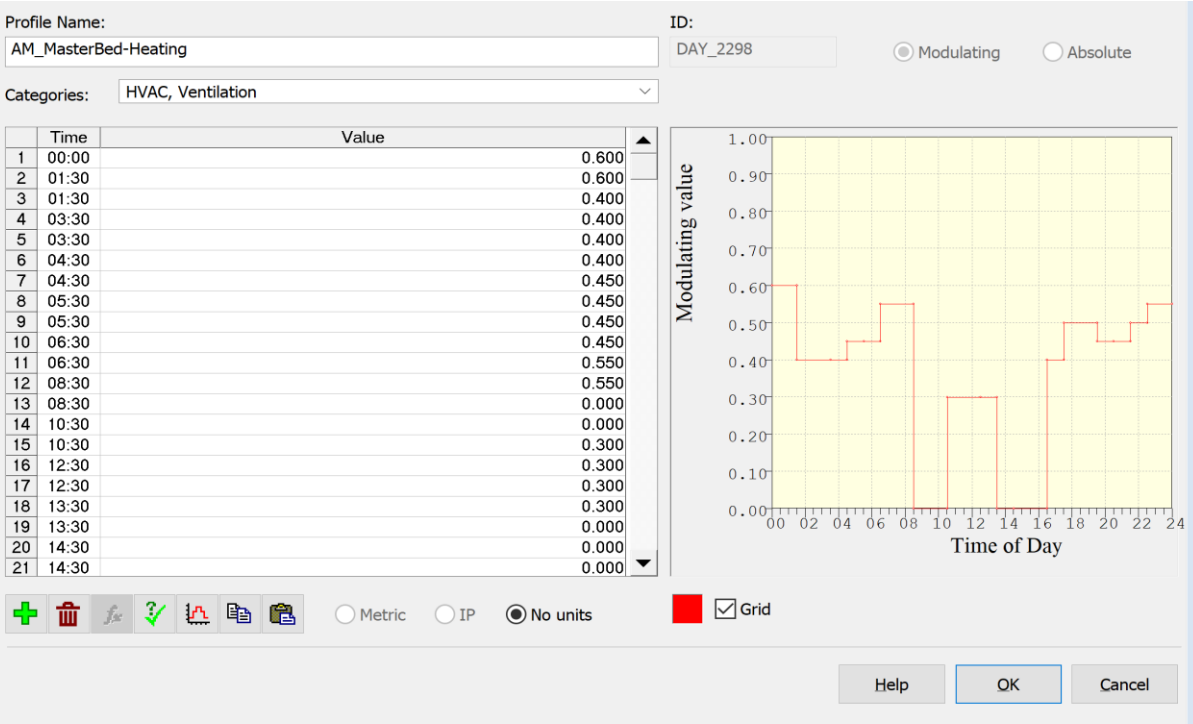


Figure 6.8 Master bedroom heating profile

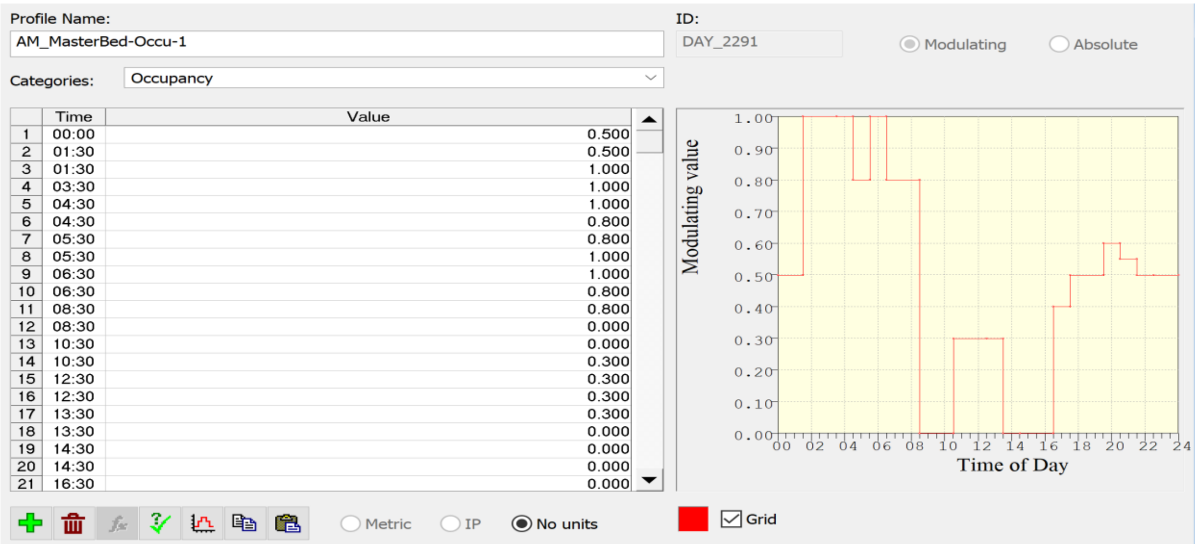


Figure 6.9 Master bedroom occupancy profile

6.3. Calibration

Once the model had been successfully constructed in the IESVE software, the simulations of the internal environment of the sample houses were performed. While calibrating, one typical winter day's data (from January) for a house with four occupants (two adults and two children) was considered. The model was calibrated with the real on-site data for that particular day for all three parameters, namely, T, RH and CO_2 levels within the four main house zones (kitchen, living room, master bedroom and second bedroom). Calibration was achieved by creating and matching different variables in the data, including occupancy, heating schedules/profiles, equipment usage, door-window and ventilation schedules. Separate occupancy is assigned for each room. However, heating and occupancy profiles can be overlapped over time because within 1 hour or even 5 minutes, occupants can move from one space to another. Therefore, an average occupancy within that hour is considered for modelling. Results downloaded from Vista were extracted in Excel format and checked with the real on-site data for that particular day. Once the model was calibrated, different simulations were run to solve the issues faced by different families.

6.3.1. Kitchen

The profile for kitchen occupancy and the heating schedule were created for running the calibration. Figure 6.10 shows the heating profile created to match the on-site data. Figure 6.11 show that the kitchen was occupied by one person, who had been inside the kitchen for some times, during morning and evening hours, with the kitchen vacant between 2 am and 8am and then between 1pm and 5pm. Figure 6.12 provides the calibration result for the CO_2 levels in the kitchen for the entire selected day.

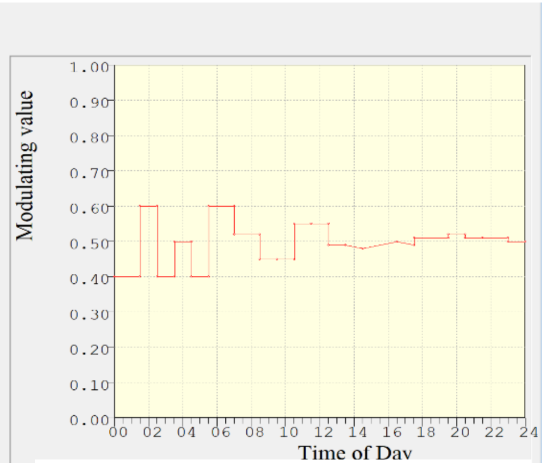


Figure 6.10 Heating and ventilation profile in the kitchen

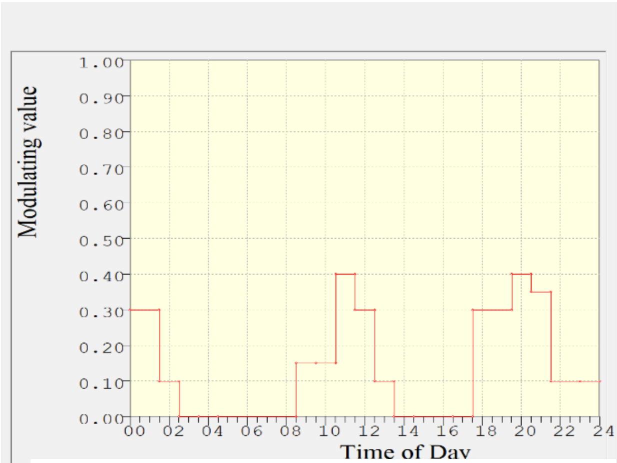


Figure 6.11 Occupancy profile for the kitchen

It was also found that the windows and doors of the kitchen were closed, which does not facilitate the movement of CO_2 across different zones. The kitchen is also equipped with a mechanical extract fan, which is a demand-controlled ventilation system for facilitating ventilation and avoiding accumulation of moisture from cooking activities.

Considering the variations in the CO_2 levels (Figure 6.12) between on-site measured values and the simulation values, both of them react in the same way to stimuli but show some variations throughout the day. The simulated CO_2 levels were marginally higher than the measured on-site CO_2 levels from 30 minutes past midnight to 9.30 hours in the morning; thereafter the on-site CO_2 levels rose above the simulated values. Also, the on-site measured CO_2 levels were lower than the simulated CO_2 values for another hour from 15:00 hours to 16:00 hours. It is, however, found that

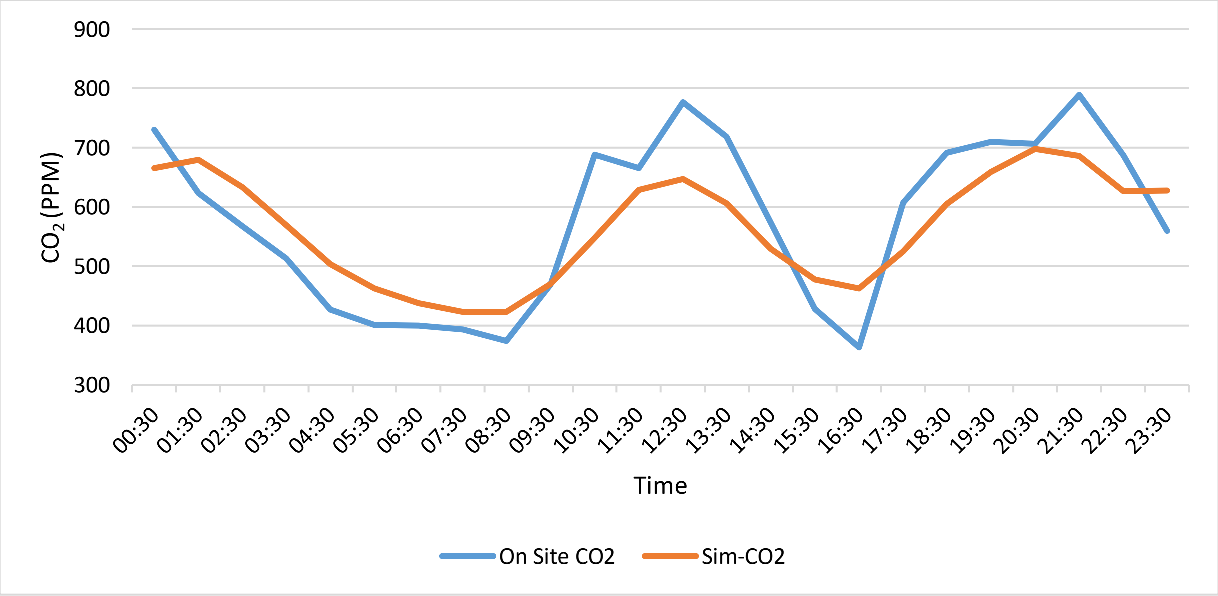


Figure 6.12 Movements in CO_2 in on-site recorded and simulated for the kitchen over one day

despite these small differences, the simulated CO_2 levels resemble well the trends as shown for the measured CO_2 levels in the house.

It is important to note that there are many exogeneous factors that influence the real CO_2 levels for a short time, such as the entry by another family member while one of the occupants was already cooking in the kitchen, and the subsequent drop in CO_2 may be due to the exit of that new occupant.

The average difference in the CO_2 levels was 11ppm, which reinforced that the simulated values closely resemble the real levels or at least follow a similar pattern. Furthermore, considering the equipment's accuracy of ±30 ppm, this difference is not significant. It was also assumed that these deviations are not significant when long-term data is considered. Figure 6.13 provides the calibration result for the predicted/measured temperature levels in the kitchen for the entire selected day.

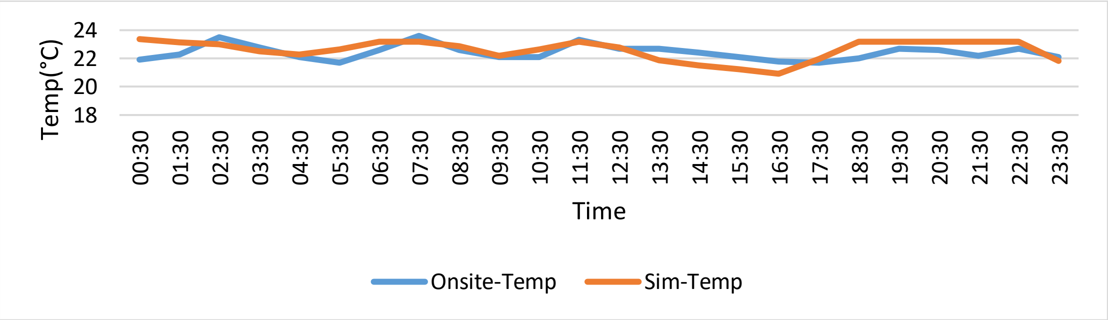


Figure 6.13 Movements in temperature in on-site recorded and simulated for the kitchen over one day

Taking the variations in temperature between on-site measured temperature levels and the simulation levels, both of them move in the same direction but show some minor differences throughout the day. The simulated T levels have been higher than the measured on-site T levels from 4.30 am and 6.30 am and again between 6.30 pm and 10:00 pm. It is, however, found that despite these differences, the simulated temperature levels resemble the same trend as the measured temperature levels in the house for a specific time.

Furthermore, the maximum variation between the measured and simulated temperature levels in the kitchen was observed at 12.30 am, measured at 1.5°C, when the simulated values were higher than the measured values. It is important to note that there are many exogeneous factors that influence the temperature over a short time, like opening or closing a door or window at a certain time, leading to loss of heat from the kitchen. This is not automatically modelled by the software unless specifically included in the model.

Moreover, the average difference in the temperature levels was calculated at 0.2°C, which also reinforced that the simulated values very closely resemble the measured levels.

Next, Figure 6.14 provides the calibration results for the relative humidity levels in the kitchen for the entire selected day.

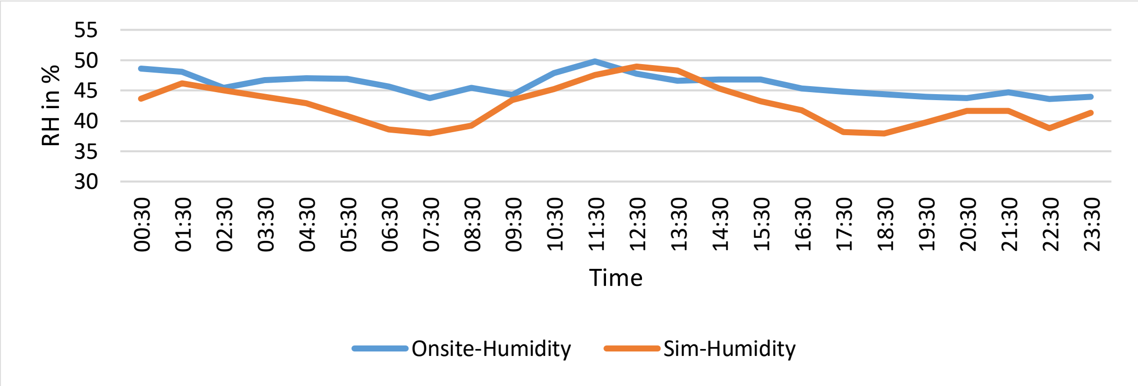


Figure 6.14 Movements in relative humidity in on-site recorded and simulated for the kitchen over one day

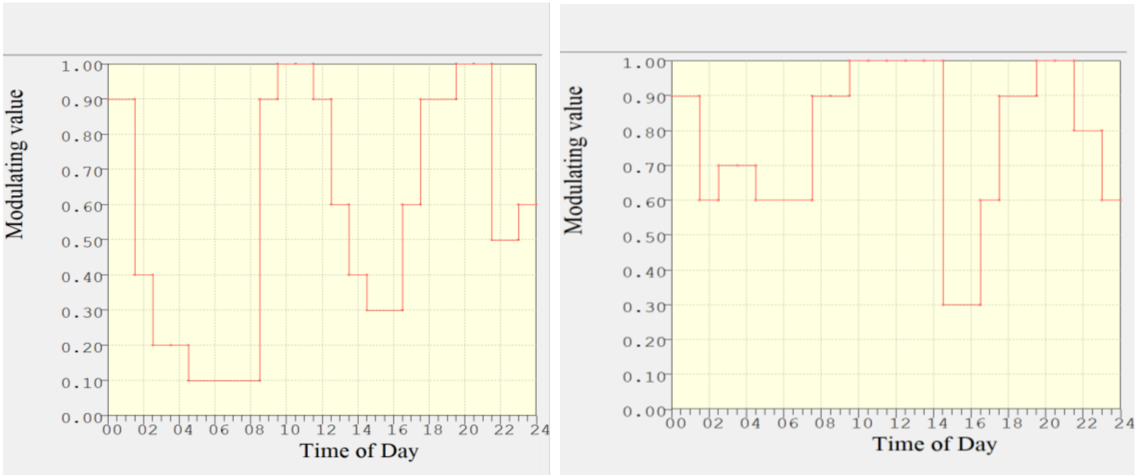
Taking the variations in RH between on-site measured RH levels and the simulation levels, both of them move in the same direction, but show some trend variations throughout the day. The simulated RH levels are lower than the measured on-site RH levels except between 12 noon and 2 pm. It is, however, found that despite these differences, the simulated RH levels resemble reasonably well the same trend as the measured RH levels in the house for the specific time. Furthermore, the maximum variation between the measured and simulated RH levels in kitchen were observed at 6.30 am, measured at 7.1%, when the simulated values were lower than the measured values. It is important to note that there are many exogeneous factors that influence the RH levels for a short time, like change in temperature, ventilation, the use of a mechanical extract, actual cooking time, etc.

Moreover, the average variations in the RH levels were calculated at 3.6%, which reinforced that the simulated values resemble that of the measured levels. It is also assumed that these deviations are not significant, when long-term data is considered.

Analysing the above results, it can be asserted that, more or less, excluding the sharp outliers owing to sudden changes in occupants' behaviour, the simulated levels of T, RH and CO_2 resemble the values as recorded on the real site. It can, therefore, be concluded that the model is calibrated with real data.

6.3.2. Living room

The daily profiles for occupancy and heating schedules for the living area were created and are given in Figures 6.15 (a) and (b).



(a) (b)

Figure 6.15 Daily (a) occupancy and (b) heating profile in the living area

The figure shows that the living area was fully occupied between 8 am and noon, and then the occupiers appear to have exited the area, returning to spend the evening time in this zone. Figure 6.16 shows the calibration result for the CO_2 levels in the living room for the entire selected day. It is assumed that the living area was occupied by all four occupants, comprising two adults and two children, and that the windows and doors of the living area were closed, and the vents were open, which clearly resemble the measured data picture.

Taking the movements in CO_2 between on-site measured levels and the simulation levels, they are similar in trends, but show some minor variations during the day. The simulated CO_2 levels were higher than the measured on-site CO_2 levels between 1.30 am and 11.30 am and between 5.30 pm and 6.30 pm. These variations are, however, relatively small and can be ignored. It may be concluded that despite these small variations, the overall simulated CO_2 levels resemble closely the same trend as the measured CO_2 levels in the house for the specific time, which is satisfactory.

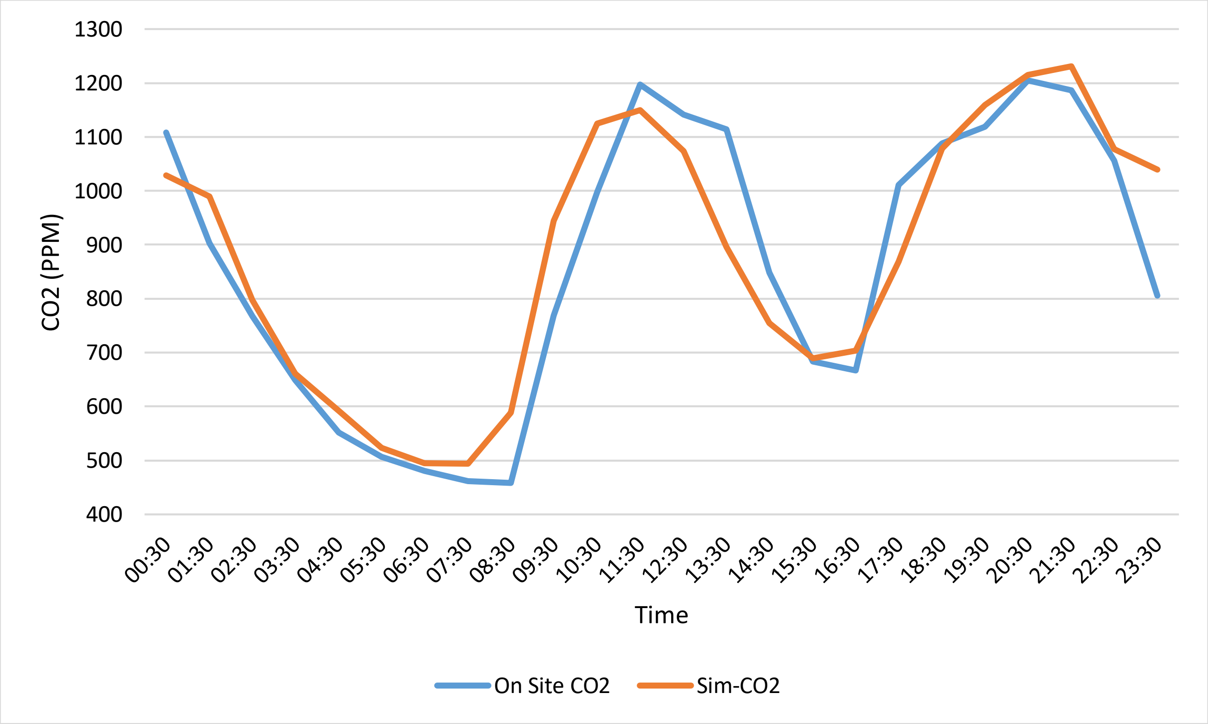


Figure 6.16 Movements in CO_2 in on-site recorded and simulated for the living area over one day

Furthermore, the maximum variation between the measured and simulated CO_2 levels in the living room was observed at 232 ppm at 11.30pm, where the simulated values were higher than the measured values. It is important to note that there are many exogeneous local factors that influence the CO_2 levels for a short time in practice, like the movements of occupants in and out of the particular house zones, with and without leaving a door slightly ajar. Moreover, from 8.30 am to 11.30 am, the CO_2 in the living area increased slightly, signifying that the occupants must have moved from elsewhere in the house to occupy the living area, after getting up in the morning, where a subsequent fall shows that they left the living area. These variations are well captured in the simulation, and closely resemble the most likely measured movements.

Moreover, the average variation in the CO_2 levels was reported as 71 ppm, which reinforced that the simulated values closely resemble the measured levels, and it is assumed that these deviations are not significant, when long-term data is considered. Figure 6.17 provides the calibration result for the relative humidity levels in the living area for the selected day. Examining the movements in RH between on-site measured RH levels and the simulation levels, the simulated RH levels have been marginally higher than the measured on-site RH levels between 9.30 am and 1.30 pm. It is, however, found that despite these variations, the simulated RH levels resemble closely (with maximum difference of 5%) the same trend as the measured RH levels in the house for the specific time.

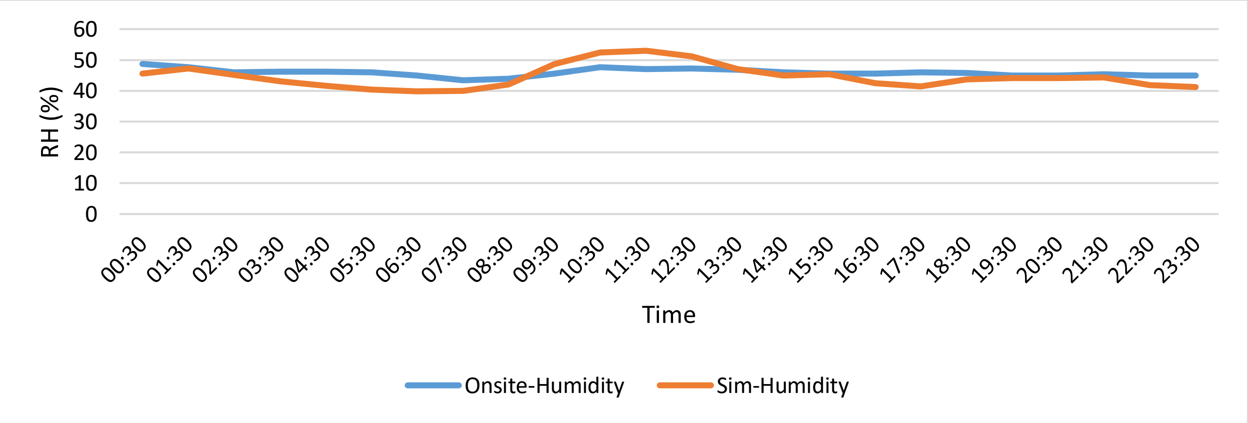


Figure 6.17 Movements in relative humidity in on-site recorded and simulated for the living area over one day

Furthermore, the maximum variation between the measured and simulated RH levels in the living area was observed at 11.30 am, where the average variations in the RH levels were calculated to be 2.8%, which also reinforced the notion that the simulated values closely resemble the measured levels.

The movements in temperature (simulated and measured) in the living room for one day are given in Figure 6.18. The figure shows the movements in the onsite and simulated readings for temperature in the living room for one day. The average variations in the temperature levels were reported at only 0.4°C. Furthermore, the maximum difference between the measured and simulated temperature levels in living area was observed at 3.30 pm, measured at 0.9°C, where the simulated values were lower than the measured values.

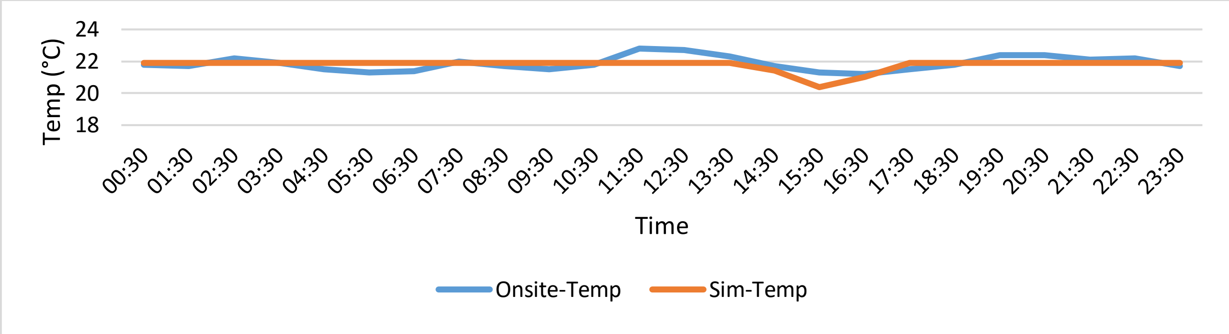
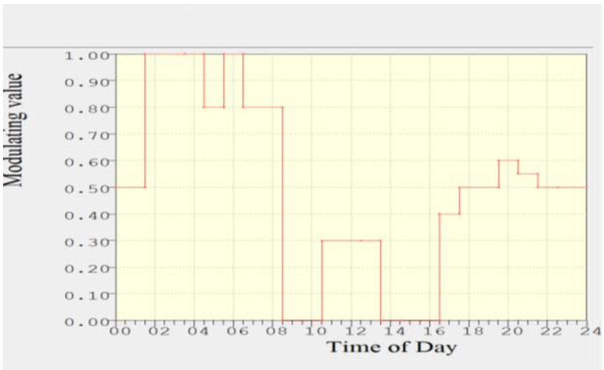


Figure 6.18 Movements in temperature in on-site recorded and simulated for the living room over one day

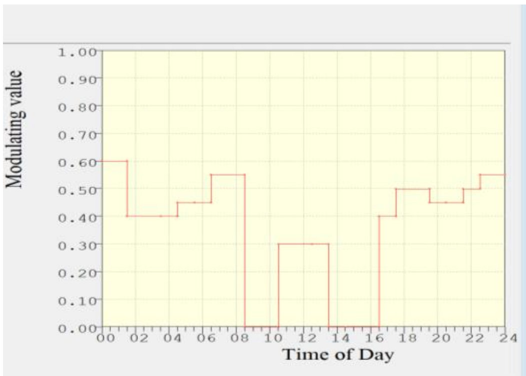
There can be some factors that influence the temperature levels for a short time, like opening or closing the doors or windows, leading to loss of heat from the living area. Analysing the above results, it can be asserted that, broadly excluding the sharp outliers owing to sudden changes in occupants' behaviour which are not modelled, the simulated levels of temperature, RH and CO_2 closely resemble the on-site values. It can, therefore, be concluded that the model is calibrated with the measured scenario for that particular chosen day.

6.3.3. Master Bedroom

The profiles for occupancy and heating schedules for the master bedroom were created and are given in Figures 6.19 (a) and (b) respectively:



(a)



(b)

Figure 6.19 Occupancy (a) and Heating profile (b) for the master bedroom

Figure 6.19 (a) shows that the master bedroom was occupied by the occupants between midnight and 8 am, that is, during normal sleeping hours. Between 8 am and 10am, the bedroom remained vacant, but between 10 and 2pm, the occupants may have moved in and out for cleaning or other purposes. Thereafter, from 4pm onwards, again some movements were detected, and the profile is created accordingly. Figure 6.20 provides the calibration result for the CO_2 levels in the master bedroom for the selected day. It was assumed that the master bedroom was occupied by two

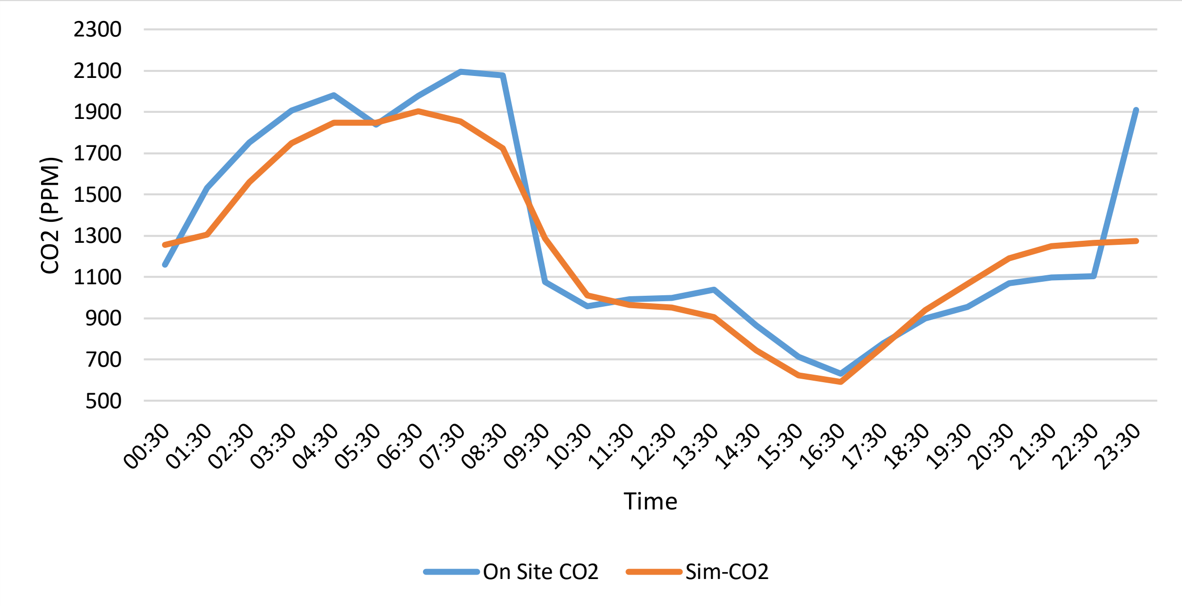


Figure 6.20 Movements in CO_2 in on-site recorded and simulated for the master bedroom over one day

occupants, and that the windows, main and en suite doors of the bedroom were closed. The vents in the room were assumed partially open throughout the day.

Taking the variations in CO_2 levels between on-site measured data and the simulation levels, both of them move in the same direction, but show some minor differences throughout the day. The maximum difference between the measured and simulated CO_2 levels in the master bedroom were observed at 8.30 am, estimated at 350 ppm, where the simulated values were higher than the measured values. It is important to note that there are many exogeneous factors that influence the CO_2 levels for a short time, like a sporadic entry or exit by family members. The CO_2 level is the most sensitive of the three parameters measured to the presence of people and is an excellent indicator of occupancy. The simulated and measured RH values in the master bedroom over one day are given in Figure 6.21. It shows that the measured and simulated RH levels for the bedroom (on the given day) are similar, both in values and direction. The maximum variation can be found at 11.30 am, when the difference is 5.9%, which is not high, and can be attributed to the occupant behaviour (like opening/ closing of adjoining door between the en suite and bedroom after a shower).

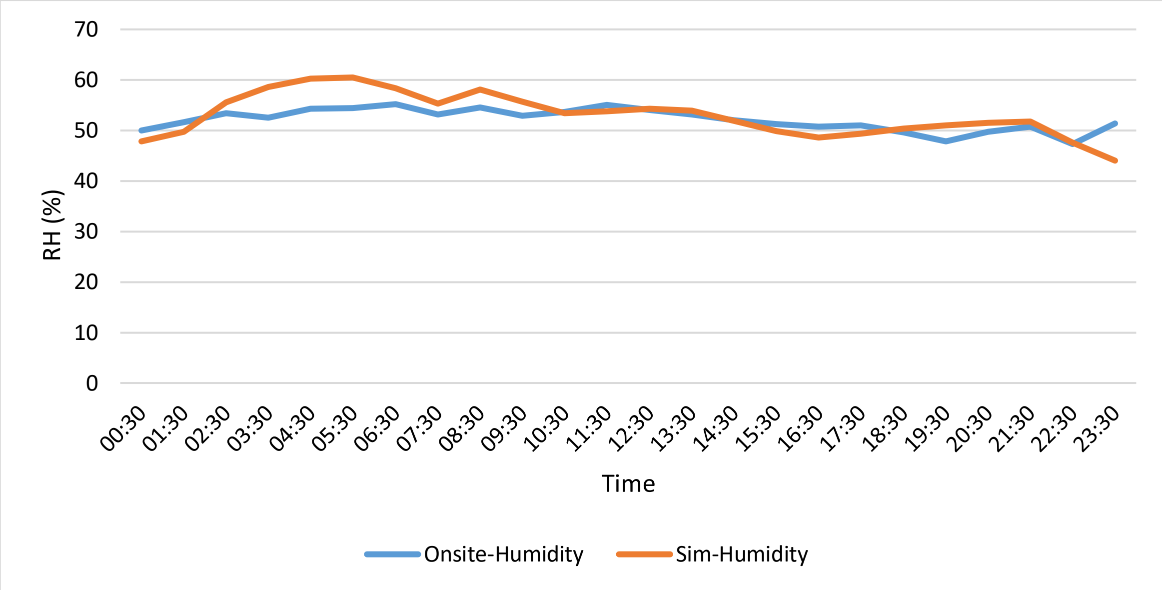


Figure 6.21 Movements in relative humidity in on-site recorded and simulated for the master bedroom over one day

The variations in temperature (simulated and measured) in the master bedroom for one day are given in Figure 6.22. The maximum variation between the measured and simulated T levels in the master bedroom were observed at 6.30 am, measured at 1.4 ^{o}C, when the simulated values were higher than the real values. Moreover, the average variations in the T levels were reported at 0.5° C, which reinforced that the simulated values closely resemble the measured levels.

Analysing the above results, it can be asserted that, broadly, excluding the sharp outliers owing to a sudden (and unmodelled) change in occupants' behaviour, the simulated levels of T, RH and CO_2 resemble the values as on site. It can, therefore, be concluded that the model is calibrated, and the simulated data can be used for further analysis and simulation, to understand the IAQ factors for the sample buildings.

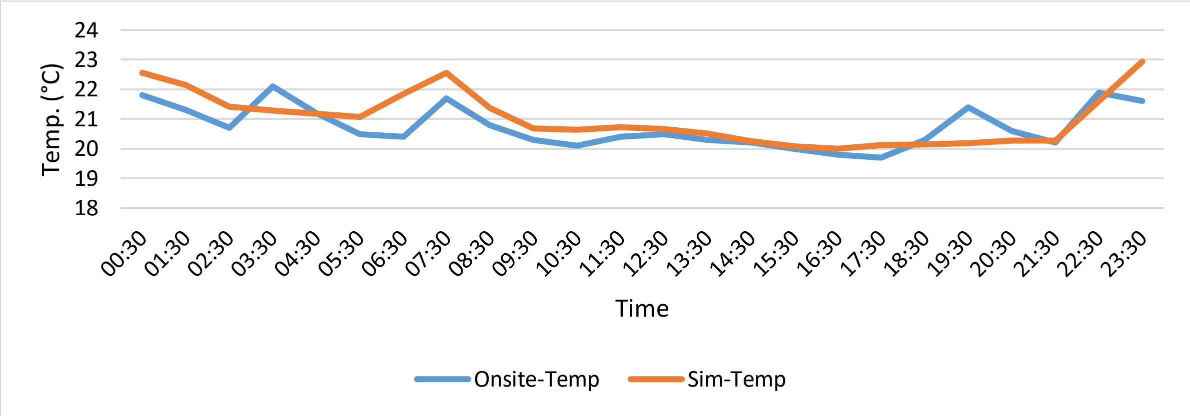


Figure 6.22 Movements in temperature in on-site recorded and simulated for the master bedroom over one day

6.3.4. Second Bedroom

The daily profile for occupancy of the second bedroom was created and is given in Figure 6.23.

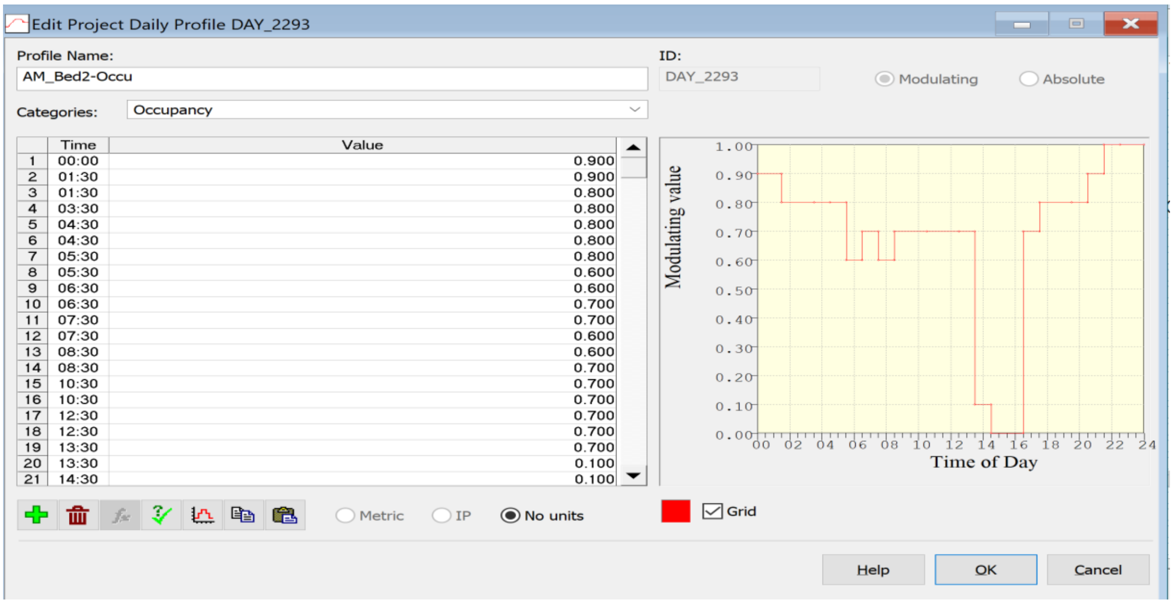


Figure 6.23 Daily occupancy profile for second bedroom

The figure shows that the second bedroom was occupied and experienced human traffic throughout the day except 2 to 4 pm. The occupants stayed in the room for most of the time between 10pm and 2pm but left the room for two hours between 2 pm and 4 pm (with the door left open), whereupon it was occupied until midnight.

Some movements inside and outside the room is visible by the fluctuations in the modulating value, which shows the percentage of occupancy during a particular interval of time.

Figure 6.24 provides the calibration result for the CO_2 levels in the second bedroom for the selected day. Input parameters in the model assumed that the second bedroom was occupied by two occupants (children) and the windows and doors of the bedroom were generally fully closed, although the vent in the room was fully open.

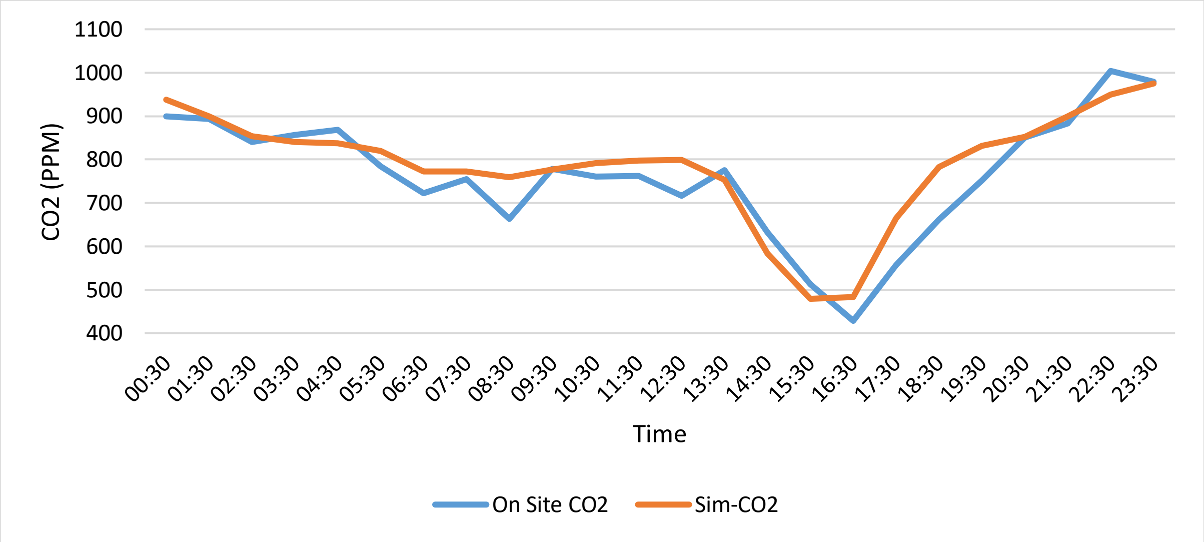


Figure 6.24 Movements in CO_2 in on-site recorded and simulated for the second bedroom over one day

Figure 6.24 shows the variations in CO_2 levels for on-site measured data and the simulation levels in the second bedroom. The result shows that both move in the same direction. The differences are there between the two, with some stronger spikes in measured data, which may be attributed to the changes in occupant behaviour, such as moving in and out of the room, leaving the door open etc. Furthermore, the maximum variation between the real and simulated CO_2 levels in the second bedroom were observed at 6.30 pm, estimated at 119 ppm when the measured values were lower than the simulated values. However, this variation is not so strong as to justify any significant differences, and thus, it is reconfirmed that the simulations are good at capturing the measured values of CO_2 in the house.

Figure 6.25 provides the calibration result for the temperature levels in the second bedroom for the selected day. The figure shows that the temperatures in the measured and simulated cases in the second bedroom show a similar trend.

However, it can be noted that the variations start increasing after 10.30 am when the simulated temperature shows a falling trend, but the measured temperature exhibits slightly different variations. This may be due to the children occupying the second bedroom, with doors or windows opening and closing in between, which are variations in measured values. However, when the overall daily data is considered, it can be

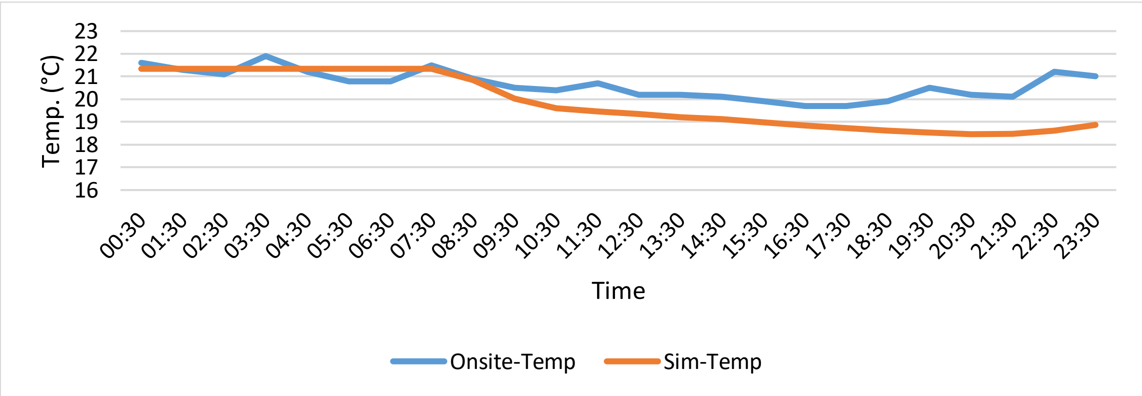


Figure 6.25 Movements in temperature in on-site recorded and simulated for the second bedroom over one day

concluded that the simulated data on temperature closely resembles the measured values and, on average, there is not much difference in the temperatures.

Figure 6.26 provides the calibration result for the RH levels in the second bedroom for the selected day. The RH values showed in the figure for the second bedroom over one day has similar trends and movements. However, some differences are noted, such as from 8.30 am onwards, when the simulated values for RH show a falling trend, but in real-time the RH shows a rising trend. This may be due to the unpredicted activities of the occupants, which can affect these values to some extent.

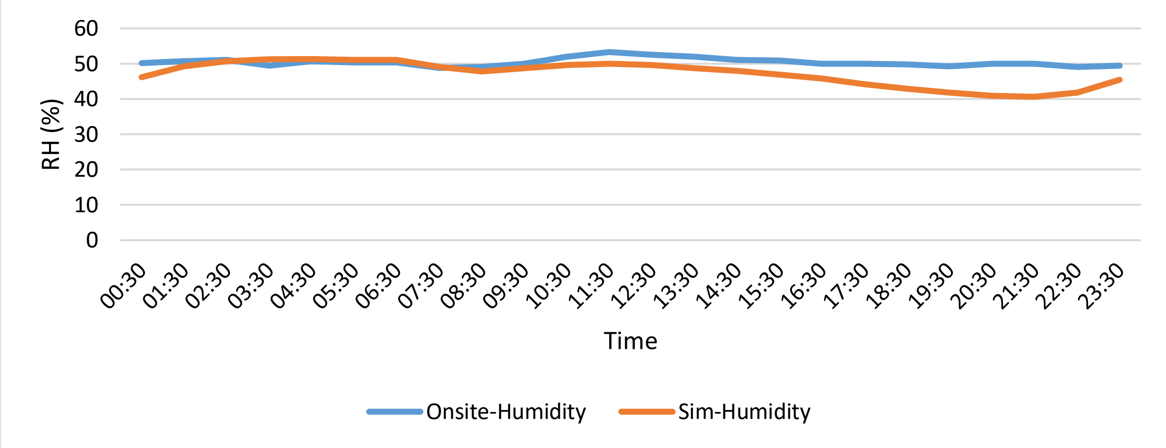


Figure 6.26 Movements in relative humidity in on-site recorded and simulated for the second bedroom over one day

Moreover, it is important to note that the measured on-site values are much sharper than the simulated values, owing to the fact that the sensors (from the on-site data) take a short while to report any sudden change in the occupants' behaviour because readings are recorded only after every 5 minutes. But, in general, the simulated values account for all key changes related to occupants' behaviour and match with the measured on-time values. Therefore, the simulated values are reasonably reliable to be used for further analyses and simulations/ sensitivity analysis.

6.4. Simulations/Results

Simulations were run in relation to modelling the problems created and/or faced by homeowners, as postulated in the previous chapters. Solutions to the respective issues will be recommended based on the modelling results. For instance, it was found that some families appeared to shut down their window Trickle vent units because they induced cold draughts. Hence, three cases are discussed in which the Trickle vents were closed, and different solutions are provided to the occupants for improving the indoor environment.

6.4.1. Bedrooms CO_2 problem and recommended solutions

Case 1 – CO_2 in both bedrooms in similar conditions

It was observed from the data that CO_2 levels in the second bedroom could be noticeably higher than those in the master bedroom, despite similar conditions of doors, windows and vent closing. Subsequently, it was cross-checked in the model that higher CO_2 levels were observed to exist in the second bedroom despite this similarity with the main bedroom. It was known that the master bedroom was attached to the en suite, which was fitted with a mechanical extract fan which runs for 24 hours every day. However, gaps under a closed door between the en suite and master bedroom helped somewhat in reducing the level of CO_2 in the master bedroom due to air exchange, which is not the case in the second bedroom. In this case, the base conditions entail that the master bedroom to landing door and the Trickle vent are closed. It should, however, be noted that the inbuilt factory setting of the Trickle vent keeps it open by about 10%, despite the fact that some occupants seal it with tape to avoid draughts.

Figure 6.27 shows a comparison of the simulated value of CO_2 in the master and second bedroom for a single day under these circumstances. The graph of the simulation confirmed the in-situ findings that the CO_2 levels in the second bedroom are often higher than in the master bedroom. Moreover, it confirmed the previous observation that the CO_2 levels were highest in the early morning (at 6.30 am in this case), which was most likely due to the accumulation of CO_2 in the room which had been occupied throughout the night while sleeping. Later, at around 7.30am in this case, as the occupants woke up, prepared themselves for the day's activities and left the room, the CO_2 levels started to reduce at a rapid pace through diffusion/dissipation, depending on whether the door to the landing was left open or not. Similar behaviour was noted in the evening, showing that CO_2 levels depended largely on the balance between occupancy (for CO_2 generation) and ventilation/dissipation (for CO_2 dissipation).

Moreover, it was found that the maximum difference in the CO_2 levels between the master bedroom and second bedroom was found to be circa 165 ppm at 7.30 am, which was attributed to the en suite door being open and the mechanical extract therein releasing some CO_2 externally. This scenario is not applicable in the second bedroom because there is no forced ventilation nearby, which causes the CO_2 levels to remain high.

Figure 6.27 CO_2 values in the master bedroom and the second bedroom over a day

Case 2- Grill/opening in both bedroom doors

As observed in the previous scenario, it was established from the sample data that the issue of high CO_2 levels in the bedrooms was observed to be the case in most of the houses. To address this problem, it was recommended that the house design be changed to provide an extra air grill in the partition above the bedroom door so that the CO_2 does not accumulate as much. It was also found that the CO_2 level increased with time when the room was occupied and, thus, it is advised that while sleeping at night, the occupants keep the main door of the room slightly open or a grill should be provided in the door which will lead to some air flow exchange, and a lesser CO_2 accumulation. It is noted that the provision of an additional smoke detector in the bedroom near that door would be highly recommended in this scenario. The effect of this change on the ventilation is illustrated in Figures 6.28 and 6.29 for the master bedroom and second bedroom respectively.

Figure 6.28 shows that the CO_2 levels in the landing were low before the door was opened or a grill inserted in the door. The average CO_2 levels on the landing were about 517 ppm, with the lowest CO_2 at 403 ppm at 3.30 pm, and highest at 631 ppm at 10.30 pm. When the change was implemented, it was found that some of the CO_2 from the master bedroom diffused to the landing, increasing the average CO_2 to 733 ppm. It was also found that the minimum level of CO_2 on the landing also rose to 488 ppm, while the maximum CO_2 levels also increased to reach 831 ppm. Similarly, when the change was implemented, the minimum CO_2 level in the master bedroom fell from 665 ppm to 635 ppm, while the decrease in the maximum CO_2 was significant, from 2175 ppm to 1630 ppm. Therefore, the average reduction in CO_2 in the master bedroom due to the grill/door being open was estimated to be 20.3%, that is, from 1417 ppm to 1128 ppm. Similarly, the change in CO_2 in the second bedroom, after implementing the advice, is as follows: Figure 6.29 shows that the CO_2 levels in the landing were low before the advice of opening the grill/door was implemented.

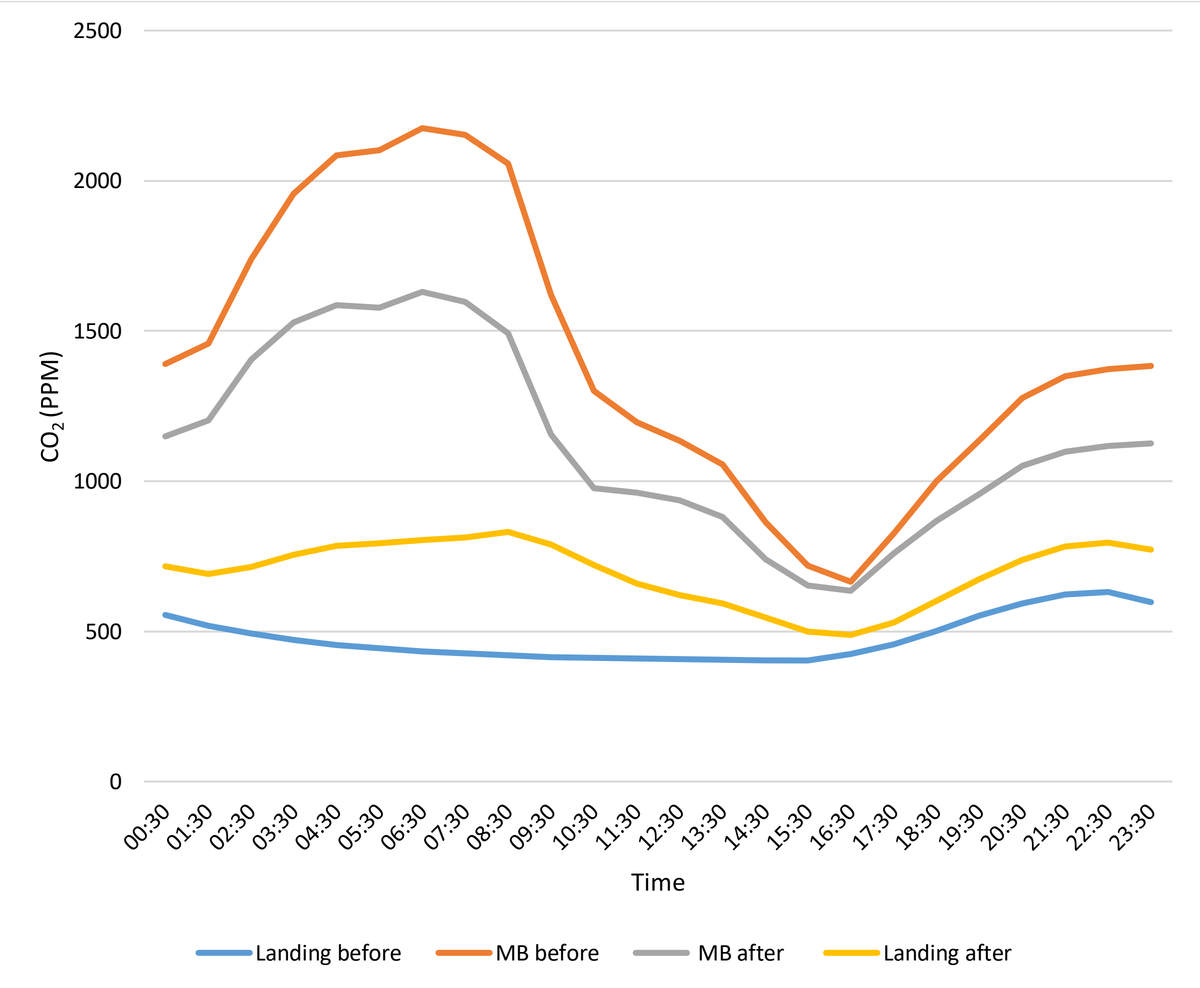


Figure 6.28 Effect of door opening on CO_2 levels in the master bedroom and landing

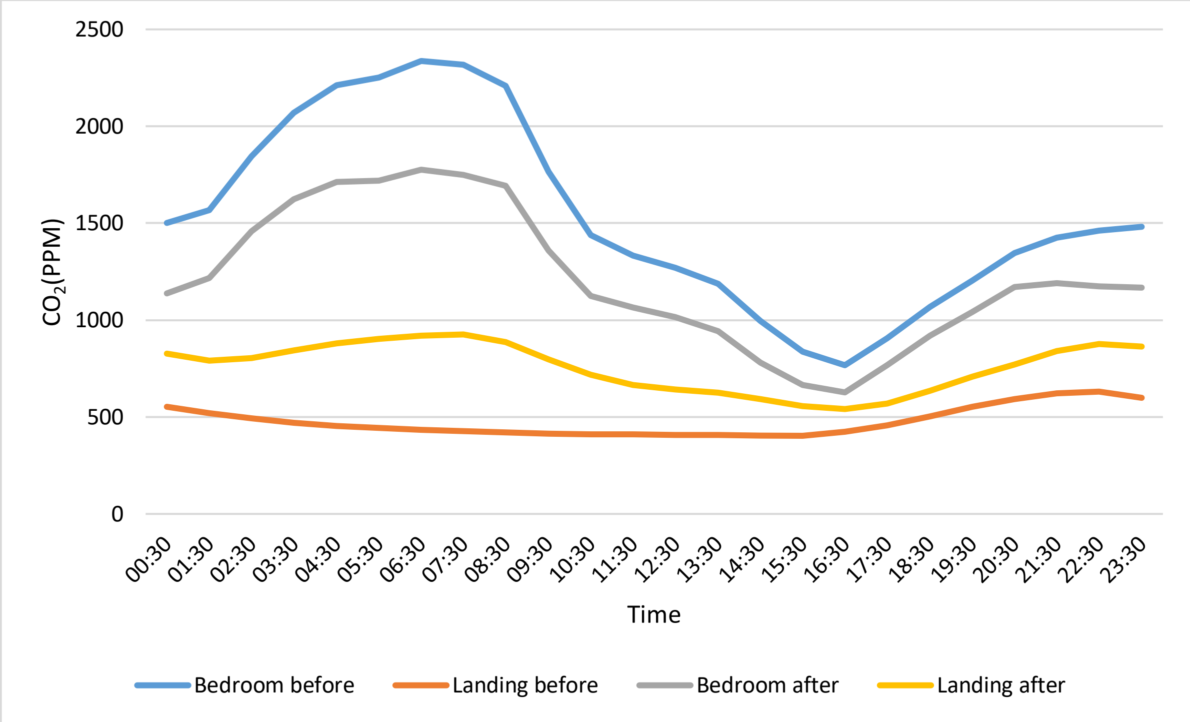


Figure 6.29 Effect of door open on CO_2 levels in the second bedroom and landing

The average levels in the landing near to the second bedroom were 557 ppm, with the lowest CO_2 at 425 ppm at 4.30 pm, and the highest at 631ppm at 7.30 am. When the advice was implemented, it was found that the CO_2 from the second bedroom diffused into the landing, increasing the average CO_2 to some extent. It was also found that the minimum level of CO_2 on the landing also rose to 573 ppm, where the maximum CO_2 levels also increased by about 300 to reach 926 ppm. Similarly, the corresponding minimum CO_2 levels in the second bedroom fell from 767 ppm to 627 ppm, while the decrease in the maximum CO_2 was significant, from 2337 ppm to 1776 ppm. Finally, the average reduction in CO_2 in the second bedroom due to the provision of a grill/ door opening was estimated at 20.9%, from 1533 ppm to 1212 ppm.

Hence, the implementation of the advice has shown positive results in enhancing the modelled IAQ for these rooms.

Case 3 Grill + extractor in landing

As observed in the previous case, when the doors of the two bedrooms are open, it causes the CO_2 levels in the bedrooms to fall and transfers some CO_2 to the landing.

Even these CO_2 levels (typically greater than 1700ppm) in any zone are not healthy for the occupants.

Hence, in this case, a simulation is undertaken to reduce the CO_2 levels from the landing area by installing an additional extract fan in the ceiling of the landing area, in the same way that the en suite extractor fan keeps the CO_2 levels down in the main bedroom. Moreover, that fan must be operational for 24 hours a day, as is the other one. The impact of this change is given in Figures 6.30 and 6.31 for the master and second bedrooms respectively.

Figure 6.30 shows that the CO_2 levels in the landing and the master bedroom were high before including an extract fan in the landing area, but after installing an extra fan the IAQ improved measurably in both zones. Figure 6.31 shows that the CO_2 in the second bedroom and landing both dropped when the extra fan was installed, though the effect in the bedroom is not as great as when the grill was included in the door.

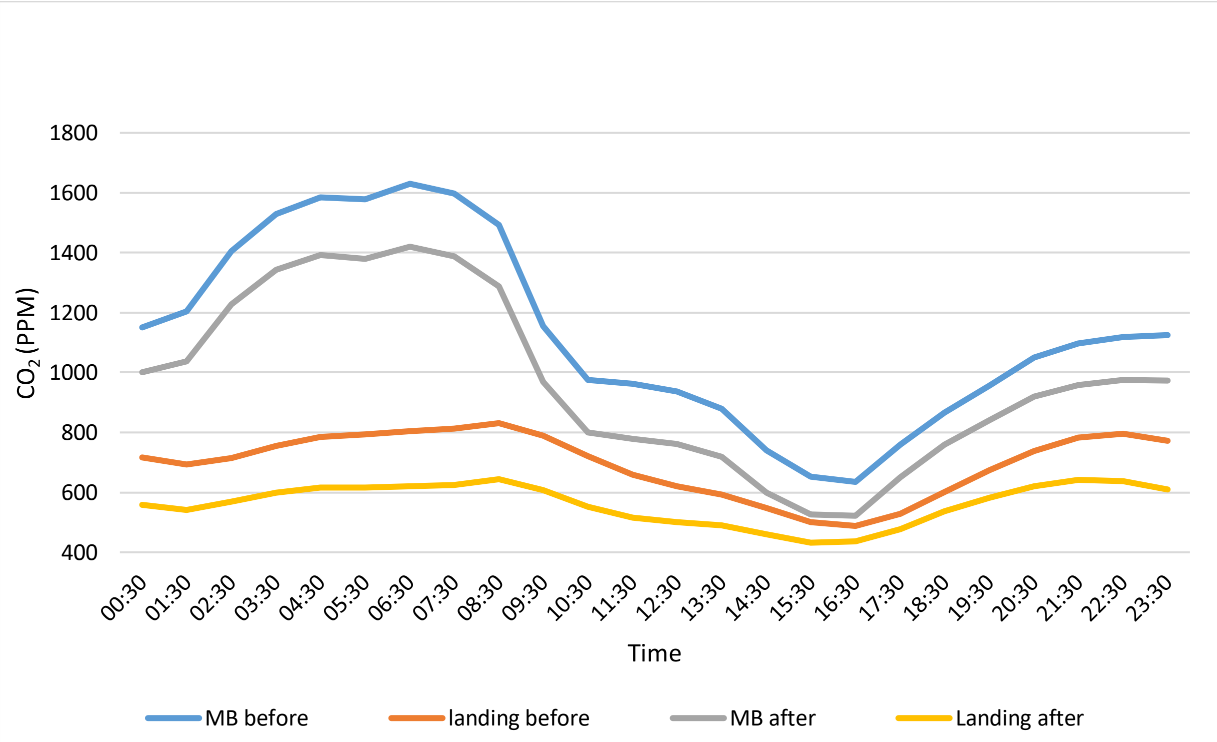


Figure 6.30 Impact of installing extract fan in the ceiling of landing, on CO_2 in the master bedroom and landing area

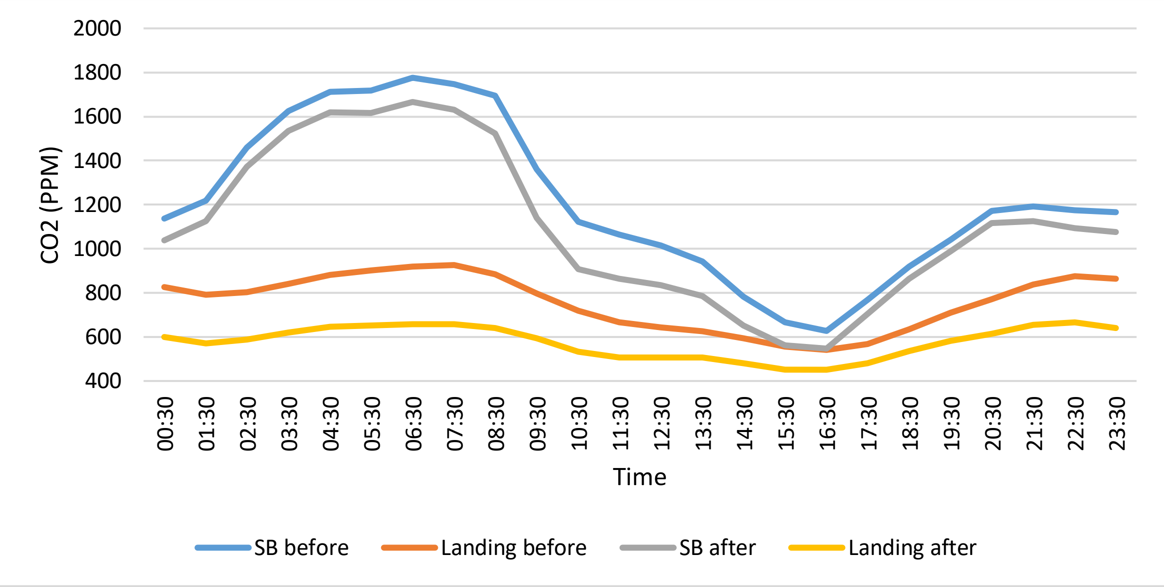


Figure 6.31 Impact of installing extract fan in the ceiling of landing, on CO_2 in second bedroom and landing area

Both changes are beneficial and are recommended to bring the CO_2 levels in the second bedroom down to more reasonable levels.

Case 4 – Grill/Extractor/ Trickle vent *open*

In this case, along with the grill for the master and second bedrooms and the inclusion of an additional fan extractor in the landing area outside the second bedroom, the effect of re-opening the window Trickle vents was investigated, with the aim to further improve the IAQ in these zones. The CO_2 levels before and after this modification are given in Figure 6.32. The figure shows the movements in CO_2 over a typical day after installing an extra fan extract in the landing area, placing a grill in the respective doors and opening the Trickle vent fully in both rooms and the door between the room and stair area/ landing is left open. It is found that the overall CO_2 levels (in comparison in all the above cases) have reduced significantly to a level where they are satisfactory, at less than 1000 ppm, in both bedrooms, compared to over 1400 and 1500 ppm in the master and second bedroom respectively.

The corresponding average CO_2 for the landing is 590 ppm. Moreover, the maximum CO_2 in the master bedroom, second bedroom and landing, before implementing any advice had been 2175 ppm, 2337 ppm and 631 ppm respectively. These levels, after all three changes were incorporated, fell to 971 ppm, 947 ppm in the bedrooms and rose to 701 ppm in the landing. As the threshold level of CO_2 for any house for good IAQ is less than 1000 ppm, these new design recommendations have reduced the peak levels, facilitating much better IAQ within the house throughout the day.

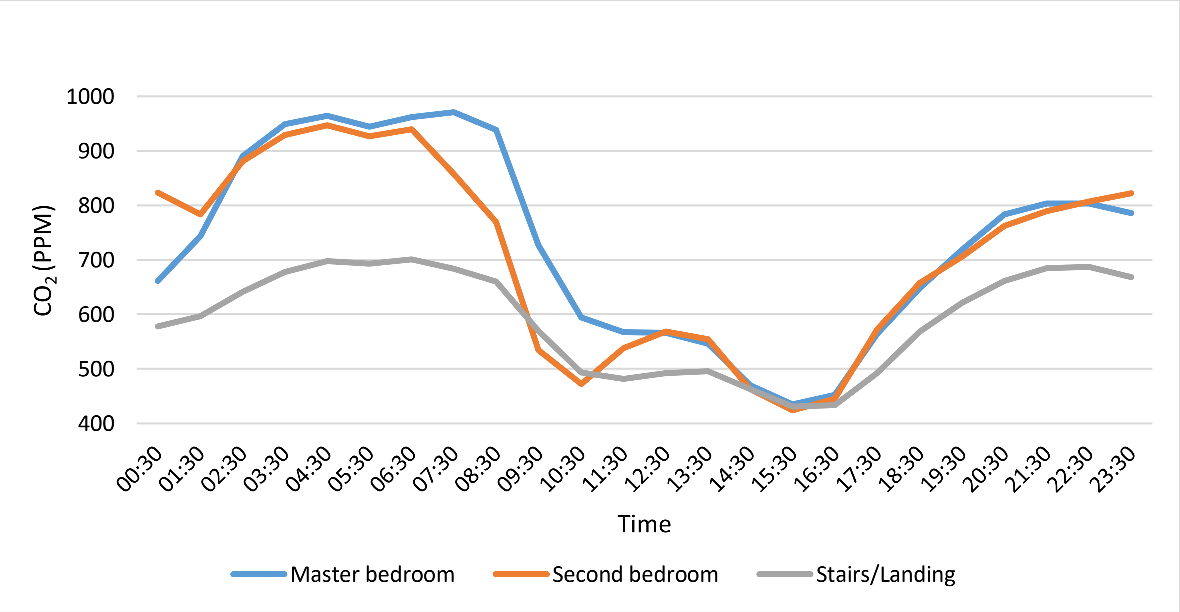


Figure 6.32 Impact of installing extract fan in the ceiling of landing, the grill at bedrooms and Trickle vent open on CO_2 levels

Overall, these actions helped achieve better exchanges within different zones in the house, preventing CO_2 accumulation in the two worst rooms for CO_2 levels, diffusing or dissipating CO_2 through enhanced mechanical extract and door openings.

Case 5 – Closing Trickle vents at night while opening them again in the morning

At the time of data collection, some occupants provided feedback that opening the Trickle vents throughout the day caused undesirable draught-like conditions and interfered with the perceived comfort level of the occupants. Consequently, further advice was given to them suggesting that they should open the Trickle vent at least in the morning when they leave the bedroom even if they chose to close the same throughout the night, to reduce the accumulation of CO_2. This scenario was simulated where the occupants closed the Trickle vent systems throughout the night, but opened them at 8.30 am and the outcomes are given in Figure 6.33.

The figure shows that the advice had modestly positive results in that it provided a solution to the draught issue, while lowering somewhat the accumulation of CO_2 levels. Compared with the initial CO_2 levels in the master and second bedrooms with no benefits, it was found that the average CO_2 levels fell from 1417 ppm to 1277 ppm

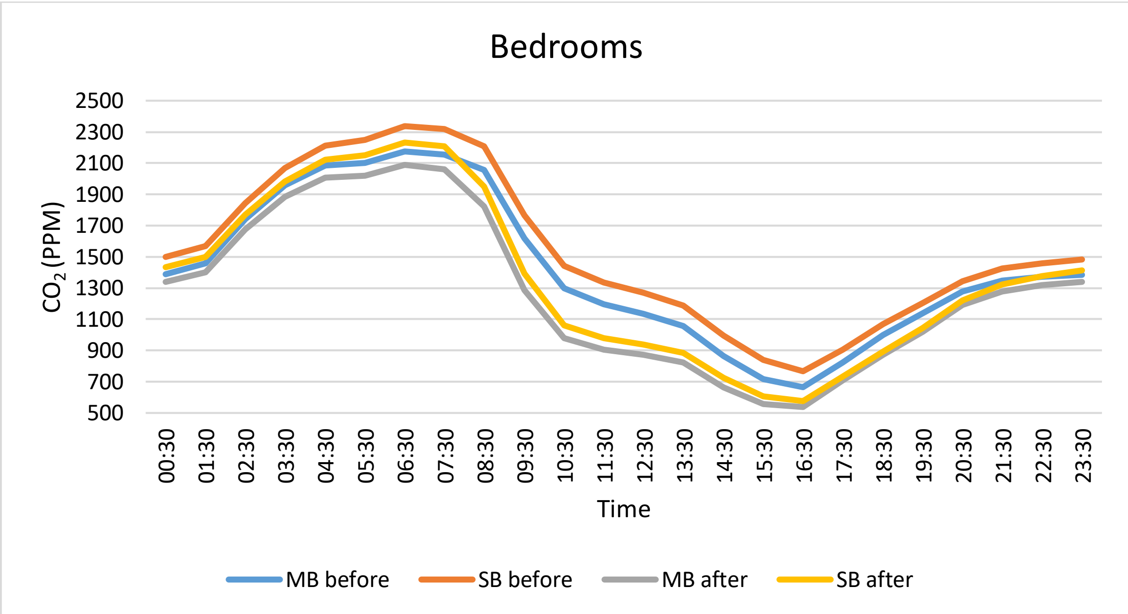


Figure 6.33 CO_2 levels in master bedroom and second bedroom before and after altering the vent opening times

after following this advice. Similarly, improvements were observed for the second bedroom, as the levels reduced from 1533 ppm to 1354 ppm.

Case 6 – Some problematic houses with the central system closed

From the entire sample, it was observed that there were a few houses in which the occupants turned off their central mechanical ventilation (MV) system completely, and these exhibited lower air infiltration. CO_2 and RH levels in such houses were about 3000 ppm and 80% respectively. Those particular houses were given the advice to put the central system and Trickle vent setting on again, but in the absence of opening the Trickle vent, the central ventilation system from the attic must be turned on so that air extract in the bathrooms continues, leading to some air exchange within the zone. Based on the simulation results, if the houses follow this advice, a measurable improvement in CO_2 and RH levels is expected. This solution can inform the occupants that even with the Trickle vent "closed", they are designed in such a way that the Trickle vent is always 10% open, and it should not be blocked. The findings of this simulation are provided in Figure 6.34.

The figure shows that when the blocked Trickle vent settings are altered to maintain the designed 10% of the opening, this leads to a significant reduction in the CO_2 levels throughout the day. It was found that the average CO_2 levels with a fully closed Trickle vent led to the accumulation of an average of 2700 ppm, peaking at 3860 ppm and with a minimum of 1475 ppm. The peak levels are injurious to the overall well-being and health of the occupants. It was, however, found that with even a 10% opening of the Trickle vent, levels were reduced by as much as 55%, to an average level of 1215 ppm. The corresponding maximum CO_2 level reduced to 1805 ppm, and the minimum CO_2 came within the recommended threshold limits of less than 1000 ppm (at 585 ppm).

It may be concluded that the provision of this advice to owners at the outset of occupation can help in preventing the existing high CO_2 levels in these problematic houses, as signified by Figure 6.34.

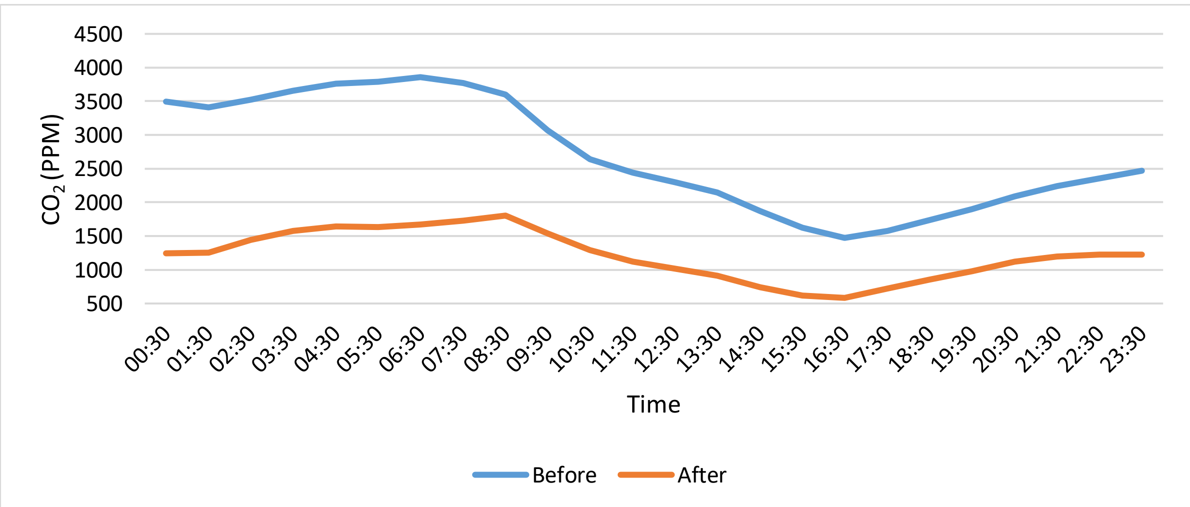


Figure 6.34 Impact of altered settings in closed MV system, in terms of CO_2 levels

Figure 6.35 shows that when the MV settings are altered from 0% to only 10% of the opening of the Trickle vent, this leads to a significant reduction in the RH percentage throughout the day. It was found that the average RH levels with a fully closed MV had an average RH of 72%, ranging from 86% to 56%. These high levels can lead to high dampness and potential mould formation. It was, however, found that turning the MV system on can lead to a reduction in RH by as much as 30%, reaching average levels of 49% with maximum RH levels reduced to 62%, and a minimum RH at 40%.

Thus, the simulation shows that the role of the ventilation system is of vital importance in maintaining a healthy environment for the occupants and that small changes in occupier habits can make a significant difference to the environmental conditions indoors.

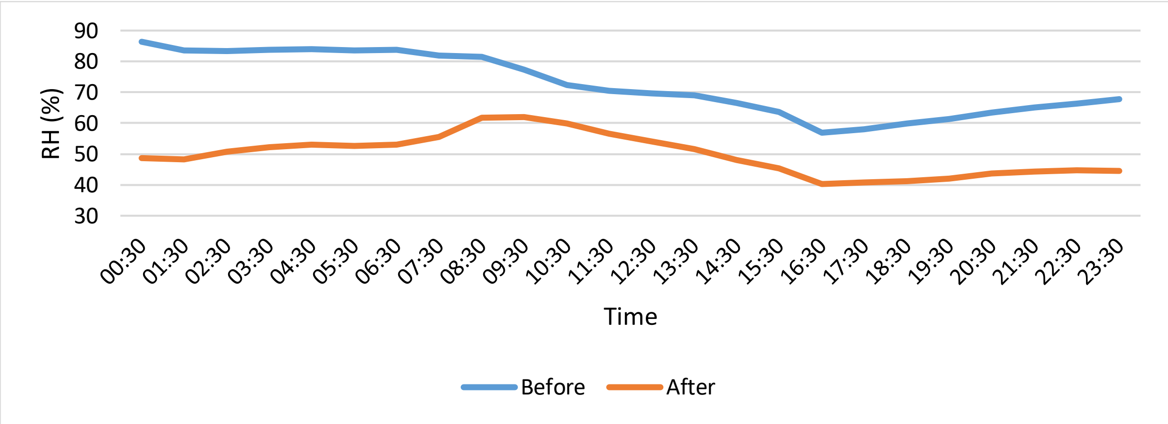


Figure 6.35 Impact of altered settings in closed MV system, in terms of RH % levels

6.4.2. Effect of Solar gain

It was further observed that for some houses, their orientation was to their advantage, and they benefited from solar gain, even in the Winter season. The occupants were advised that the days when the sun was shining, they can switch off their internal heating systems and use solar energy to heat the various south facing zones. To test this scenario in the model, the heating system was turned off in order to find out the impact of solar gain alone for those houses. Four different scenarios were examined to identify the effect of solar gain on the temperature history of different house zones, discussed as follows:

Case A*:* If the kitchen is in the front of a south facing house, then the effect of solar gain during daytime (10.30 to 5pm here) after shutting off the heating system may be observed, as given in Figure 6.36.

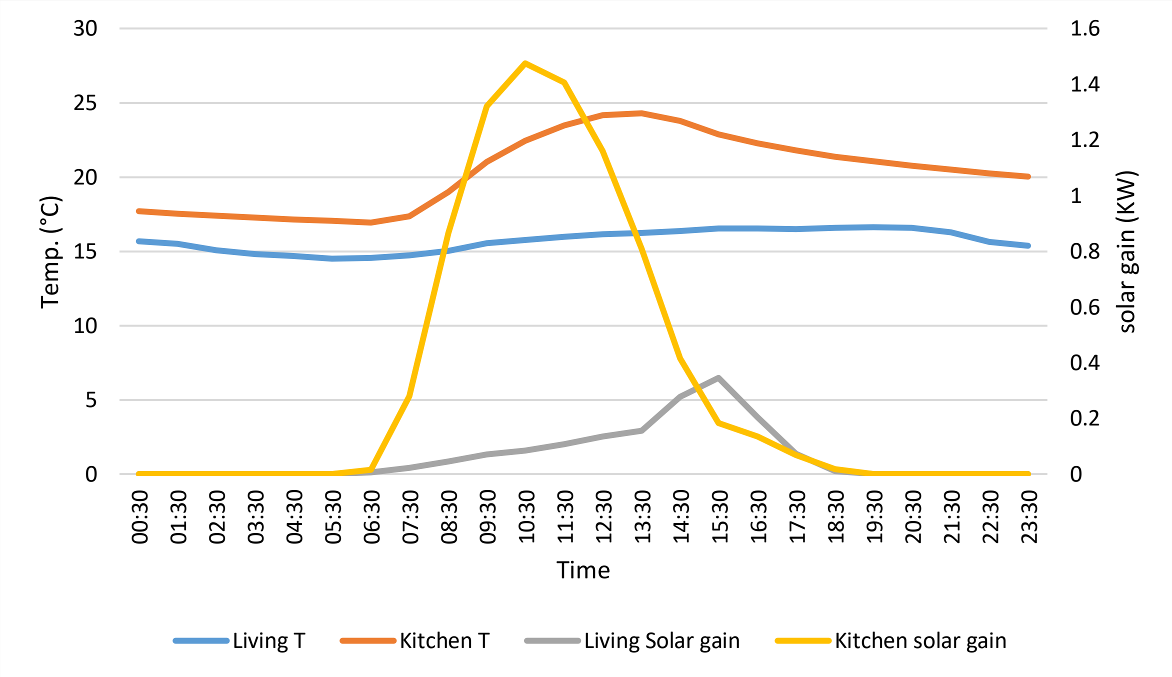


Figure 6.36 Solar gain in Case A when the door is closed between the kitchen and living room

The figure shows that the solar gain in the kitchen had reached a maximum between 7.30 am and 3.30pm. At the peak hour, the solar gain without heating was so high as to exceed the kitchen temperature levels with heating, indicating there was no need to use the heating system that day. A solar gain in the living area was also observed but was marginal in comparison with that of the kitchen, which the model showed was partly due to the door being closed between the two rooms.

Case B*:* In this case, the door between the kitchen and living room was kept open to investigate how solar gain in the kitchen might transfer to the adjoining zone, as illustrated in Figure 6.37. The figure shows that when the door between the kitchen and living room was open, solar gain affects the temperature in not just the kitchen, but also the living area. The solar gain is beneficial in that the kitchen successfully inflates the temperature in the living room (by 2 to 3^{o}C), but to a lesser degree. This indicates that the insulation in these houses is so good that the heating system could be turned off if the

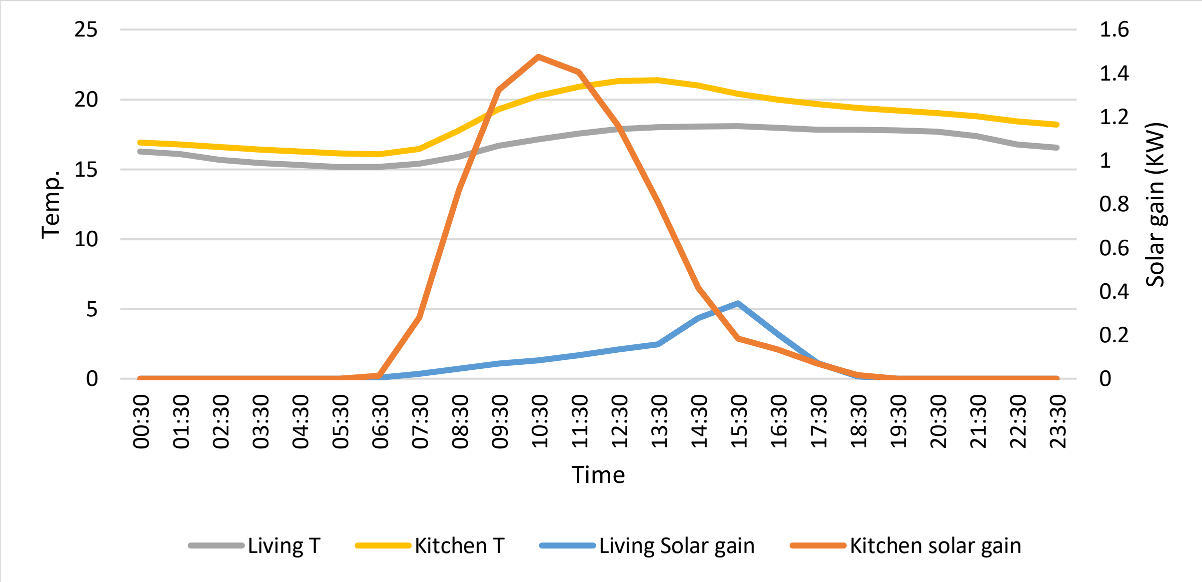


Figure 6.37 Solar gain when door between kitchen and living area is kept open

temperature in the kitchen and living area can be maintained at comfortable levels by leveraging solar gain alone.

Case C*:* It was found that due to the kitchen windows being closed when the heat was trapped inside without air exchange flow, some occupants tended to feel too warm. In attempting to maintain a comfortable temperature, they opened the windows rather than opening the internal doors. The results of this simulation may be observed in Figure 6.38, illustrating the case where from 9.30 am to 2pm the kitchen window is opened with the door between the kitchen and living area closed and then opened subsequently.

The figure shows that the initial trend of solar gain followed the pattern as previously, but when the window was opened, the solar gain captured was lower as the temperature in the kitchen reduced when the window was open. Also, when the window was closed, even with lower solar gain, the temperature was higher. A similar pattern of changes was observed for the temperature in the living area in both the cases, when the adjoining door between the kitchen and living area was left open.

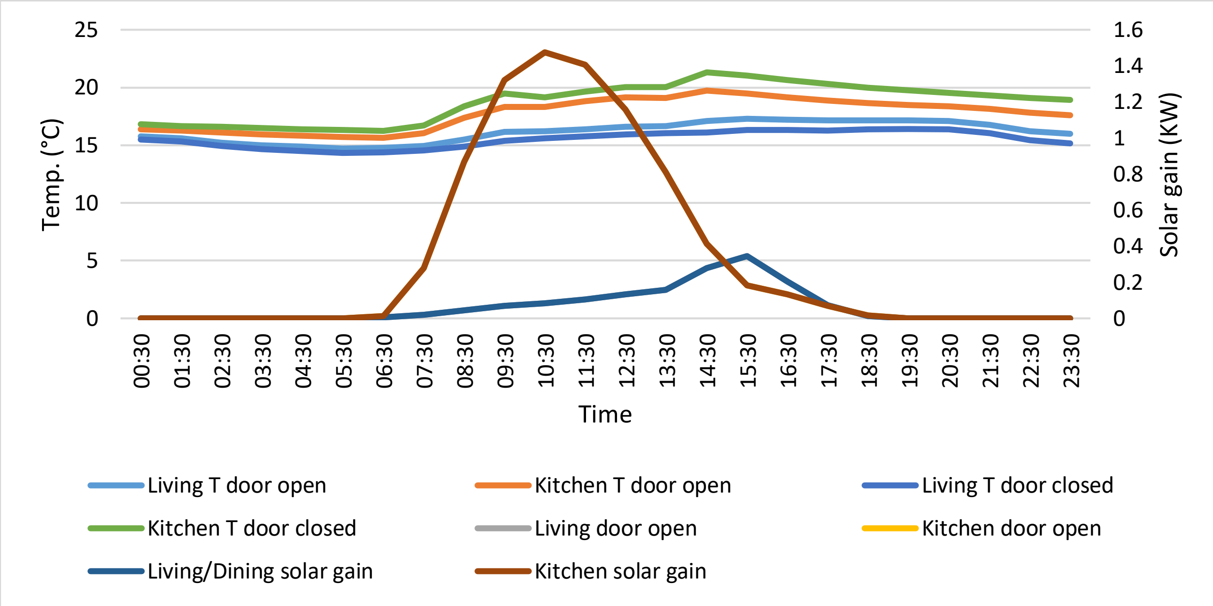


Figure 6.38 Impact of advice on internal door opening rather than window on the temperature in kitchen and living area

6.4.3. En suite Case

Generally, it is observed that the en suite experiences higher RH as compared to any other zone. It is, therefore, advised that the adjoining door between the en suite and master bedroom be left open after taking a shower but not during. The rationale for the advice is that the accumulated pooled water and RH after a shower can be dissipated through mechanical ventilation but does so more effectively through the opening of the adjoining door which will alleviate the condensation issues in the en suite through evaporation and diffusion. To better understand the role of open doors to dissipate the RH, the following scenarios are considered:

Case A: This is the base case in which both the doors to the master bedroom (en suite and landing) are closed during and after taking a shower. The impact on RH is given in Figure 6.39. The figure shows that from 5.30 am until 10.30am, the RH in the en suite is elevated, rising to a peak at 8.30 am, signifying the periods when the occupants take a shower.

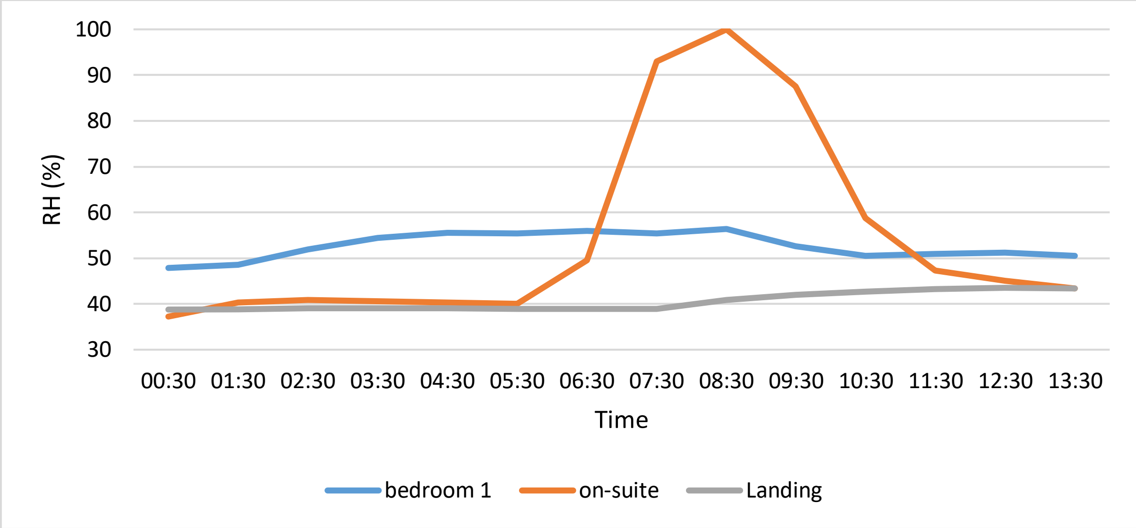


Figure 6.39 Impact of RH in different house zones when both nearby doors are closed after a shower

When the door between the en suite and bedroom and between the bedroom and landing are closed, it is observed that the maximum RH in the en suite was 99.9% at 8.30 am. At that time, the RH was also at its maximum in the bedroom at 56.3%. This is due to the transfer of some RH under the door from the en suite to the bedroom. The maximum RH in the landing was noted at 43.5%, at about 10.30am, which is indicative of the fact that there is little if any transfer of RH from the en suite to the landing due to the closed doors. On average, the RH in the en suite, bedroom and landing were calculated to be 54.5%, 52.6% and 40.5% respectively, which are reasonable but for two hours the RH was over 90% in the en suite. Thus, by keeping the doors closed, the impact of RH is negligible in the master bedroom and landing areas, but of concern in the en suite.

Case B: In this case, the adjoining door between the en suite and master bedroom was kept open after the shower, while the door between the bedroom and landing was kept closed. The modelled effect on RH in all these three zones is given in Figure 6.40.

It can be observed that by opening the door after a shower, the accumulated RH in the en suite diffuses to the master bedroom, such that the level of RH is high in both the bedroom and en suite. However, there is not much impact on the RH in the landing area because the bedroom door towards the landing is closed.

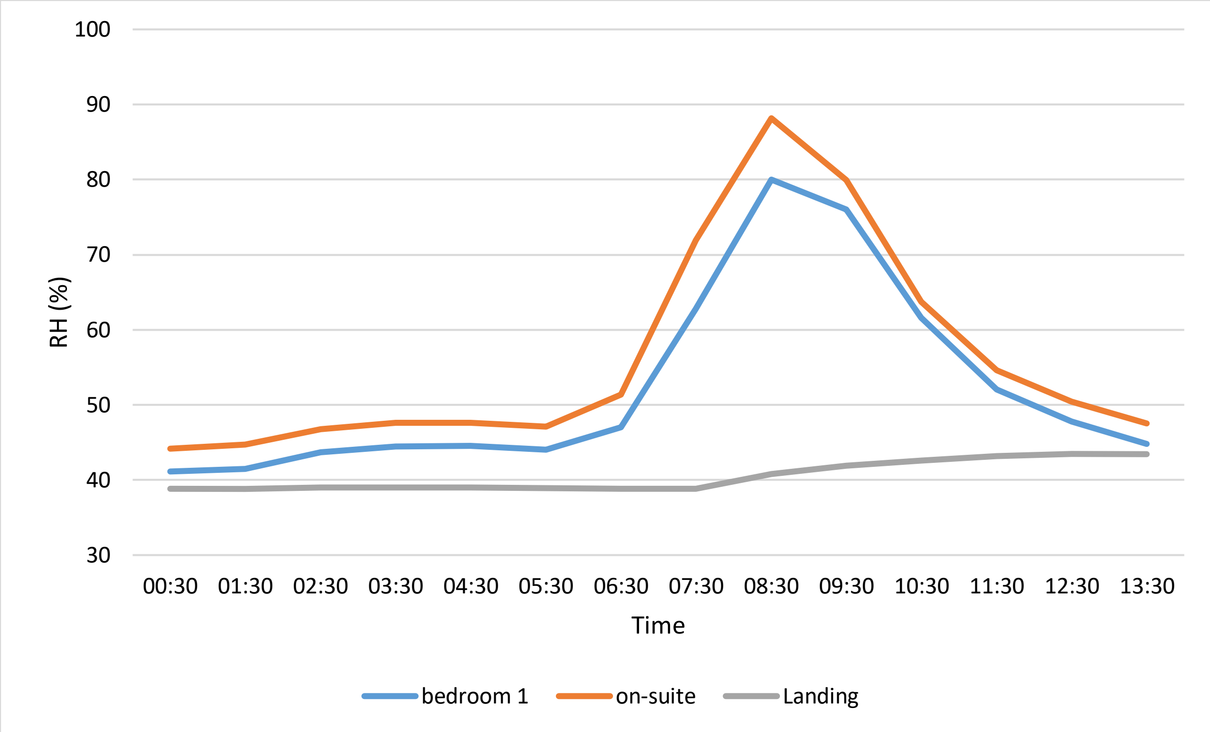


Figure 6.40 Impact of RH in different house zones when the door between en suite and master bedroom is kept open after a shower

The maximum RH in the en suite showed a slight decrease compared to the base case, falling from 99.9% to 88.2%, while the average RH in the bedroom rose from 54.5% to 56.0%. Opening the door between the en suite and master bedroom deteriorates the IAQ in the bedroom considerably as the maximum RH in the master bedroom rose from 56.4% to 80% but does not improve the RH in the en suite by as much due to the relative volumes of space involved.

Case C: In this case, the adjoining doors between the en suite and bedroom and between the master bedroom and landing area are kept open. The impact on the RH level in all three house zones is given in Figure 6.41.

The figure shows that when both doors are opened, it leads to an increase in the RH level in the landing, but improves the RH in the en suite and master bedroom. The maximum RH level in the bedroom was only slightly higher than the base case, at 60.8% as compared to 56.4% initially, when all doors were closed. Moreover, the average RH in the master bedroom was the lowest of all three scenarios at 45.6%.

In the en suite, the maximum RH was the lowest of the three scenarios at 71.9%, as compared to 100% and 88.2% previously.

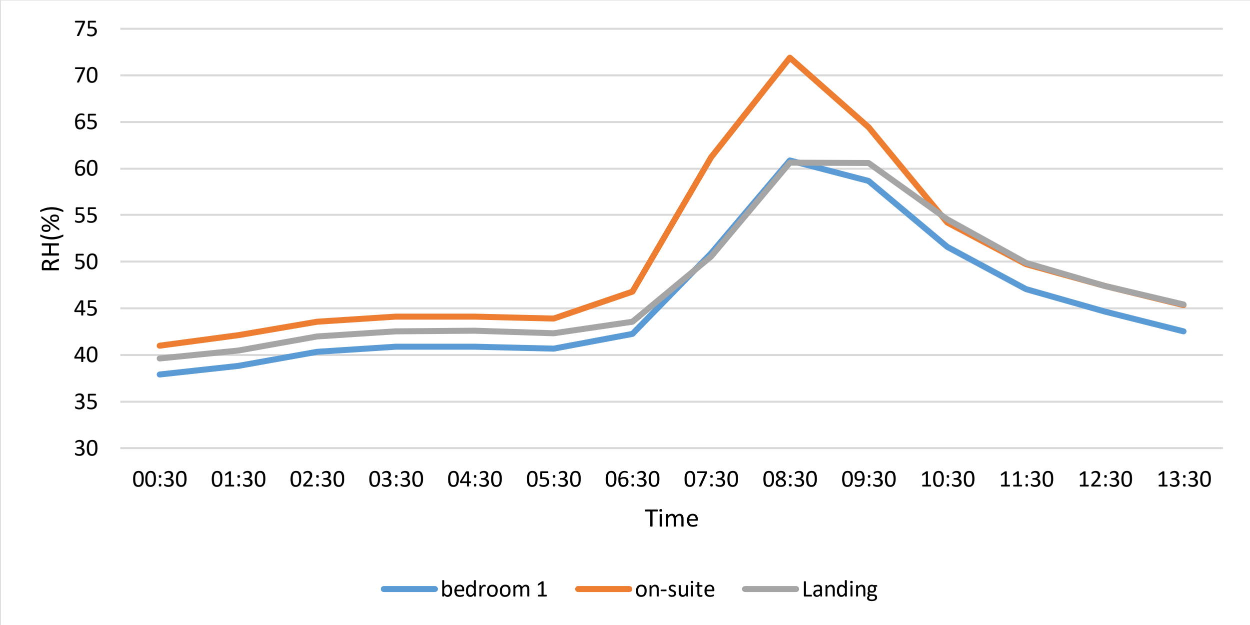


Figure 6.41 Impact on RH when both the doors are kept open after the shower

In the landing area, the maximum RH rose to 60.6% due to dissipation of moisture from the en suite to the bedroom to landing, but is within an acceptable range due to the new extractor fan in the landing, which was inserted, as described earlier. Nonetheless, the maximum RH in the landing was still under the recommended threshold levels and is not considered problematic. Thus, the opening of doors between the en suite, master bedroom and landing area (after a shower) is the preferred solution and recommended for maintaining good IAQ which can be further benefitted by the continuous running of the new extractor fan in the landing area.

6.4.4. Living room with higher occupancy levels

As extracted from the findings in the previous chapter, it was found that in some houses the level of CO_2 in the living area was high during the weekends. The reason postulated was the larger gatherings of friends and relatives. To simulate this case, the occupancy was increased from the average of 3.5 occupants to 6-7, and the consequent change in CO_2 levels were observed. It was further assumed that the temperature was kept constant, so that the temperature independent change in humidity could be found - both the CO_2 and RH increased due to the changes in the occupancy. To maintain good IAQ, the occupants were advised that they should open the door towards the hallway rather than an outside door or window due to the cold weather outside. Figures 6.42 and 6.43 show the modelled changes in the CO_2 and RH levels respectively, before and after implementing this advice.

Figure 6.42 shows that, after following this advice, the CO_2 levels in the living area decreased noticeably, as the higher CO_2 concentration was transferred to the hallway area, where the extraction fan from the landing will help to dissipate the additional CO_2 levels (due to the stairs cut out). The maximum CO_2 was at 1833 ppm at 9.30 pm, which reduced by 32.8% to 1380 ppm simply by opening the door. Similarly, the average CO_2 also reduced from 1231 ppm to 989 ppm. Figure 6.43 shows that, after following the advice, the RH levels in the living area decreased, as the higher RH concentration was transferred to the hallway area, where the new extraction fan (from earlier advice) will help to dissipate the additional RH levels.

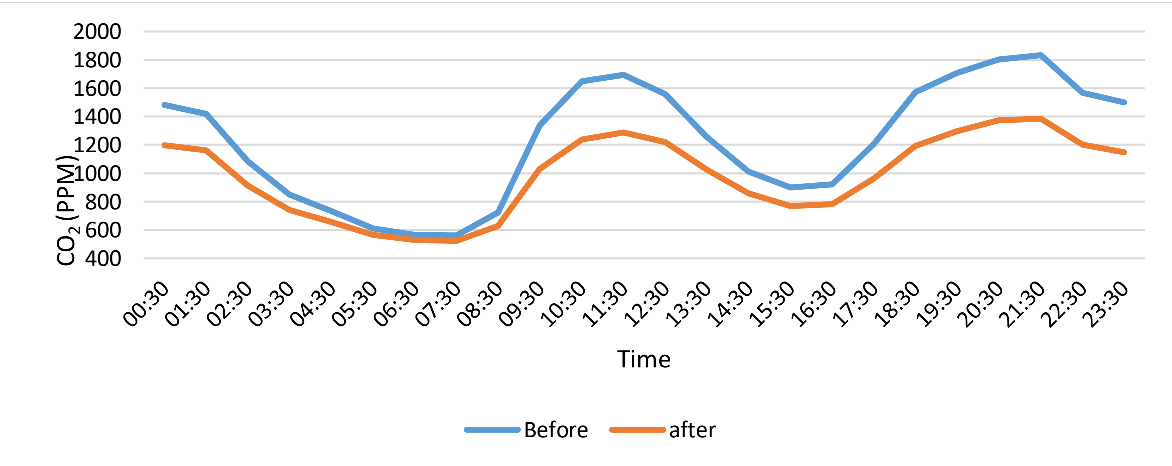


Figure 6.42 CO_2 levels in the living area by increasing the occupancy

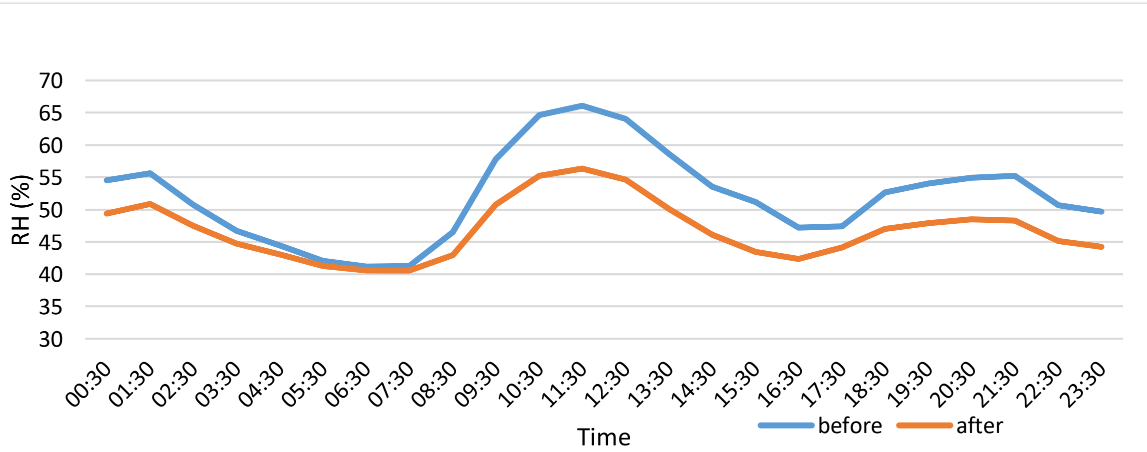


Figure 6.43 RH levels in the living area by increasing the occupancy

It was found that the minimum RH before advice was 41.2%, which reduced to 40.6% after following the advice. The maximum RH was at 66.0%, which reduced to 59.6%. Similarly, the average RH reduced from 52% to 47.9%.

It can, therefore, be inferred that the advice to open a door to the hallway is more efficient for reducing the CO_2 levels in a crowded living area than opening an outside door or window, with some beneficial effects also on the RH.

6.5. Summary

A number of important findings and observations have been made after analysing the simulation results from these houses, which may be stated as follows:

- The CO_2 levels in the second bedroom is generally higher than the master bedroom and is highest in early morning after accumulating during sleep at night. The high accumulated of CO_2 levels in the two bedrooms can be relieved by opening the internal doors when leaving the rooms.
- By installing grills in the bedroom doors or keeping the internal door slightly open while sleeping at night (notwithstanding the fire consequences), accumulation of CO_2 in the rooms can be largely avoided. By doing this, the CO_2 from the master bedroom will be dissipated to the landing area, which can further be removed by installing an extract fan in that area. This extract fan can be left operational throughout the day.
- The bedroom Trickle vents should be left open throughout the night so that CO_2 is not accumulated. However, if by doing so, the occupants experience a cold breeze/draught and close the Trickle vent at night, they may open the Trickle vent in the morning at the time of leaving the room. This will dissipate the overnight accumulated of CO_2 within a few hours but will do little to reduce the overnight accumulations.
- The central mechanical ventilation system and Trickle vents in the houses should always be kept on/open, so that the extraction of CO_2 and RH from the bathrooms and en suite lead to proper air exchange within the building. If this is done, the IAQ is generally satisfactory, as designed.

- The houses must also use their heating systems efficiently, such that on the days when the solar gain is high, the occupants can completely switch off the internal heating systems during the daytime so that the heat from solar gain can be trapped for efficient utilisation. They can open their internal doors rather than windows to further exploit this trapped heat from the sun.
- The high relative humidity tends to persist in the en suite after taking a shower, which has the potential to cause high moisture, condensation, and mould formation issues nearby. Thus, to mitigate this problem, it has been shown through simulations that opening the adjoining door between the en suite and master bedroom will help dissipate the higher CO_2 levels faster. Also, when the door between the master bedroom and landing is opened, the excess CO_2 levels dissipate to the landing area, which can be removed by installing an extra extract fan in the landing.
- Higher occupancy causes the RH and CO_2 levels in any house zone to significantly increase. Such high CO_2 and RH levels continue to remain in that zone even after the occupants vacate the zone unless Trickle vents or doors are opened to ventilated spaces.

7. Predicting the Results from Modelling

7.1. Testing the Hypothesis and Solutions

It has been shown that the simulations justify the advice issued to home occupiers based on the findings (as discussed in the previous chapter). In this section, the robustness of the model is tested by examining whether or not it has the ability to predict the IAQ in other houses in a different location. A sample of 12 houses is considered using the derived model in which important variables that impact the temperature, RH and CO_2 levels in different zones of the houses are assessed. The aim of this analysis is to test the hypothesis arising from the findings made on the houses in the previous chapter: That the behavioural patterns in the indoor conditions in houses due to occupant behaviour can be predicted using an IES virtual model and verified in practice. The layout plan of these houses is presented in Chapter 3, in which the typical house has a similar interior structure as that of the houses considered in the previous two chapters. There is, however, one distinction, namely the living room and kitchen in these houses are adjoining, without any walls or partitions in between. Before the model is actually tested using the above simulations, a descriptive analysis of the key variables of temperature, RH and CO_2 are studied to learn about the internal environment. The data analysis pertains to the overall evaluation of the 13 new houses in the selected estate at Location 2 assessed over the period of half a year. The data is divided into seasons to investigate the different IAQ parameters for Autumn, Winter and Spring. It is important to note that the data for Summer could not be collected owing to the pandemic restrictions, which delayed the move-in period for the homeowners.

7.2. Descriptive Analysis

7.2.1. Autumn

Table 7.1 shows the temperature, RH and CO levels for three key areas in the houses considered in the sample. It can be observed that the highest average temperature was noted in the kitchen at 19.8^{o}C, while the minimum average temperature was in the second bedroom at 19.1°C. Similarly, the maximum average RH was noted in the

Table 7.1 Average temperature, RH and CO_2 levels for 12 houses in Autumn

Average of all 12 houses						
	T °C		**RH %**		**CO_2 ppm**	
	Mean (SD)	**CV**	**Mean (SD)**	**CV**	**Mean (SD)**	**CV**
Kitchen + Living area	19.8 (±1.8)	8.9	59.3 (±6.1)	10.3	761 (±287)	37.8
Master Bed	19.5 (±1.7)	8.6	59.6 (±4.6)	7.8	828 (±369)	7.8
Second bed	19.1 (±1.7)	9.0	60.0 (±6.4)	10.7	759 (±361)	47.6

second bedroom at 60%, while the minimum average RH was 59.3% in the kitchen area. The average CO_2 levels were observed to be highest in the master bedroom at 828 ppm, while the lowest levels were found to be in the second bedroom at 759 ppm. It, therefore, shows that during the autumn season, there are no major variations in the temperature among different house zones, while there are some minor variations in RH and CO_2 in different zones. However, these variations are not significant, but give an overview of the conditions in different zones in this season.

7.2.2. Winter

Table 7.2 shows the average temperature, RH and CO_2 levels for three key areas in the houses considered in the sample. It can be observed that the highest average temperature was noted in the living area at 20.2°C, while the minimum average temperature was in the second bedroom at 19°C. Similarly, the maximum average RH was noted in the kitchen and living area at 54.4%, while the minimum average RH was at 50% in the second bedroom.

The average CO_2 levels were observed to be highest in the master bedroom at 799 ppm, while the lowest levels were found to be in the second bedroom at 780 ppm. It, therefore, shows that average CO_2 levels are much higher in Winter in all the zones. The CO_2 in the bedroom is the highest, which is probably due to occupants staying inside the room for the whole night, and more so when the door of the room is closed. Higher coefficient of variance (CV) in some cases show the level of dispersion around the mean. For instance, in second bedroom, there is 53.2% variation around the average value of CO_2. These findings contrast with those of the Autumn season because the overall CO_2 levels in the Winter season are high, which may be due to reduced ventilation in colder weather.

Table 7.2: Average temperature, RH and CO_2 levels for 12 houses in the Winter

Average of all 12 houses						
	T ºC		**RH %**		**CO_2 ppm**	
	Mean (SD)	**CV**	**Mean (SD)**	**CV**	**Mean (SD)**	**CV**
Kitchen + Living area	20.2 (±1.6)	7.9	54.4 (±5.1)	9.4	781 (±248)	31.8
Master Bed	20.0 (±1.2)	5.9	52.9 (±3.4)	6.5	799 (±233)	29.2
Second bed	19.0 (±1.9)	10.3	50.0 (±4.0)	7.9	780 (±415)	53.2

7.2.3. Spring

Table 7.3 shows the average temperature, RH and CO_2 levels for three key areas in the houses considered in the sample. It can be observed that the highest average temperature was noted in the kitchen and living area at 19.5ºC, while the minimum average temperature was in the second bedroom at 18.6ºC. Similarly, the maximum relative humidity was noted in the kitchen and living area at 51.7%, while the minimum relative humidity was at 51.3% in the second bedroom.

Table 7.3 Average temperature, RH and CO_2 levels for 12 houses in Spring

Average of all 12 houses						
	T ºC		**RH %**		**CO_2 ppm**	
	Mean (SD)	**CV**	**Mean (SD)**	**CV**	**Mean (SD)**	**CV**
Kitchen + Living area	19.5 (±2.5)	12.7	51.7 (±6.4)	12.5	674 (±226)	33.5
Master Bed	19.4 (±2.2)	11.5	51.5 (±4.1)	7.9	815 (±336)	41.2
Second bed	18.6 (±2.1)	11.3	51.3 (±6.5)	12.7	583 (±209)	35.8

These are within experimental error and so can be considered as not significantly different. Finally, the average CO_2 levels were observed to be highest in the master bedroom at 815 ppm, while the lowest levels were found to be in the second bedroom at 583 ppm. These variations are owing to the fact that temperature is highest in the kitchen due to cooking activities and the higher temperature setpoint in the living area, while the highest CO_2 is due to higher occupancy and lack of ventilation for the time period. The lowest temperature and CO_2 in the second bedroom are because it is occupied for the least time and by a lesser number of people on average. The highest RH in this zone can also be due to a lower temperature.

7.2.4. Overall Analysis

From Tables 7.1 - 7.3, it can be observed that the average temperature in all the house zones is generally lower during Winter, not surprisingly. The temperature difference in different seasons is attributed to the use of heating, setpoints and external weather conditions, which is likely to impact the internal conditions in the dwellings. Similarly, it is found that the average RH is in a reasonable range in all house zones throughout the year.

In contrast, the CO_2 levels are higher during Winter, and lowest in Spring. This may be due to colder weather giving rise to a lesser use of the extracts and ventilation, leading to a higher accumulation of CO_2 in Winter. Moreover, it is found that the temperature and CO_2 levels in all three seasons are found to be a minimum in the second bedroom because it is occupied by just one person in most cases as compared to the master bedroom. However, there are certain discrepancies in other variables and zones. For example, the temperature is found to be the highest in the kitchen during the Winter and Spring seasons, but in Autumn, the highest temperature was found to be in the kitchen and living area. This may be attributed to the solar gain differences in different seasons, the orientation of the house, greater occupancy in the open kitchen/dining area or the use of more heating in the master bedroom during Winter. Moreover, these variables will be further studied in the second half of the chapter on modelling, whereby these differences will be studied in the light of the difference in occupant behaviour.

Similarly, in Autumn and Spring, the lowest RH was found to be in the kitchen, implying the efficient use of mechanical ventilation and trickle vents. The second bedroom exhibited the lowest RH in Winter which could be attributed to the high temperature in Winter in this zone. Also, in different seasons, the RH showed low variance, implying that it was in a reasonable range throughout all seasons, implying there is effective removal of generated RH and low risk of mould growth. The small differences may be attributed to the occupational behaviours of the people in these houses, which are discussed in detail in the second half of this chapter.

Finally, the master bedroom showed the highest CO_2 levels during all three seasons. It is also important to note that since the sample number of houses is small, the probability of any particular houses, with extreme temperatures, RH or CO_2 levels, being outliers, has the potential to alter the averages. To better understand the nature of these outliers, the exceedances for different houses (and their respective house zones) are studied in the next section.

7.3. Zone-wise Exceedances

7.3.1. Living/Kitchen

In Figure 7.1 the living rooms and attached kitchens are examined, where the highest exceedances were for temperatures less than 18^{o}C. Moreover, higher exceedances were witnessed in Winter and Spring, and less so in the Autumn, which is due to the cooler external weather due to seasonal change. 6 houses out of 11 (Figure 7.1) experienced exceedances in temperature for less than 5% of the time, while 4 houses showed exceedances for about 100% of the time, specifically houses A12, A13, A15 and A18.

In Spring, 6 houses exhibited exceedances for more than 20% of the time. Houses A12, A13 and A15 exhibit 100% exceedance in temperature throughout the season, in which the temperature remained less than 18^{o}C throughout. Finally, in Autumn, houses A01, A02 and D04 showed exceedances for about 20% of the time. The lower temperature in the kitchen and living area may be attributed to the lesser use of the heating system in the zone due to their personal preferences.

Figure 7.1 Temperature exceedances in the living/kitchen area; T = 18-25°C (in yellow); T< 18°C (in blue), and T> 25°C (in red).

In Figure 7.2 the houses showed higher incidences of RH exceedances during Spring and Autumn, as compared to Winter. This may be due to the temperature values in the zone in the respective seasons. It is further observed that the highest exceedances were exhibited by houses A12, A13 and A15 in Spring at 100% of the time, and at house A17 in Autumn for about 90% of the time. It is also important to note that the same house zone can entail significantly higher variations in RH for different seasons. For instance, house A17 experienced no RH exceedance in Spring, while the exceedances are about 35% during Winter, and 90% in Autumn. These variations may be due to the usage patterns of the occupants, which will be further explained and modelled in the next section.

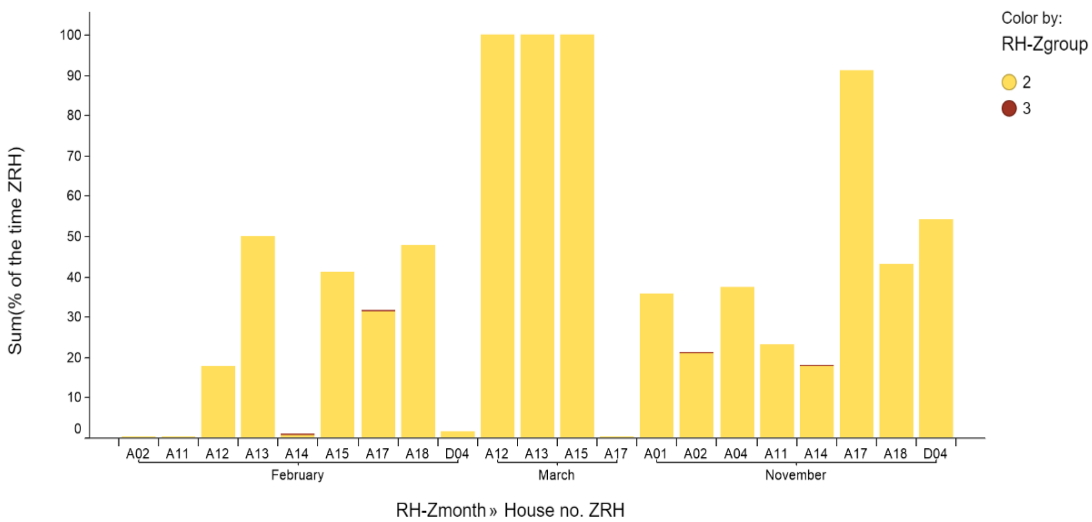


Figure 7.2 RH exceedance (yellow: RH more than 60%; Red: RH more than 80%)

From Figure 7.3, the variations in CO_2 for these houses has also been evident for different seasons. That is, the houses show higher CO_2 exceedances during Winter and Spring and least exceedances during Autumn. In Winter, four houses, namely A12, A13, A15 and A18 show CO_2 exceedances of more than 1500 ppm for about 50% of the times. During Autumn, the highest exceedance is witnessed by A17, for about 60% of the time.

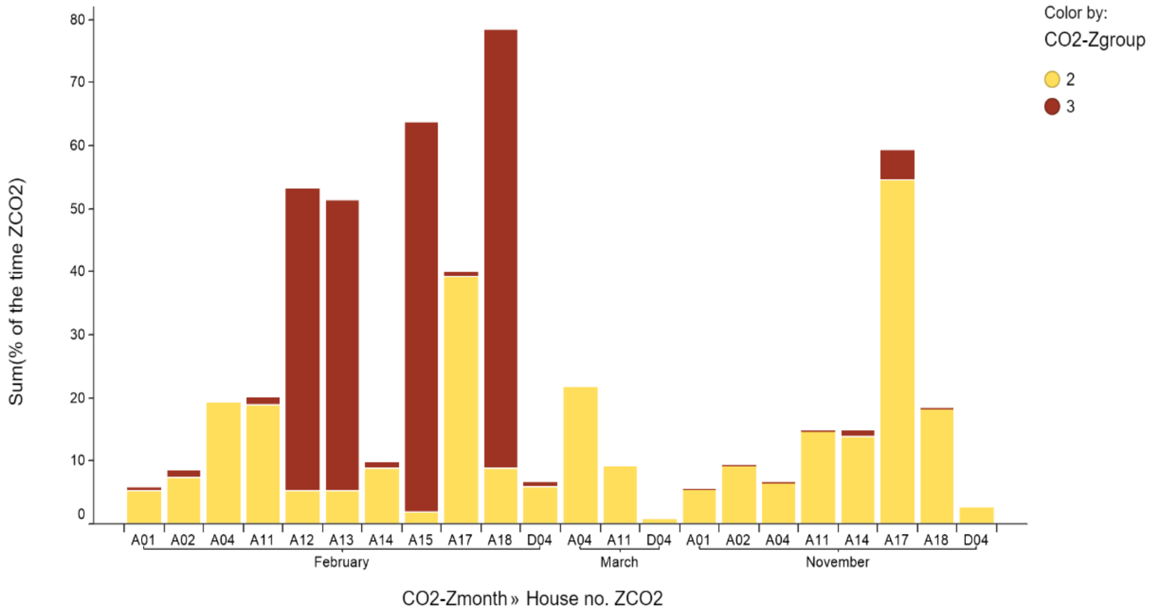


Figure 7.3 CO_2 exceedances (yellow: CO_2 more than 1000 ppm; Red: CO_2 more than 1500 ppm)

7.3.2. Master bedroom

The exceedances in temperature in the master bedroom for less than 18 ^{o}C are given in Figure 7.4 and were greater during Winter and Spring. 7 houses showed temperature exceedances for less than 30% of the time, while 4 houses had exceedances for more than 80% of the time. In Spring, 7 houses had exceedances for more than 30% of the time, out of which 4 houses exhibit temperature below 18^{o}C throughout the season. Finally, during Autumn, out of the data from 8 houses examined, 4 houses showed no exceedances, while the remaining ones experienced temperature less than 18^{o}C for more than 30% of the time. The highest exceedance for temperature lesser than 18^{o}C was observed in house A01, for about 90% of the times.

The exceedances in RH in Figure 7.5 were highest in Spring and lowest in Winter. About 5 houses showed no exceedance in Winter, and four houses showed exceedances (RH > 60%) for more than 20% of the time. The highest exceedance for RH > 60% was experienced by house A13 for about 50% of the time.

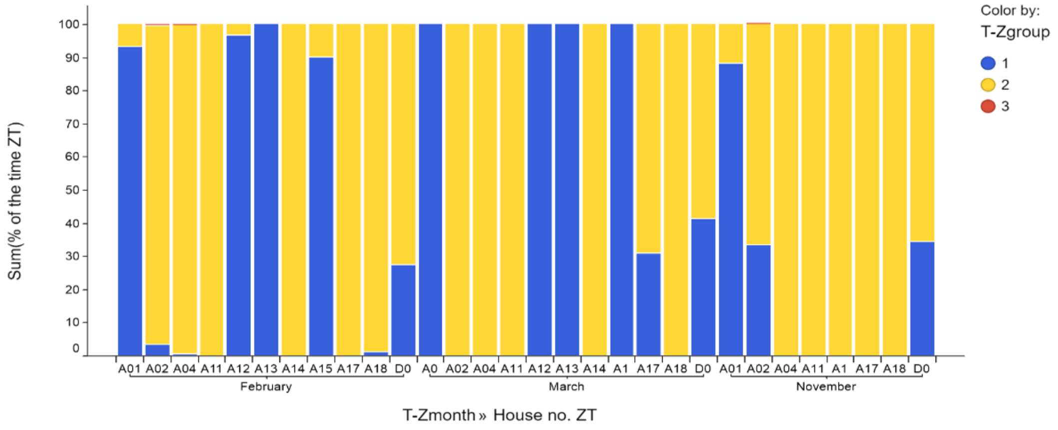


Figure 7.4 Temperature exceedances in the master bedroom (Yellow: normal temperature (between 18 and 25°C); Blue: temperature lower than 18°C, and red indicated exceedance of higher than 25°C).

In Spring, 3 out of 5 houses showed exceedance of RH>60% throughout the season, while the other two houses experienced exceedance for less than 5% of the times. In Autumn, all the houses showed RH exceedance for more than 20% of the time. 4 houses experienced an exceedance for more than 35% of the time, with the highest exceedance by A17 for about 85% of the time. These variations may be due to different factors, such as the number of occupants, their usage patterns of ventilation, closing and opening of doors etc., which will be explained later in the chapter.

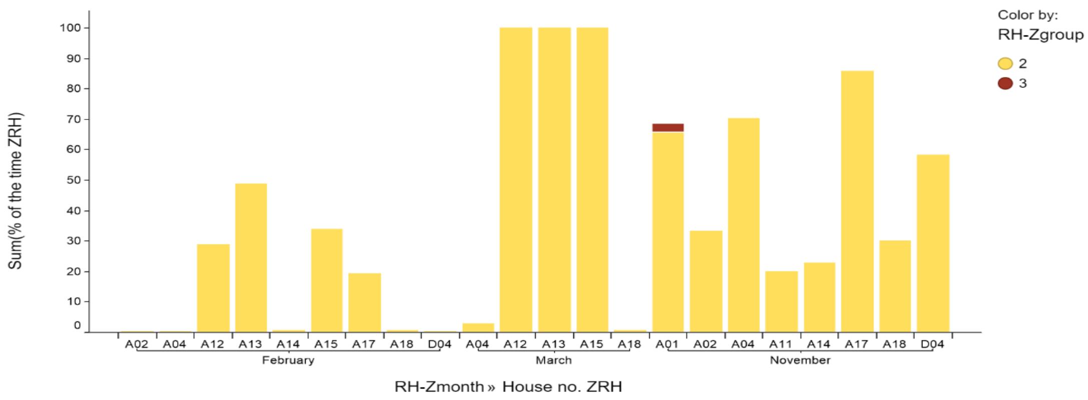


Figure 7.5 RH exceedances in the master bedroom (yellow: RH more than 60%; Red: RH more than 80%)

The CO_2 exceedances in Figure 7.6 were higher in the master bedroom, and were most prominent during Winter and Spring. All houses showed exceedances, while an exceedance of CO_2 greater than 1500 ppm was shown in houses A12, A13 and A15 for about 50% of the time. In Spring, the highest exceedance was evident in house A02, and 5 houses showed exceedances for more than 20% of the times. Finally, in Autumn, the CO_2 exceedances in 5 houses were for more than 25% of the time, and the worst performance in terms of highest CO_2 was witnessed in A17 for about 60% of the times.

These exceedances in houses with similar construction and heating/ventilation systems indicate that the CO_2 level depends on how the occupants live inside the different house zones, and use the ventilation leading to movement or accumulation of the CO_2. These reasons will be further examined in the next section, and these exceedances along with their specific reasons will be probed.

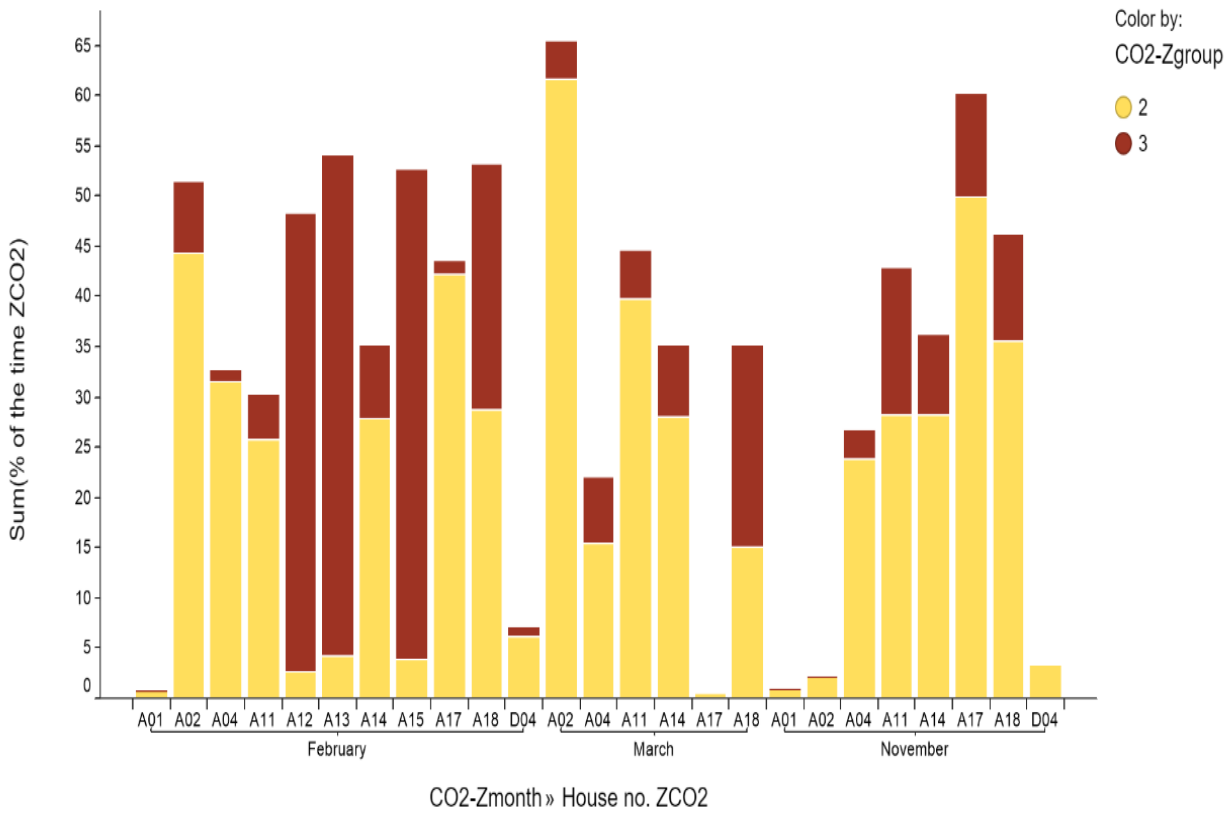


Figure 7.6 CO_2 exceedances in the master bedroom (yellow: CO_2 more than 1000 ppm; Red: CO_2 more than 1500 ppm)

7.3.3. Second bedroom

The exceedances in the second bedroom shown in Figure 7.7 were highest in Winter, however, four houses showed no exceedances in temperature of lesser than 18°C. Four houses, A12, A13, A15 and A17, showed exceedances 100% of the time. During Spring, only three houses showed exceedances of temperature lesser than 18°C, while the rest experienced no exceedances. A01 experienced temperature less than 18°C for about 95% of the times, while A07 was for about 70% of the times. Finally, in Autumn, 3 houses showed no exceedances, while the remaining 5 showed exceedances for more than 30% of the time. The highest exceedance was experienced by A02, in which the house experienced a temperature below 18°C for about 90% of the time.

Figure 7.7 Temperature exceedances in the second bedroom (Yellow: temperature (between 18 and 25°C); Blue: temperature lower than 18°C, and red indicated exceedance of higher than 25°C).

In Figure 7.8, all three seasons showed high incidences of RH exceedances (of greater than 60%). In February, the highest exceedance was shown by A17 for about 80% of the time, while in Spring, A12, A13, A15 and A17 suffered from high RH throughout the season. Finally, in Autumn, A17 shows RH exceedance for almost 100% of the time, followed by D04 for about 90% of the times. This indicates that these two houses, D04 and A17, with such a high RH for most of the times, would have poor IAQ, leading to mould formation.

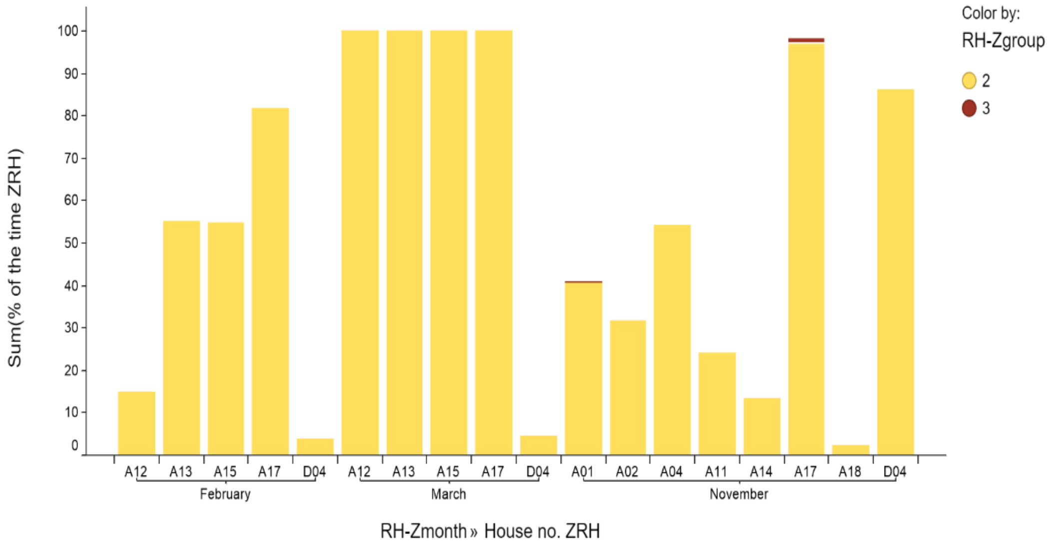


Figure 7.8 RH exceedances in the second bedroom (yellow: RH more than 60%; Red: RH more than 80%)

The CO_2 exceedances (Figure 7.10) showed high variation for the three seasons in the study. The highest CO_2 exceedance (for more than 1500 ppm) was found is Winter, followed by Autumn, and least during Spring. In Winter, all the houses, except A17 and A18, had exceedances more than 10% of the times, while A12, A14 and A15 suffered from CO_2 levels more than 1500 ppm for about 50%-55% of the time. In

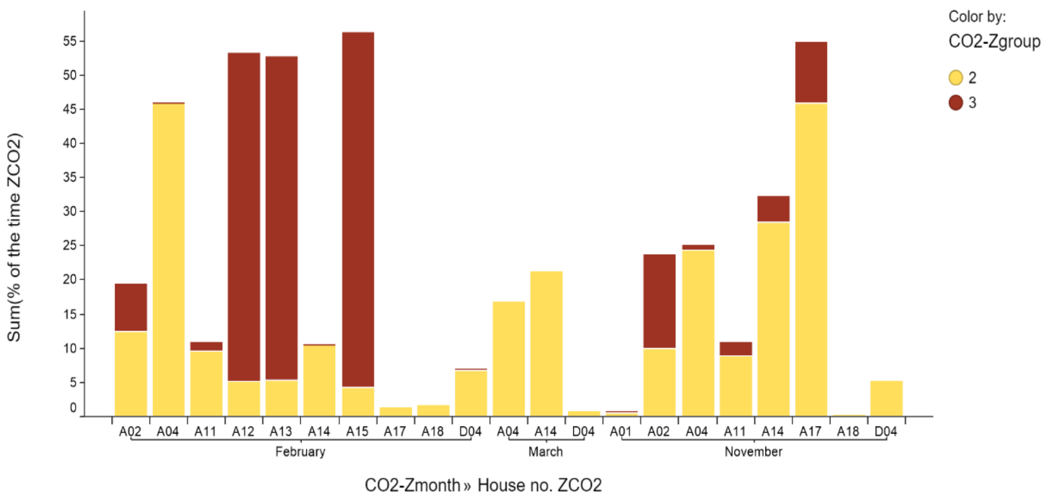


Figure 7.9 CO_2 exceedances in the second bedroom (yellow: CO_2 more than 1000 ppm; Red: CO_2 more than 1500 ppm)

Spring, all the houses showed CO_2 exceedance, at greater than 1000 ppm, for less than 20% of the time. Finally, A17 showed maximum CO_2 exceedance for about 55% of the time, followed by A14 for about 32% of the time and A04 and A02 for about 25% of the time. Thus, the high exceedances of CO_2 is likely to cause a poor IAQ in these specific houses, with the consequence of causing poor health of the occupants.

7.3.4. En suite

The highest exceedances in temperature (Figure 7.10) of less than 18^{o}C was evident in the en suite, which may be attributed to the continuous running of the mechanical extract full time. A04 and A11 showed least exceedances, while houses A17, A01, and D04 showed highest exceedances in all three seasons. It can, therefore, be concluded that these three houses, despite being similar to others, have different indoor environments, and the internal occupancy behaviour needs to be modelled to find out the reason for this trend, and advise the occupants of necessary changes to address this.

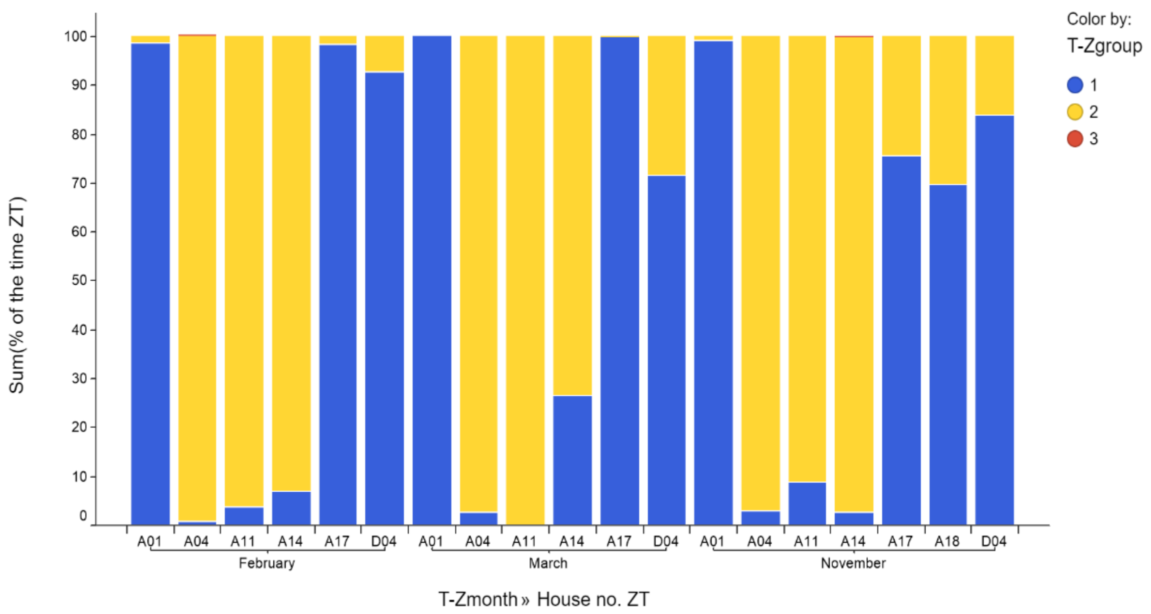


Figure 7.10 Temperature exceedances in the en suite (Yellow: temperature (between 18 and 25°C); Blue: temperature lower than 18°C, and red indicated exceedance of higher than 25°C)

The exceedance in RH in the en suite zone (Figure 7.11) is highest in Autumn and least in Winter. Houses A04, A17 and D04 showed the highest exceedances in every season surveyed, while houses A01 and A11 showed the least exceedances in Winter and Spring. It indicates that some houses (despite having the same house layout) are experiencing poor IAQ in terms of higher RH, with the risk of mould development. The reason for such high exceedances must be explored, and it may be due to occupant behaviour, poor use of vents, extract fans and closing/ opening of adjoining doors. These factors will be studied in depth in the next section.

In summary, what this analysis demonstrates is that similarly constructed houses with similar heating/ventilation systems can exhibit quite different IAQ in different zones of the houses, dependent largely on occupant behaviour, not the house infrastructure. Having learnt about the average and exceedances in the IAQ variables, namely temperature, RH and CO_2 of this set of houses, the next step is to learn how far the simulations can assist with guidance on improving the IAQ in some extreme cases.

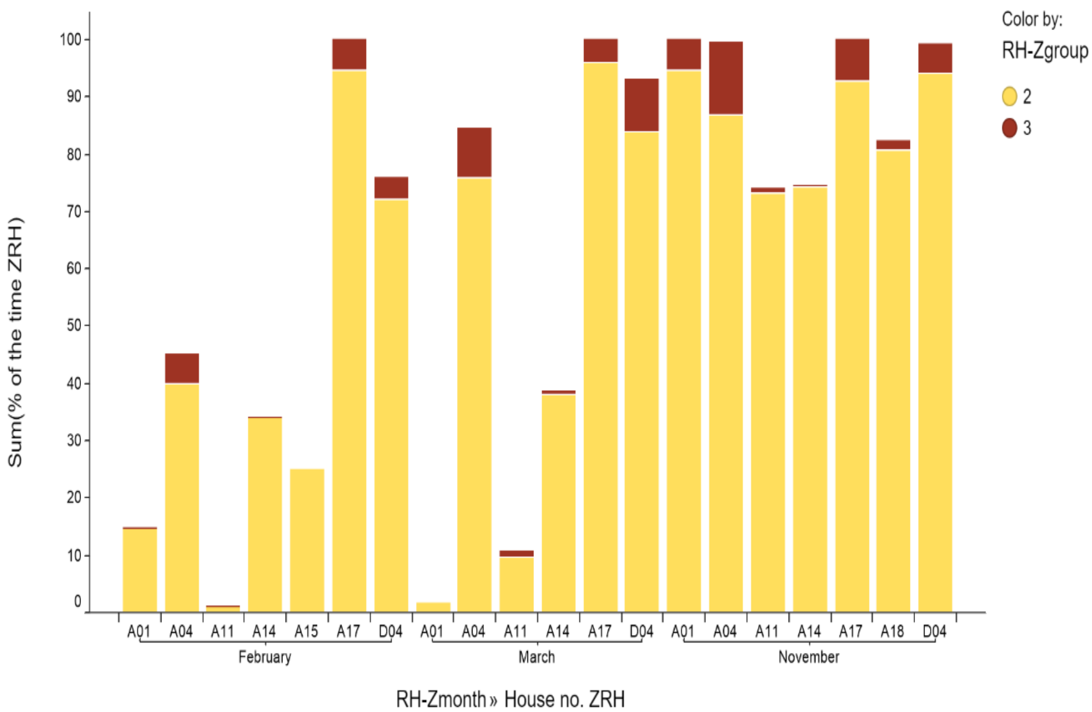


Figure 7.11 RH exceedances in the en suite (yellow: RH more than 60%; Red: RH more than 80%)

7.4. Hypothetical Cases to Assess Human Behaviour

In this section, five hypothetical cases are analysed to learn how far the model results are applicable in these houses. These are some imaginary cases to see if they match what was observed in the last chapter with the other set of houses at Location 2. Advice was not given to the occupants of these houses, but hypothetical cases are observed to see the impact on IAQ, if advice had been given.

7.4.1. Case 1-Living room/Kitchen

It has been studied in the previous modelling chapter that when the windows, doors and mechanical vents in the living area/ kitchen are closed after evening cooking activity, this leads to higher RH/CO_2 at night-time. It is also assumed that soon after the use of the area in the evenings, the occupants move to their respective rooms, keeping their doors closed. This does not of itself lead to rapid accumulation of RH/CO_2, but when the doors, windows and vents are closed, the RH/CO_2 that is emitted from humans breathing, drying clothes, cooking or showering is trapped until the door is opened again the next morning. This may have an implication for well-being or high moisture formation, which is often the cause of condensation and mould formation.

To present this case, post-advice modelled results are plotted against the simulated data, as given in Figures 7.12 and 7.13 for RH and CO_2 respectively. These figures show the initial values generated by simulation on RH and CO_2 respectively for the initial and post-advice implemented case. It is found that the initial RH and CO_2 levels had been high in the living/kitchen area. However, if the advice is implemented by the occupants, and they open their vents, doors and windows, the RH and CO_2 can be significantly reduced.

To undertake the analysis, in IESVE thermal modelling, the profile for the case was developed using the project daily profile (showing the percentage of occupancy throughout the day) for kitchen and living occupancy, as given in Figure 7.14. The profile shows that the base occupancy condition is considered at 3 to 4 occupants.

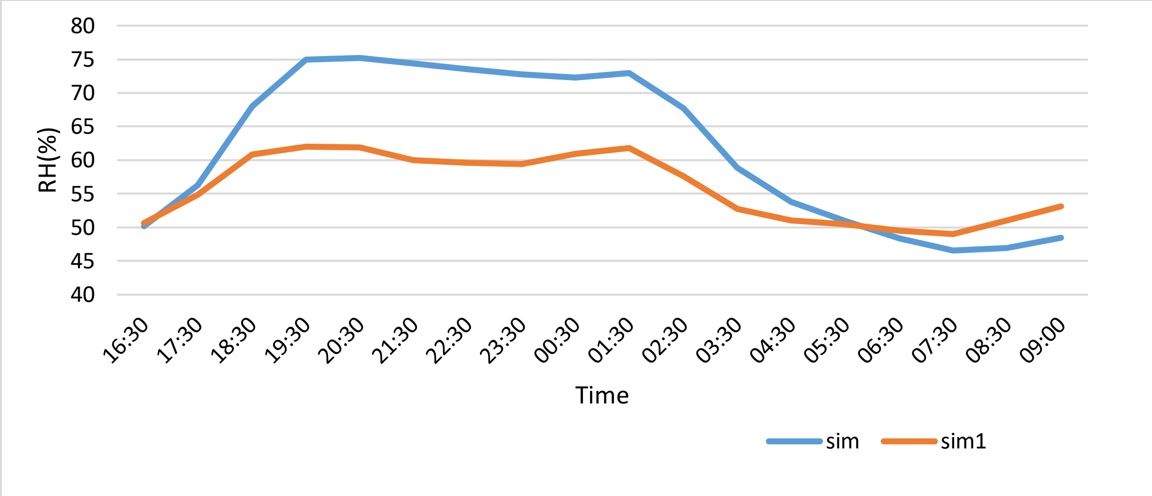


Figure 7.12 Initial (sim) and post-advice (sim1) implemented in simulation for RH in the kitchen/living area

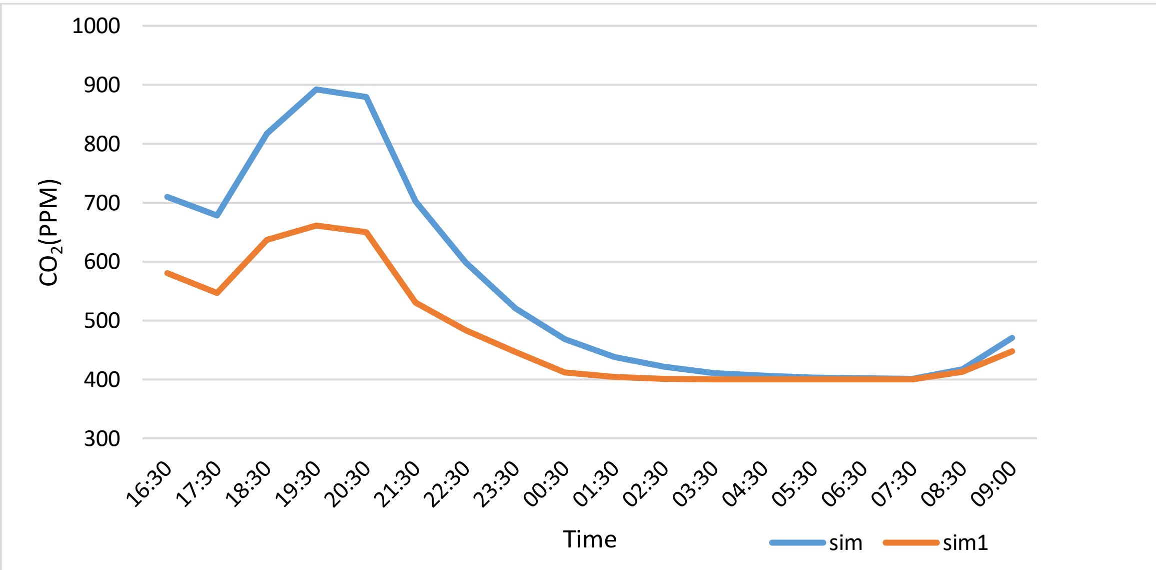


Figure 7.13 Initial (sim) and advice (sim1) implemented in simulation for CO_2 in kitchen/living area

The daily profile specifies the time and values in terms of the proportion of occupancy at specific hours. Moreover, in the base condition, the vents and windows are kept closed, the kitchen door to the foyer is half open while the living area door is fully shut.

Furthermore, to find whether this case is realistic or not, the on-site data on RH and CO_2 for one of the houses (house A08) is compared, as given in Figure 7.15.

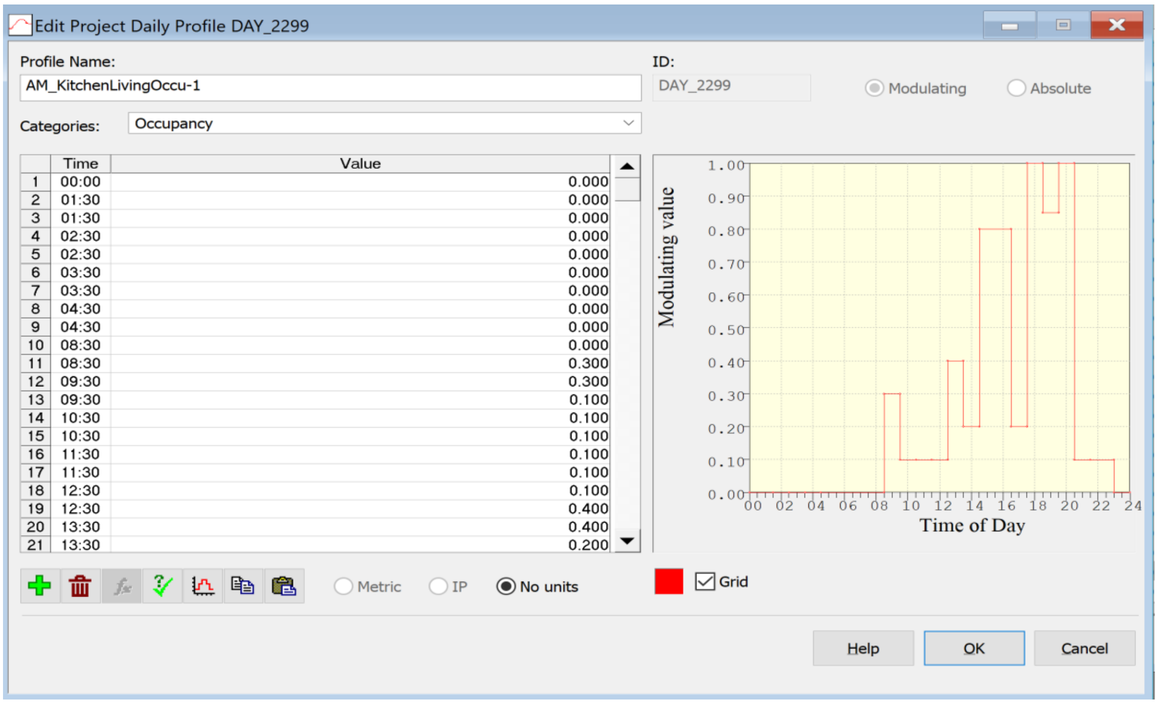


Figure 7.14 Daily occupancy profile for living/kitchen

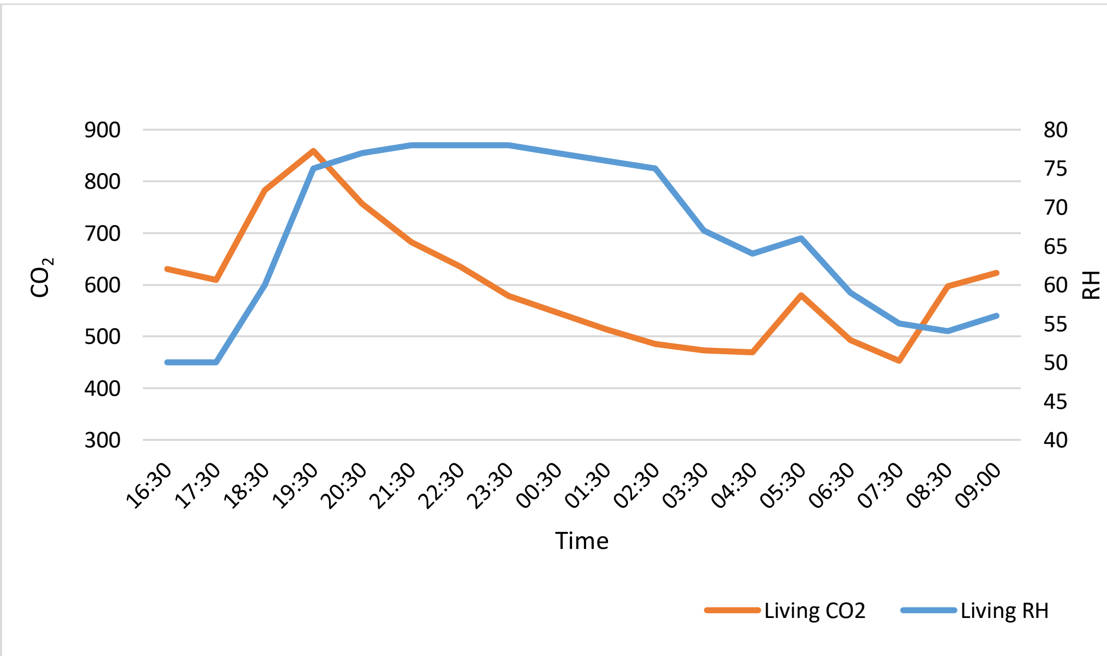


Figure 7.15 On-site (monitored) data on RH and CO_2 of House A08

From this figure, it can be found that high CO_2 and RH levels, as simulated (in Figure 7.13 and 7.14), are actually experienced in the houses (Figure 7.16). Hence, in reality, if these houses follow the advice of opening the vents, windows and doors, they are likely to experience much better IAQ in terms of reduced RH and CO_2 levels, as explained earlier.

7.4.2. Case 2 – En suite

When the ventilation systems are completely off in the en suite, this leads to an accumulation of RH in that room immediately after taking a shower. Moreover, a very high RH persists there for many hours due to residual standing water, implying a high probability of moisture condensation as well as future mould problems. To investigate this scenario, the relevant data in computed in the simulation with the base condition that one occupant is present, and the extractor fan is off (Figure 7.16).

Now, as per the advice derived in the previous section, the central system should be switched on, and the mechanical extract becomes operational. The variations in the RH level in the en suite when the extract was closed (base condition) and opened (if advice is followed) is given in Figure 7.16:

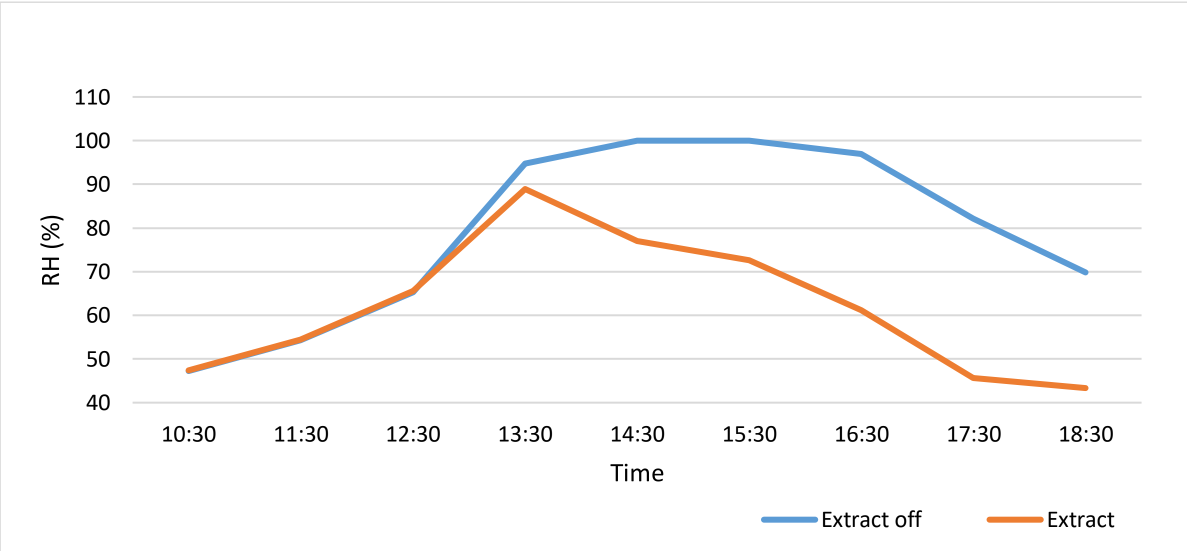


Figure 7.16 Simulations for en suite, switching the en suite extract on and off

This illustrates that when the central system is open, and the extract fan is operational, the accumulated RH is much lower as compared to the case when it is closed. The extractor is automatically fully on when the RH is more than 80% and the door/windows are closed. Moreover, the accumulated RH dissipates at a higher rate because the extract moves it out. Hence, if the occupants follow this advice, the IAQ level in the en suite zone can be significantly improved. This behaviour is further witnessed by typical data extracted from one house, as presented in Figure 7.17.

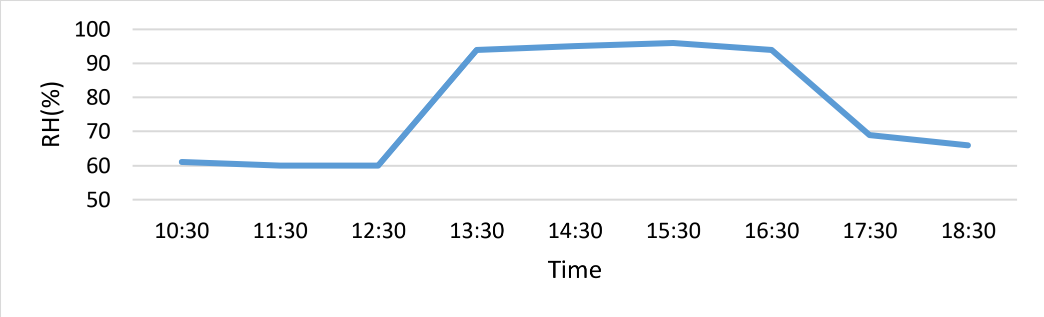


Figure 7.17 RH (%) in en suite- onsite data (A04)

This graph shows that the en suite experiences a much higher RH between 12.30 pm and 3.30pm due to the shower activity and the moisture is trapped inside the area, until the door is again open at 4.30, and the excess RH dissipates quickly. Thus, it can be concluded that many houses experience a similar IAQ feature, as simulated in Figure 7.17, and following the proffered advice will help them in reducing the RH levels.

7.4.3. Case 3 – Impact of high occupancy

In this case, it is considered that when a small get-together party is hosted, and the occupancy in the living area/kitchen increases to 6-7 people over a weekend evening, it poses a threat due to an accumulation of CO_2 when the vents, windows and doors are closed (the base condition). To better represent this simulation, a new daily occupancy profile (Figure 7.18) was created by plotting the time and values with the change in occupancy level. The values depict the higher occupancy causing changes in CO_2 levels from 6 pm onwards.

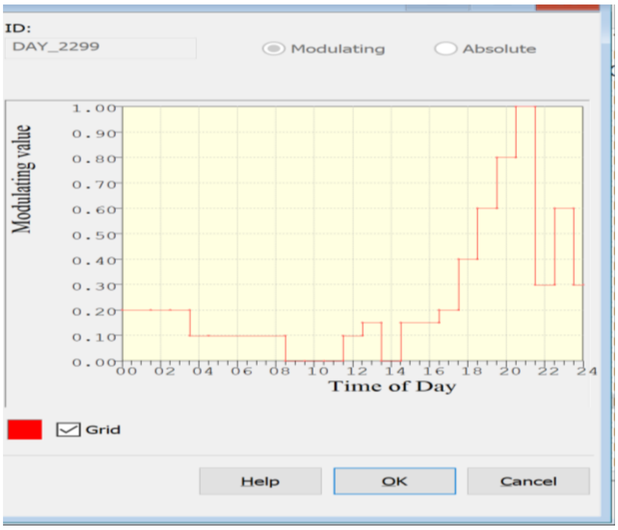


Figure 7.18 Daily occupancy profile for the kitchen/living area

It can be found that under the base condition, the CO_2 levels were as high at 2000 ppm and, until 5.30 am in the morning, the CO_2 emissions remained higher than 1000 ppm. It shows the worst-case scenario, and is unhealthy for the occupants.
To correct this situation and improve the IAQ, the occupants are advised in terms of three scenarios, thus:

Scenario 1: The occupants are advised to keep the trickle vents fully open
Scenario 2: Along with fully open trickle vent, the door of the kitchen into the hallway must be kept half open.
Scenario 3: The advice given is to keep the trickle vent fully open, kitchen door half open into the hallway, and the living door kept half open.

The findings of the base case as well as the above three advice cases are presented in Figure 7.19:

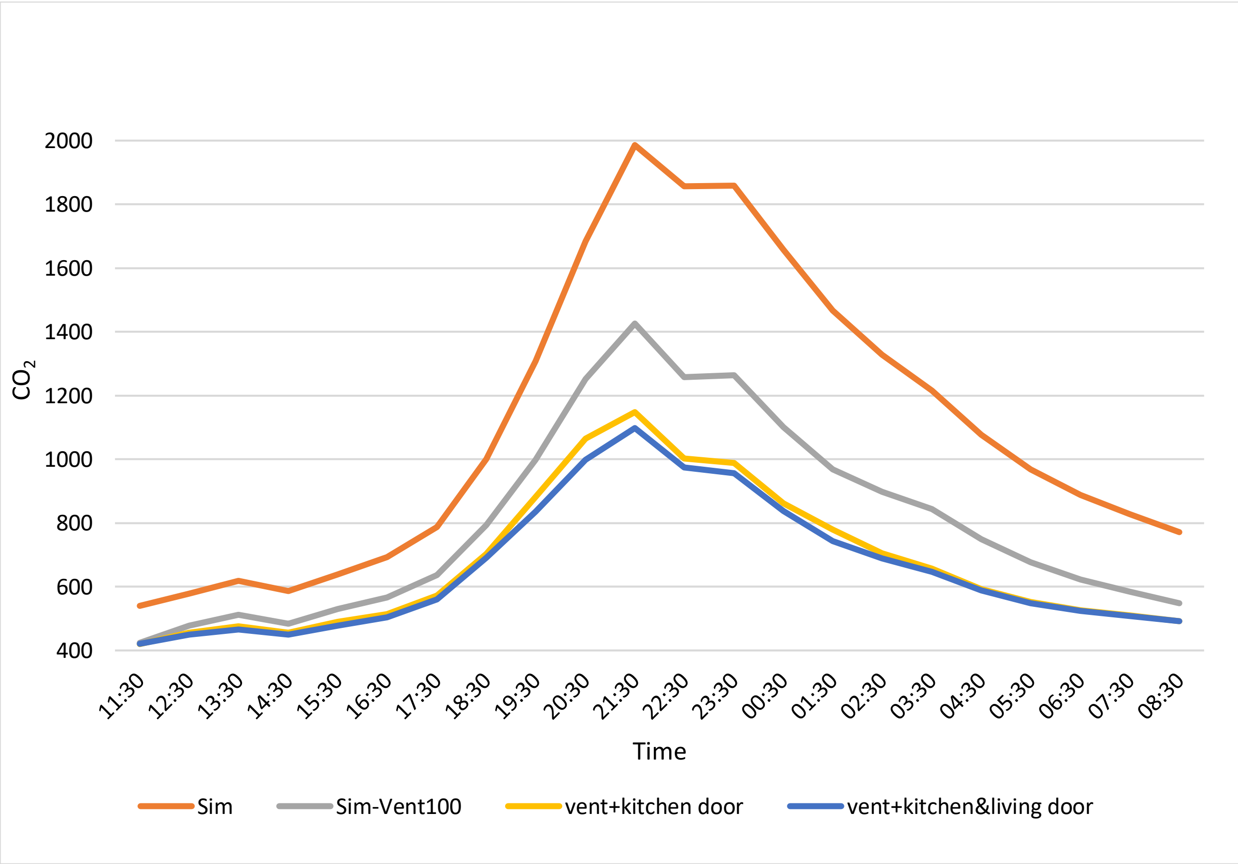


Figure 7.19 CO_2 levels in the living/kitchen area in different situations (Sim: base case)

When the trickle vent is fully open (grey line) it is observed that the CO_2 decreases from 2000 ppm at 22.30 hours, to 1400 ppm, and thereafter, it further reduces the CO_2 emissions to below 1000 ppm in the next three hours. It indicates that the efficient use of trickle vents prevents the accumulation of CO_2, and helps dissipate it at a faster rate, thereby, improving the IAQ of the house zone.

When the kitchen door towards the hallway is kept half open, a further reduction in CO_2 levels was observed. The highest CO_2 levels were around 1150 ppm, and after 10.30 pm, the CO_2 levels fell under 1000 ppm because, with the opening towards the hallway, the generated CO_2 will be able to diffuse outside, leading to a better IAQ in the kitchen.

In the final scenario, when the living area door is also opened along with the other conditions in previous cases, there is a substantial fall in CO_2 as compared to scenario 2 leading to a maximum value of only 1098 ppm.

Hence, it can be stated that opening the trickle vent fully and the kitchen door towards the hallway are highly effective interventions for reducing the CO_2 accumulation in the room, and improves the IAQ. While this, of course, is to be expected, the quantification of the extent of CO_2 accumulation and its reduction through occupant action is of interest when giving advice to homeowners.

To check whether or not the above behaviour is realistic, onsite data was studied and it was found that many houses experience such high CO_2 levels and sudden drops in CO_2. An example of one such house (A02) is presented in Figure 7.20.

It can be stated from this graph that the CO_2 starts rising from 6.30pm, and attains a peak of over 2000 ppm at 9.30pm. At around 11.30pm, even when the guests or family members started to leave the house (with doors opening and closing), the CO_2 levels are still over 1000 ppm until about 4.00 in the morning. This shows that the accumulated CO_2 takes a considerable time to dissipate if the door/vent is not left open. Thus, as this scenario resembles the same movements as in the below simulation, it can be deduced that if the house occupants follow the advice suggested in scenarios 1 to 3 above, they will experience lower CO_2 and better IAQ.

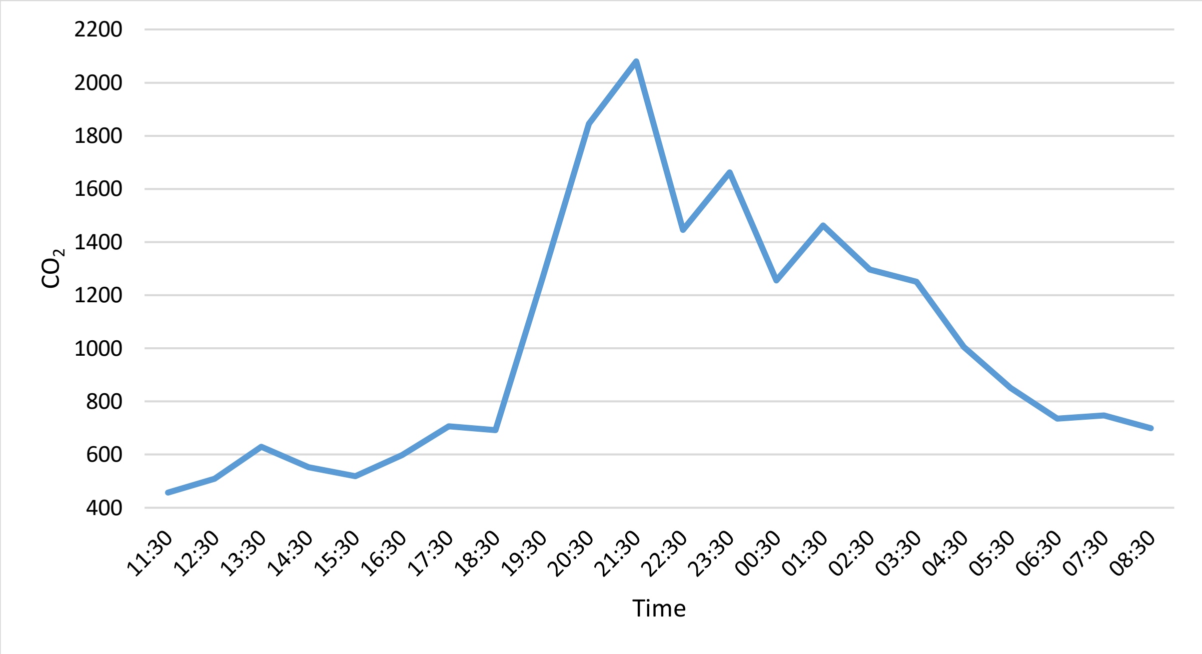


Figure 7.20 Onsite data for CO_2 in the living/kitchen area in House

7.4.4. Case 4 – Impact of adjoining spaces

In this scenario the CO_2 levels are found to be higher in the bedroom when the en suite door and the main door of the bedroom to the landing are kept closed. Thus, to hypothesize this case, it is created in the simulation assuming two occupants. The daily occupancy profile is created in Apache, by plotting the values of occupancy in accordance with the different day timings, as given in Figure 7.21.

The figure shows that the bedroom is occupied by the occupants till 8 am and thereafter they leave the room. They re-enter the room at night at 8 pm. Another daily profile is created for the opening door schedule, varying with occupancy at different points of time in a day, as shown in Figure 7.22.

It is found that the CO_2 levels are naturally and actually high with the vents and doors closed. To improve the IAQ and reduce the CO_2 levels, the simulation of the advice that the vents must be completely open is plotted in Figure 7.23. By implementing this advice, the improvement in CO_2 levels is clear, even with two-person occupancy.

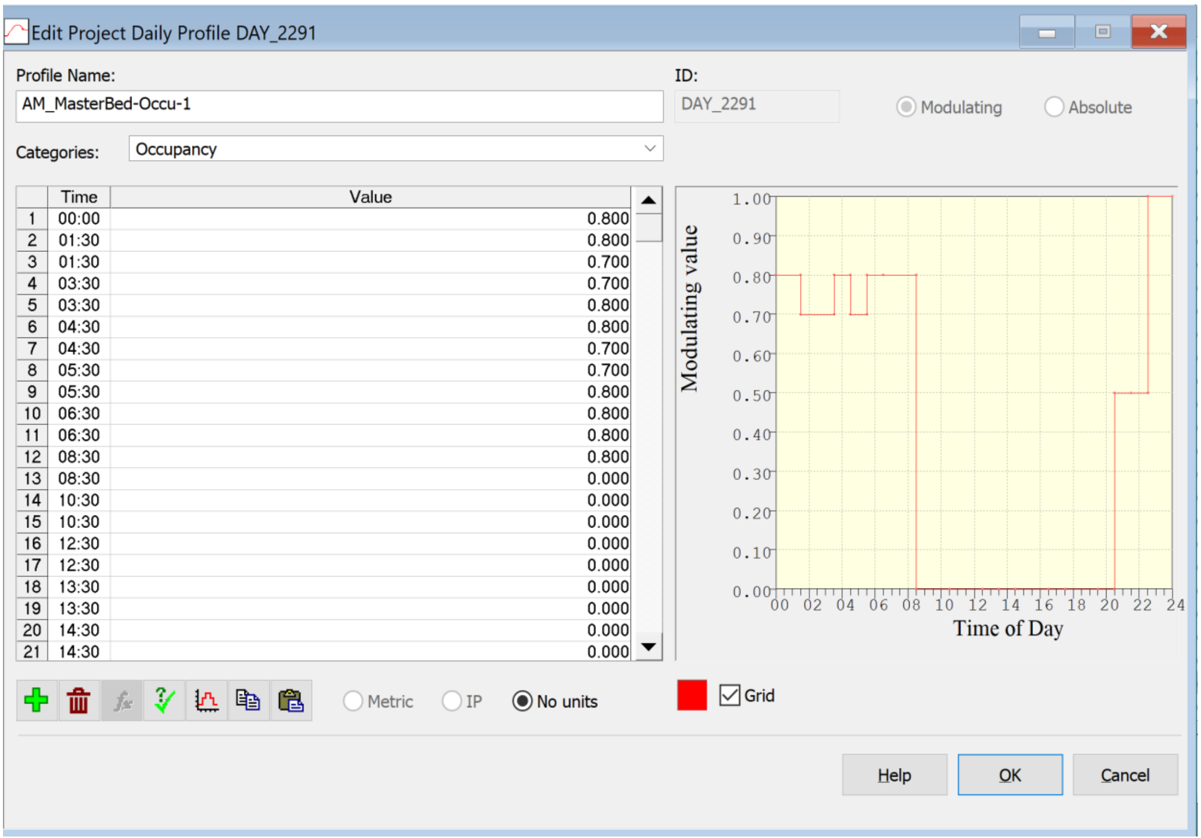


Figure 7.21 Daily occupancy profile for the master bedroom

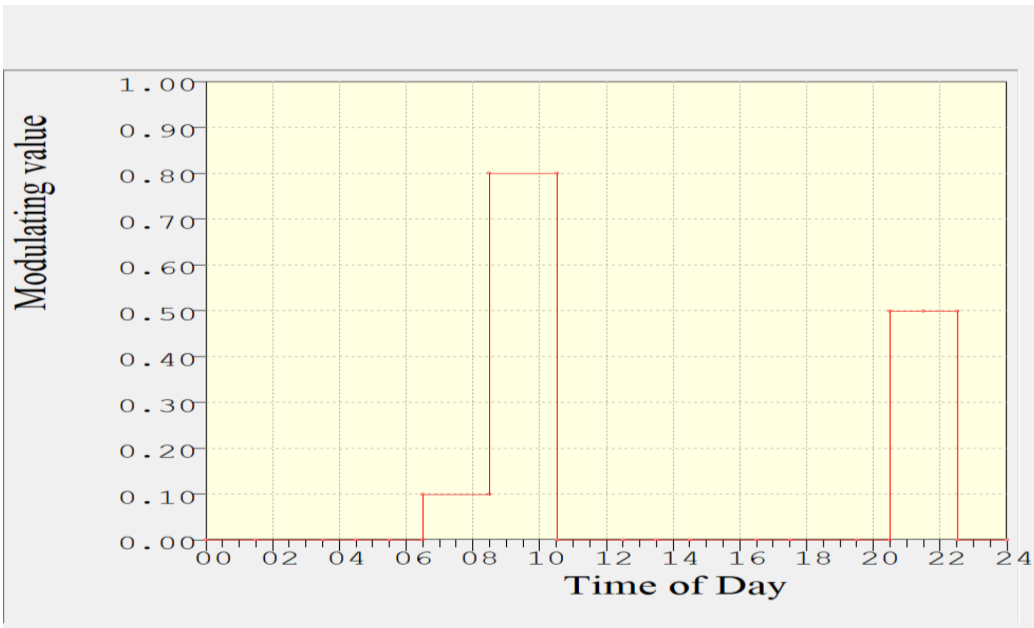


Figure 7.22 Daily profile for door opening schedule

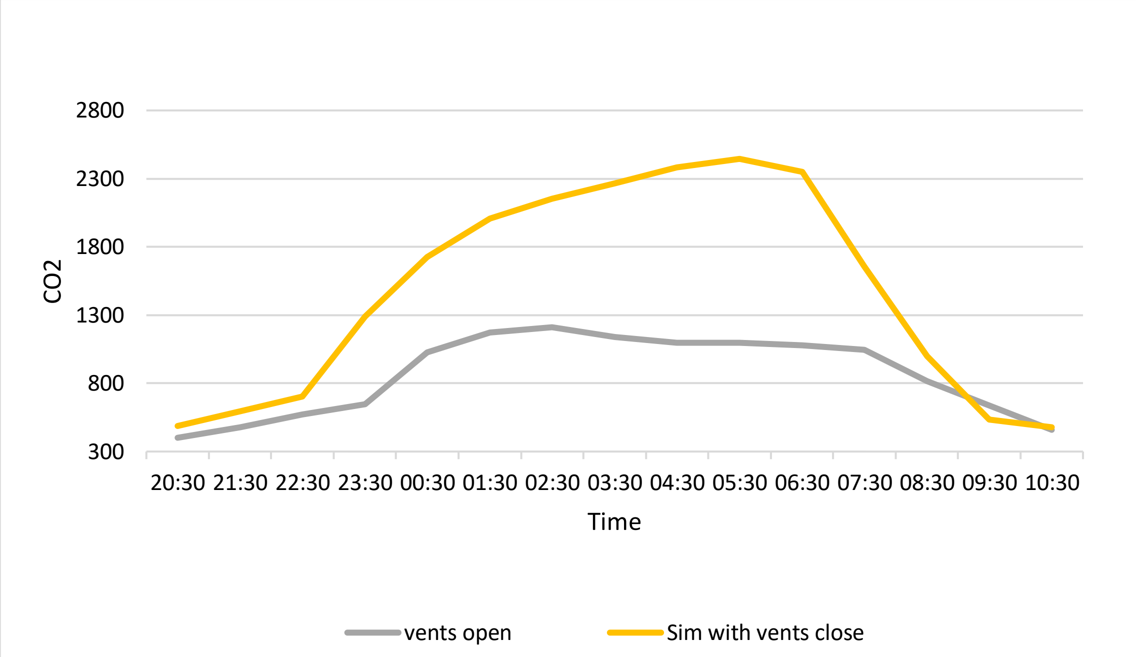


Figure 7.23 Simulation of CO_2 in the master bedroom

This figure shows that when the vent is completely open, the accumulated CO_2 levels were significantly lower, such that the maximum concentration of CO_2 reduced from 2400 ppm to 1150 ppm. Also, the overall CO_2 for the entire day has decreased significantly.

The model in this base case resembles the measured scenario for on-site data. It is found that the CO_2 in the bedroom at night-time remains high, as given in the two houses A11 and A14 (Figure 7.24)

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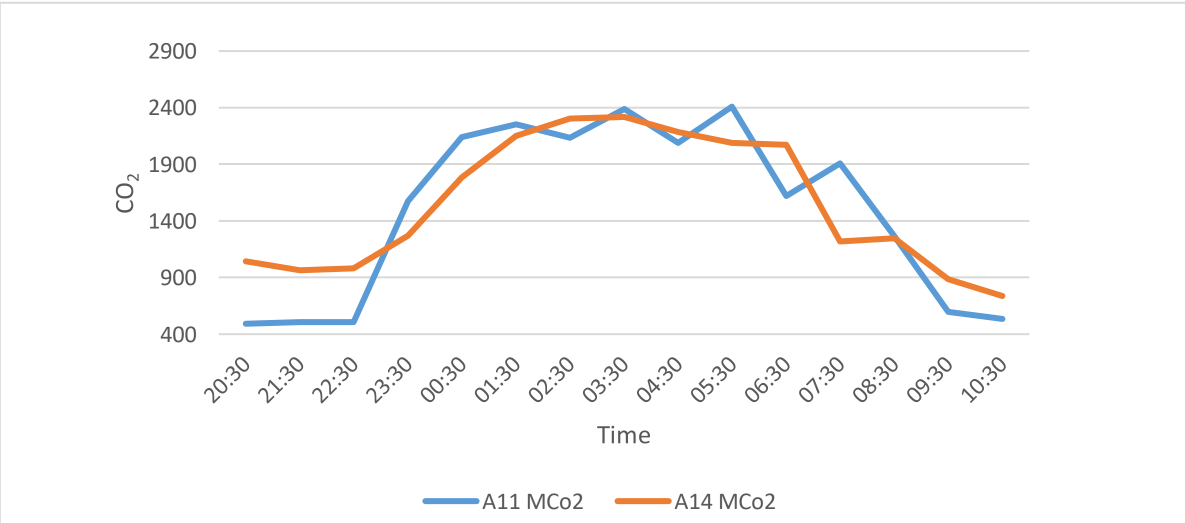

Figure 7.24 Onsite CO_2 levels in master bedroom

The graph shows that in both the A11 and A14 houses, the CO_2 level is consistently high between 11.00 pm and 8.30 am and that the doors and vents are closed. Thus, the above-mentioned simulated model can be applied to measured data, and if they implement the advice, they can reduce the CO_2 levels, and enhance the overall IAQ.

7.4.5. Case 5 - Setpoints

In this case the temperature in the master bedroom is assessed during the night, due to the change in the temperature setpoints and heating schedules. It was observed that as the setpoints are set much higher, and the schedule means heating is on throughout the night, this causes high temperature within the house. This is an obvious case, but it is still modelled to see the extent of effect it can have. To improve the comfort level and reduced temperature, the following two advice scenarios are tested:

Scenario 1: Reduce the setpoint from 22-25^oC to 20-22^oC.

Scenario 2: With the base heating setpoints, the schedule is changed such that the heating system will be operating from 6am to 8am in the morning and 7.30pm to 10pm in the evening only.

The impact of these is simulated as shown in Figure 7.25. The graph shows that the overall temperature for the master bedroom is high if the advice is not followed. Firstly, when the heating setpoint is reduced, the overall temperature follows the same trend as the base case, but has a reduced temperature, with falling temperature after 10.30 pm.

Secondly, when the heating schedule is made variable, the temperature graph has smoothed, showing that the overall temperature reduced, and was stable at a lower temperature during the night. It shows that the heat when the heating system was switched on was elevated consistently for a larger time duration, showing the optimal use of the device if scenario 2 is chosen. A similar incidence for higher temperature was also experienced in reality in House A02 at location 2, and is presented in Figure 7.26.

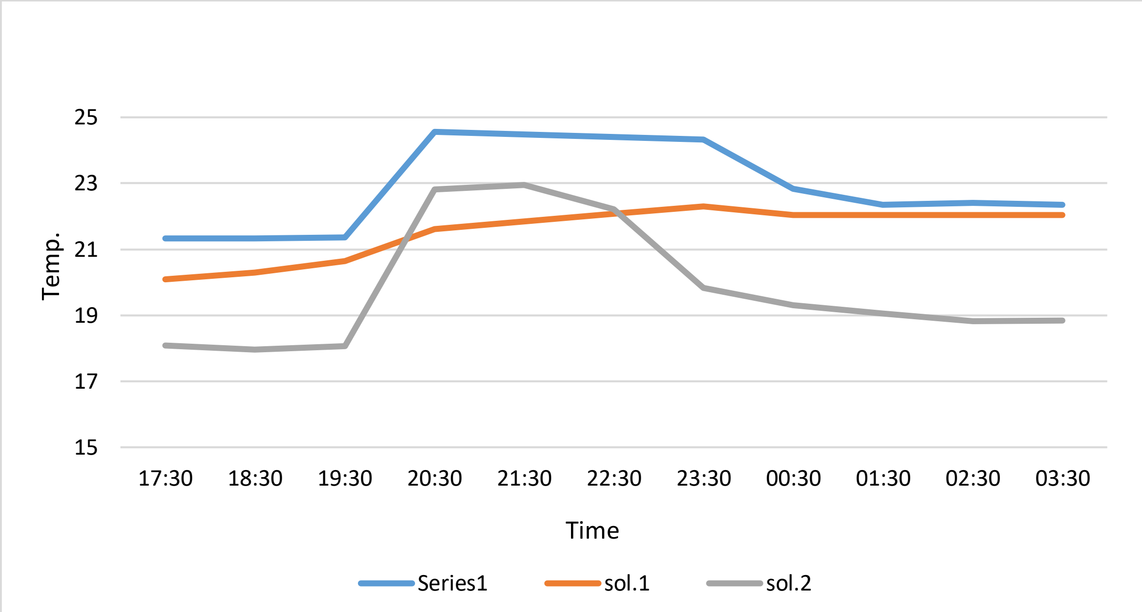

Figure 7.25 Simulated temperature in a bedroom for the base case, and two advisory solutions

The graph shows that the temperature is as high as 25°C in both the living room and master bedroom, and the average temperatures are high throughout the night. It clearly shows that the above simulated behaviour is possible in real time, and the occupants can improve the IAQ by implementing the advice in scenario 2.

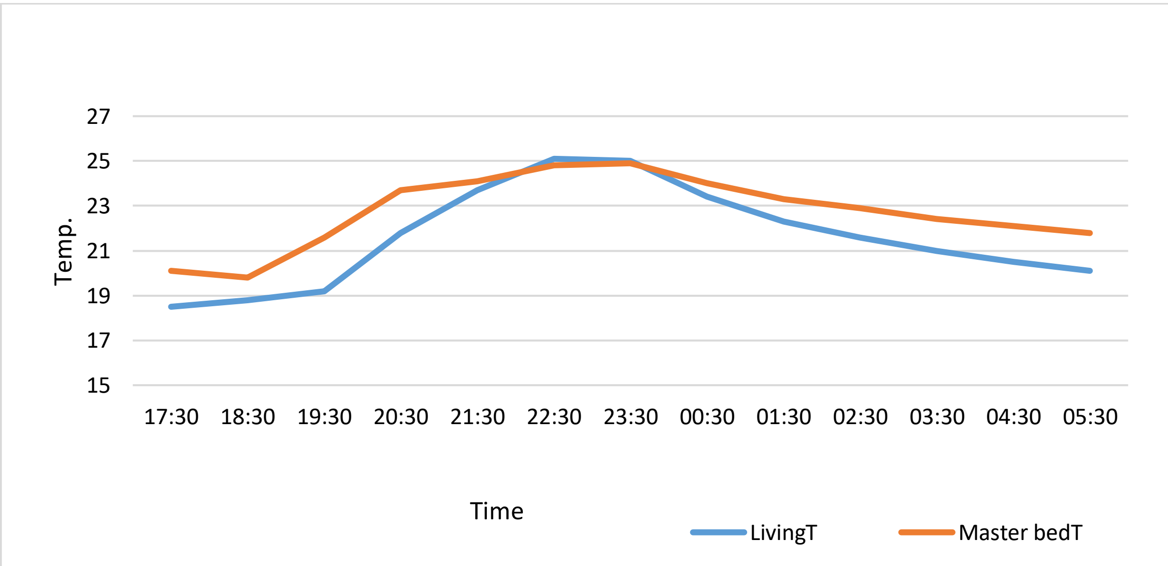

Figure 7.26 Simulated temperature in a bedroom for the base case, and two advisory solutions

7.5. Summary

Some of the important findings from the study are as follows:

One of the major findings is that advice arising from the simulations can be effectively utilised in measured onsite scenarios. That is, the above findings can be successfully applied in predicting scenarios in other buildings in other locations that are borne out by experience:

- The RH and CO_2 can be reduced in real scenarios when the vents, doors and windows are opened, as appropriate, for the living and kitchen areas.
- The opening of the mechanical extract and operation of the central system successfully dissipates the high post-shower RH from the en suite, especially when the local doors are kept open afterwards.
- The excess CO_2 in the living room, accumulated during high occupancy over an extended period of time, can be reduced by opening the vent system to 100%. It can further be improved if the door towards the hallway is opened, as it helps diffuse some excess CO_2 to the hallway area, which can, thereby, be dissipated further with the help of an extra extract fan in that area.
- The higher CO_2 from high and continuous occupancy in the master bedroom can successfully be reduced by keeping the vents open.
- Setting the heating setpoints higher and scheduling the system to be on for the entire day/night will overheat the house and waste energy.
- Setting the setpoint lower at 20–22^{o}C will be helpful in reducing the overall temperature in the house.
- One of the optimum ways to maintain a reasonable temperature in the living area or master bedroom is to keep the setpoints for only one or two periods in a day, for example, for two hours in morning and in the evening, and keeping the door closed to retain the heat inside and keep the room warmer. Many people do this automatically to conserve energy and the simulation showed the sensitivity to this strategy.

It is important to note that the set of houses, as tested in the hypotheses, are similar to the houses to be considered for developing, predicting and testing the proposed model. The main point of difference was that the model-tested houses had five house zones, while the hypothesis- tested houses have four main zones since the living area and kitchen were one with no wall separating them. It is important to note that this difference entails certain pros and cons, with respect to the IAQ in the building, thus:

- Advantages of combined kitchen and living area-
    - The heating in the kitchen (from cooking activity as well as solar gain from the kitchen window) can be utilised for warming up the living area, and, thereby, the heating system can be set up at a lower temperature or switched off for whole or some part of the day at certain times of the year. It will also save on the energy consumption and costs for the house.
    - The higher CO_2 level in the living area due to higher occupancy will be better distributed due to a larger room area. Moreover, the vent in the kitchen will be helpful in dissipating the excessive CO_2 levels from the living area.
- Disadvantages of a combined kitchen and living area-
    - Higher RH levels in the kitchen due to poor ventilation would potentially lead to condensation and mould formation in the living area.
    - Since the living area is mostly used by the occupants during evenings and mornings, and at weekends and get-togethers, it is likely to have higher incidence of CO_2, which will also be accumulated in the kitchen area, and require better management of different aspects of IAQ in this zone.

7.6. Overall Summary

In conclusion, it is found that the proposed model is successfully calibrated with the help of measured on-site data and tested on another set of 12 similar houses in a separate location. However, it is crucial to note that these houses share similar design characteristics and are in same vicinity, and thus, it is likely to experience similar climate conditions. It has been shown in this chapter that through a study of the data and through simulation of scenarios, if operated properly, with some additional vent extracts and adherence to good advice, it has been successfully predicted that these houses can be lived in with healthy IAQ. However, without that advice and adherence to that advice, the nature of A-rated houses currently is such that there will be cases where the IAQ is less than optimal and unhealthy in extreme cases.

Finally, the model provides good scope for future research, and the model can further be tested and utilised in different kinds of buildings, areas and locations, and may be generalised for improving the overall IAQ in the building sector.

8. Conclusions and Recommendations

Given the existing drivers for reducing energy and increasing airtightness, there are emerging issues such as inadequate ventilation and poor indoor air quality. Poor indoor air quality has an effect not only on human well-being but also on the efficiency and physical and mental welfare of the occupants. Moreover, in a SARS-CoV-2 pandemic situation, these types of sealed buildings in which indoor space is shared pose a major infection risk (Qian et al. 2021). Recent findings support the hypothesis that air pollution can increase susceptibility to SARS-CoV-2 infection (Filippini et al., 2020). Therefore, the COVID-19 pandemic emphasises the need to prioritize design strategies to improve IAQ in modern energy-efficient buildings with proper guidance for occupiers on optimising that IAQ. This research has identified a number of problems and issues, and this is evidenced both from the data and also the feedback from occupants. These included high CO_2 levels in certain zones, closing vents due to draughts, turning off the ventilation system completely, overheating in the Summer, mould growth, etc.

Following an in-depth review of IAQ and energy efficient houses, it is realised that there is a need for proper ventilation regimes and occupier guidelines to explain the need for the provision of proper ventilation as controlled by the occupants over time. Excessive ventilation regimes can lead to sub-standard thermal efficiency, while ineffective ventilation can lead to persistent condensation, mould growth and poor IAQ. Moreover, since this review provides documentary evidence that airtight buildings can be associated with many respiratory diseases, it calls for changes in design and creating awareness in occupiers for maintaining good IAQ along with energy efficiency. It is also evident from the literature review that occupants' behaviour greatly contributes to the building's energy consumption and the IAQ (Chapter 2).

Occupant’s behaviour is very unpredictable and different people react differently to the same indoor environment. In order to conduct an in-depth study, it was important to develop a methodology to assess the gathered indoor data of energy efficient houses. A large set of valuable measured data over all seasons was gathered from

57 A-rated family homes in Ireland by using remote and wireless LoRaWAN sensors (Chapter 3).

In the first set of gathered data, from 44 houses at Location 1, the overall effects of different variables (orientations, house types, occupancy, seasons, house zones and different times of the day etc.) on all three internal parameters (temperature, humidity and CO_2) were analysed (Chapter 4). For example, the temperature is mostly affected by heating and the orientation; however, the temperature effect was uneven across different zones of the house, as signified by the orientation of the particular room or zone. Humidity and CO_2 are not directly affected by house type or orientation but are indirectly so. To investigate further, the impacts of different family and occupant behaviours on the indoor air quality of these selected houses were studied in detail. Although the houses under study were fundamentally similar in construction, there were many factors that influenced their IAQ. Results suggest that mean CO_2 levels were, surprisingly, less dependent on the overall occupancy in the house, but depended strongly on occupants' ventilation behaviour and preferences. The impact of ventilation on indoor CO_2 levels was most evident in the Winter months due to lesser window opening events. High CO_2 and RH levels were found in both of the bedrooms often due to blocked ventilation slots, thus leading to a reduced number of air changes. (Chapter 5).

Thus, to mitigate this problem, it has been shown through simulations that opening the adjoining door between the en suite and master bedroom will help dissipate the higher RH and CO_2 levels faster. Also, when the door between the master bedroom and landing is opened, the excess RH/CO_2 levels dissipate to the landing area, which can be removed by installing an extra extract fan in the landing. Dissipation of moisture from the en suite into the master bedroom was identified as problematic on a number of occasions, causing a measurable increase in RH in the master bedroom. It was more severe when the en suite door was left open during showering.

Therefore, it is recommended to keep the door closed during showers, but to open both en suite and bedroom door after taking a shower so that moisture build-up in the en suite can be removed at a faster rate. Both the DCV and open en suite and master bedroom doors are found helpful in reducing humidity faster. It will increase the humidity of the master bedroom, but only to some extent (<5%), which is not normally sufficient to develop any mould growth (Chapter 6).

Whilst it may be a reasonable expectation that a house with a continually running ventilation system with open trickle vents can deliver sufficient air change rates - and the performance data suggests that this results in compliant internal environmental conditions – a significant question remains as to what conditions occur when occupants tend to interfere with the system as designed. Indeed, the feedback from occupants indicated several instances where trickle vents were sealed. However, it was predictable behaviour, for example, that vents were turned off in Winter to prevent cold draughts or that mechanical ventilation filters were not being cleaned regularly.

A summary of key findings of this research project, the contribution to knowledge which meet the objectives outlined in Chapter 1, and the future research possibilities and recommendations are outlined in the subsequent sections that conclude this thesis.

8.1. Key Findings

The key findings signify the impact of different independent variables (occupancy, advice, orientations, and house types) on each of the three dependent variables (temperature, CO_2 and RH) for different seasons and house zones.

- During all four seasons, the temperature is strongly affected by the orientation of the buildings, which can be due to the solar gains. However, it is observed that the temperature effect is uneven across different zones of the house, as determined by the orientation of the particular room or zone. Thus, the difference between rooms is often due to the fact that some rooms become warmer than others due to greater solar gain, while some take more time to warm (due to lesser or no solar gain). South oriented rooms have temperature nearly 2°C higher on sunny days without heating and kept these areas warmer for a longer period. The kitchen and master bedroom exhibit a higher temperature as compared to the other zones in South oriented houses because they are in the front side of the house, and attract high solar gain. The kitchen temperature is also impacted by the cooking activities and the living space by mechanical heating, which called for further investigation about temperature differences depending on the time of the day.

- It is also important to note that the highest impact of CO_2 was observed in the master and second bedrooms, implying that the ventilation was most ineffectively used in those areas compounded by high occupancy.
- Occupancy is an important factor for CO_2 levels, since a greater number of occupants implies a higher emissions of CO_2. But this was not always the case because there were a few examples of houses with a similar number of occupants, but quite different CO_2 conditions. Moreover, while regressing the variables, occupancy did not evolve as the most important variable, which called for further investigation to understand the implication of occupancy on CO_2 levels. Because different families were following different ventilation regimes this impacted their CO_2 levels and had an even greater effect than occupancy as a whole.
- Humidity and CO_2 were not strongly affected by house type or orientation, but were indirectly affected due to changes in indoor temperature with subsequent ventilation.

To further assess the IAQ in detail, the impacts of different family and occupant behaviours on the indoor environmental quality were analysed.

- The consequences of delivering professional advice to selected occupiers were examined on a set of informed and placebo houses. It was found that the IAQ factors showed significant improvement following adherence to that advice. Once again, some contrasting findings were made, wherein the post-advice improvements in the IAQ factors were either small, negligible, or not long lasting. Only 50% of the houses took the advice given and changed their behaviour and that too was not sustained for a longer period. Most occupiers changed their behaviour back after 2.5 to 3 months.

- The CO_2 levels (one of the IAQ factors) for closed door versus open door (one of the suggestions for improvement given) were assessed. It was concluded that when the door of the second bedroom was left slightly open, the CO_2 levels were measurably lower as compared to when the door was closed during sleeping hours. This, therefore, showed that the advice provided to the occupants of the houses was effective and of significant benefit to the occupants, albeit unseen, however, where they failed to follow or sustain that advice, no longer term improvements in the IAQ factors resulted.
- Another important finding of the study is that when the houses kept the door between the en suite and master bedroom partially open during sleeping, the accumulation of CO_2 (one of the IAQ factors) was reduced measurably, because the excess CO_2 was removed by the mechanical extract in the en suite. This feature is of some importance and helped to significantly lower the CO_2 levels in a double occupancy master bedroom, to levels lower than a single occupancy second bedroom.
- It is found that different zones of the house, due to their design, are suffering from poor IAQ. For instance, the second bedroom, when being on the North side of the house, was not able to benefit from any solar gain. It also suffered from very high CO_2 levels when vents were blocked, and doors were kept closed at night. However, by making slight changes to the design, such as installing an extra extract in the landing area and inserting a vent grill above the door of the second bedroom, such houses could experience much reduced CO_2 and humidity levels in the second bedroom.

To substantiate these findings, a 3D thermal/humidity model was prepared in IES-VE after calibrating the IAQ data for one typical family house. A number of important findings and observations were made after analysing the simulation results from these houses, which may be stated as follows:

- That the CO_2 levels in the second bedroom is generally higher than the master bedroom and is highest in early morning after being accumulated from sleeping at night because there is a continuous extract fan running in the adjoining ensuite to the master bedroom.

- The high accumulated of CO_2 levels in the two bedrooms can be relieved by opening the internal doors when leaving the rooms.
- By installing grills in the bedroom doors or keeping the internal door slightly open while sleeping at night (notwithstanding the fire consequences), accumulation of excessive CO_2 in the rooms can be avoided. By doing this, the CO_2 from the master bedroom will be dissipated to the landing area, which can further be removed by installing an extract fan in that area. This extract fan can be left operational throughout the day.
- The bedroom Trickle vents should be left open throughout the night so that CO_2 is not accumulated. However, if by doing so, the occupants experience a cold breeze/draught, they should leave the trickle vent open in the morning at the time of leaving the room. This will dissipate the overnight accumulated of CO_2 within a few hours, but will do nothing to reduce the overnight accumulations.
- The central mechanical ventilation system and trickle vents in the houses should always be kept on/open, so that the extraction of CO_2 and RH from the bathrooms and en suite lead to proper air exchange within the building.
- The houses must also use their heating systems efficiently, such that on the days when the solar gain is high, the houses can completely switch off the internal heating systems during the daytime so that the heat from solar gain can be trapped for efficient utilisation without overheating. They can open their internal doors rather than windows to further utilise this trapped heat from the sun.
- The relative humidity tends to be much higher in the en suite after taking a shower (despite having a powerful extraction system installed), which has the potential to cause high moisture, condensation, and mould formation issues. Thus, to mitigate this problem, it has been shown through simulations that opening the adjoining door between the en suite and master bedroom will help dissipate the higher CO_2 levels faster. Also, when the door between the master bedroom and landing is opened, the excess CO_2 levels dissipate to the landing area, which can be removed by installing an extra extract fan in the landing. The building contractor responsible for the houses in Locations 1 and 2 has adopted this design changes in over 1000 new houses planned for 2023.

- Higher occupancy causes the RH and CO_2 levels in any house zone to significantly increase. Such high CO_2 and RH levels continue to remain in that zone even after the occupants vacate the zone unless doors are opened to ventilate spaces.

One of the major findings is that advice from the simulations can be effectively utilised in predicting future performance, as evidenced here by measured onsite scenarios in Location 2. That is, the above findings can be successfully applied in other buildings in other locations with similar construction and ventilation types. Some of the important findings from this aspect of the study are as follows:

- The RH and CO_2 can be reduced in real scenarios when the vents, doors and windows are opened, as appropriate and as designed, for the living and kitchen areas.
- The opening of the mechanical extract and central system helps to dissipate the high post-shower RH from the en suite.
- The excess CO_2 in the living room, accumulated during high occupancy over an extended period of time, can be reduced by opening the vent system to 100%. It can further be improved if the door towards the hallway is opened - it helps diffuse excess CO_2 to the hallway area, which can thereby, be dissipated with the help of an extra extract fan in that area.
- The higher CO_2 from high and continuous occupancy in the master bedroom can be reduced by keeping the vents open.
- Setting the heating setpoints higher and scheduling the system to be on for the entire day/night will overheat the house.
- By setting the setpoint lower, say at 20–22°C, will be helpful in reducing the overall temperature in the master bedroom.
- One of the optimum ways to maintain a reasonable temperature in the living area or master bedroom is to keep the setpoints on for only one or two periods in a day, for example for two hours in morning and in the evening, and keep the door closed to retain the heat inside and keep the room warmer. Many people do this automatically to conserve energy and the simulation showed the sensitivity to this strategy.

As a deliverable from this research, using the conclusions listed above, a user guideline for occupiers of A-rated home was developed by the AMBER team and is reproduced here in Appendix K. A similar guide for designers was also produced and is reproduced in Appendix L.

8.2. Contribution to knowledge

The aim of this research was to investigate IAQ of A-rated houses in Ireland. This thesis has addressed the following core objectives outlined in the introduction to this thesis.

1) To study IAQ of energy efficient homes

Three different parameters of IAQ (temperature, relative humidity and carbon dioxide emissions) were examined to observe the indoor air quality patterns in 57 A-rated residential buildings during all 4 seasons. Multi linear regression was used to assess the impact of design-related factors such as house orientation, house zone, type of house, occupancy and season on the different aspects of indoor air quality.

2) To understand occupant's behaviour in energy efficient homes and IAQ advice

To understand the impact of occupants' behaviour on indoor air quality parameters in residential dwellings, patterns of usage were established for each home through interpretation of the gathered data and feedback sessions from occupants. It was determined whether or not the houses can be operated in a way to ensure adequate IAQ throughout the year whilst maintaining perceived adequate comfort levels. Behavioural patterns were analysed in detail using different tools such as TIBCO, iScan, and Excel. Some advice was given to each and every house after 6 months of data analysis, to allow the identification of where occupant actions have likely improved or reduced IAQ levels compared to baseline unchanged cases. The consequences of these actions on maintaining perceived comfort levels were also examined.

3) To model family behaviour and provide recommendations for a better IAQ

A model was created in IESVE software based on a family usage/behaviour and recommendations were provided based on different simulated results covering most of the IAQ problems faced by different families in Location 1. A set of occupier guidelines (Appendix K) were developed for the promotion of more efficient operation of these houses to optimise both energy usage and occupant comfort. A set of guidelines for designers (Appendix L) was also developed to improve the predictability of outcomes compared to actual IAQ performance.

8.3. Recommendations and Future Work

The research has fulfilled the objectives outlined in Chapter 1, but the need for future research has become apparent. Future work could be carried out in the following areas:

1) It has been shown in this research that through the installation of grills in bedroom doors, the accumulation of CO_2 in these rooms can be avoided. By doing this, the CO_2 from the bedrooms can be dissipated to the landing area, which can further be removed by installing an additional extract fan in that area. But this can raise fire issues and to deal with this limitation, a smoke detector in each bedroom and closable grill should be installed. The acceptability and success of this intervention should be explored in practice.

2) Excess CO_2 and RH are the main issues which have been observed during this study. Although this research project has provided solutions to most of these IAQ issues in future home designs, it is recommended that a dashboards/IAQ detector is installed in all rooms as this is likely to become the norm in future. This technique had proven to be very effective in schools, as was observed during the execution of the commercial part of the AMBER project. If occupants can see a colour variation in their IAQ screens based on the environmental conditions, there is a high chance that an occupant will

take definitive action to improve the heating/ventilation in that zone. At present changes in RH and CO_2 largely occur unperceived by the occupant.

3) This study was limited to similar houses in one locality, and it should be extended to other type of housing and locations. For example, multi-storeyed residential apartments will have some variations in the data and behaviour patterns.

4) This research study mainly focussed on three IAQ parameters (T, RH and CO_2). It can further be extended to study other IEQ parameters like particulates in the air, lighting, thermal comfort, aural comfort and visual comfort. There is also a possibility to examine chemical and biological pollution inside buildings. These additional parameters could further improve the indoor environment to provide enhanced overall holistic guidelines for domestic living in the future.

5) This research has not focussed on the energy aspects of such A-rated houses, though the AMBER projects undertook considerable research in this area, as have many other researchers. It would be beneficial to combine energy and IEQ research aspects together, which can be greatly beneficial for occupants as well as the overall environment.

6) There is a lot of rich data gathered during this research, whereby this same data can be used for further statistical and sensitivity analysis for future researchers and further findings can be drawn.

8.4. Personal Reflection

This following part aims at describing the personal thoughts and critical observations that emerged during this research. The composition of the research framework and mind map had thoroughly been developed in connection with the research objectives.

Many scientific articles, relevant literature and previous research on topic had been systematically read and analysed in order to gain an understanding of the research phenomena. The chosen studies contributed to a thorough analysis and deeper understanding of indoor parameters, occupants' behaviours and living environment in energy efficient airtight houses. Undertaking the literature review helped answer some questions, posed new questions and the project a starting direction. In the first year of study, the author became accustomed to how a PhD research project should be approached. The second year was when the 'real' physical work actually began while trying to maintain a reasonable work-life balance. This was a period of exploration and experimentation, trying out different ways of approaching the data gathering tasks, gaining a better understanding of instrumentation and data gathering by doing the pilot study on 5 houses and by interacting with the homeowners.

Reflecting on the experiences of conducting this thesis, it is realized that every PhD student has their own personal journey. Concerning the whole process of the dissertation, it should be noted that it all was challenging, intriguing and exciting. Generally, the author gleaned much about the energy efficient or sustainable housing sector and its operation giving rise to hugely varying indoor conditions in these houses. This specific subject is an ongoing challenge for today's designers in the light of unpredictable human behaviour.

Through this research, the author interacted with like-minded researchers, policymakers, and practitioners who were interested in similar outcomes. This process was valuable to connect with many who can now be considered as colleagues, mentors, advisors, and friends. Most of the information that the author accumulated on the topic was of great value and aligned with the current state-of-the-art knowledge on low energy buildings and occupant's behaviour. The interaction sessions with the homeowners revealed different problems faced by occupants in highly efficient buildings. The discussions in the form of personal meetings allowed insights into the perspectives of the different people to be gained, approaching the problem from their perspective. The communication with the homeowners provided certain information that would have been hard acquire from merely examining the respective scientific articles and literature, or indeed from the data gathered, as it is taken from direct experience. It helped in analysing the millions of items of data gathered from these houses. The interpretation of that data combined with the information gained from the residents resulted in very informative and useful insights.

This research involved installing over 285 sensors in 57 houses to gather 5 min interval data for between 12 to 18 months. Data was retrieved from wireless sensors in an unobstructive way using a cloud platform and this data was processed using emerging software tools.

The most demanding and time-consuming requirement of the study was that of analysing the data. The challenge was to choose which data was most relevant and represnetative, and to compile and present it in a way that was both interesting and meaningful, to facilitate systematic analysis and conclusions. The data analysis process, undertaken in many different ways, using various tools, enable reflection on observations in different ways, allowing more confident interpretation of events and behaviours as they were understood to be. It would have been helpful if one could have lived in one of those properties for a short period, installing further sensors at different locations to test the interpretations and verify the postulated results. As one of the limitations of this study was not to disturb the residents during this entire process, if 48 hours of one or two actual family's behavioural pattern could be recorded by monitoring their routine remotely, this could give some further meaningful insights.

Once the data has been acquired, the analyse and writing up of the entire thesis was a process of learning. Different tools were used to present and analyse this large chunk of data in different ways. The writing also did not always flow well, with only one or two pages to show for several days work on occasions. While reflecting on the experience of writing a thesis, true enjoyment of this process was realised, at least for most of it. On reflection of what was learned that was most valuable, it was truly seeing that persistence pays off.

The conclusion of this dissertation is not generalized universally, as one of the aims is to investigate why occupants in A-rated homes do not behave in a way that is expected. Some of design suggestions have already been taken on board by the design and construction team for another set of houses which is very satisfying. It also provides an opportunity to gather further data from those houses to verify the findings of this work.

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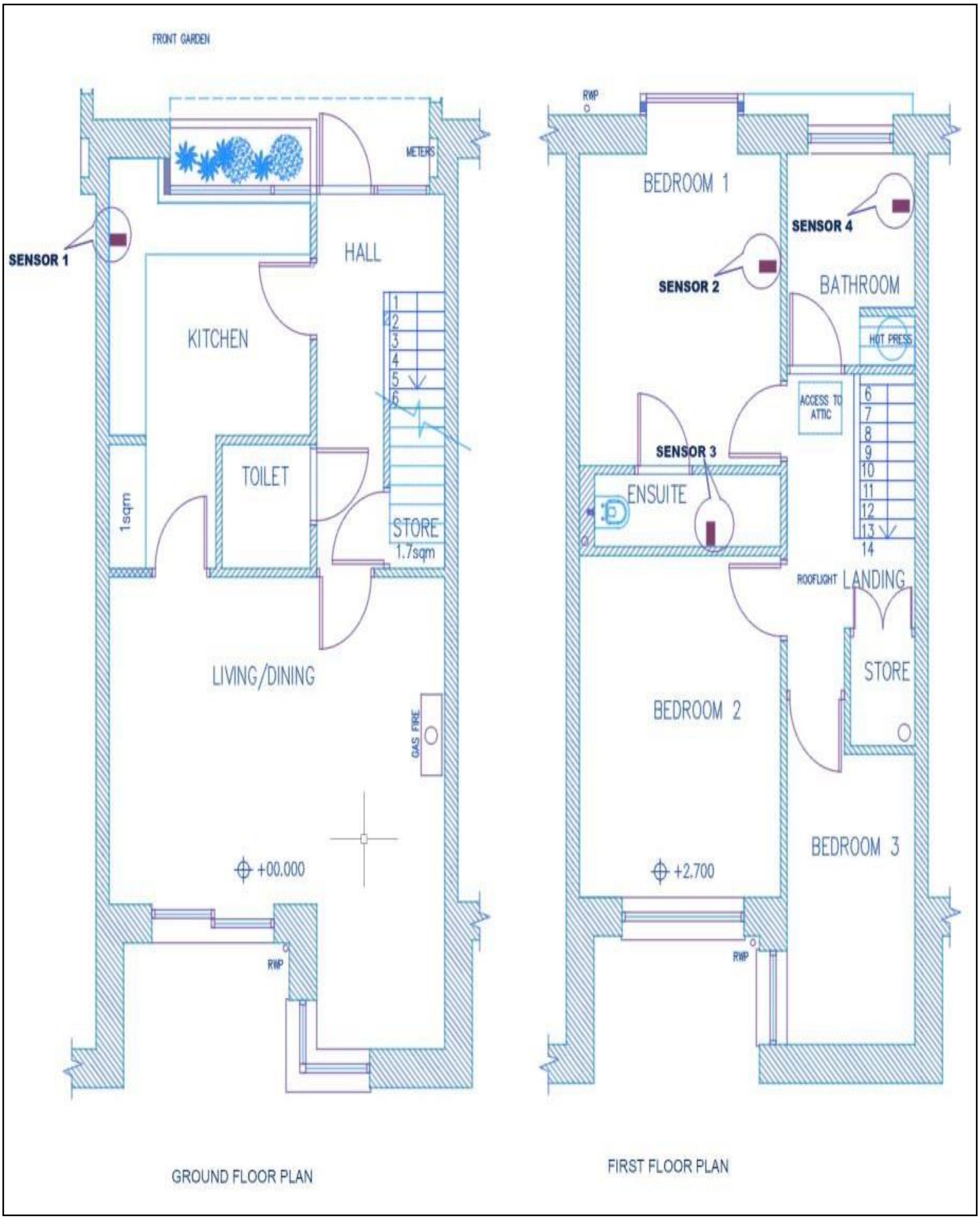
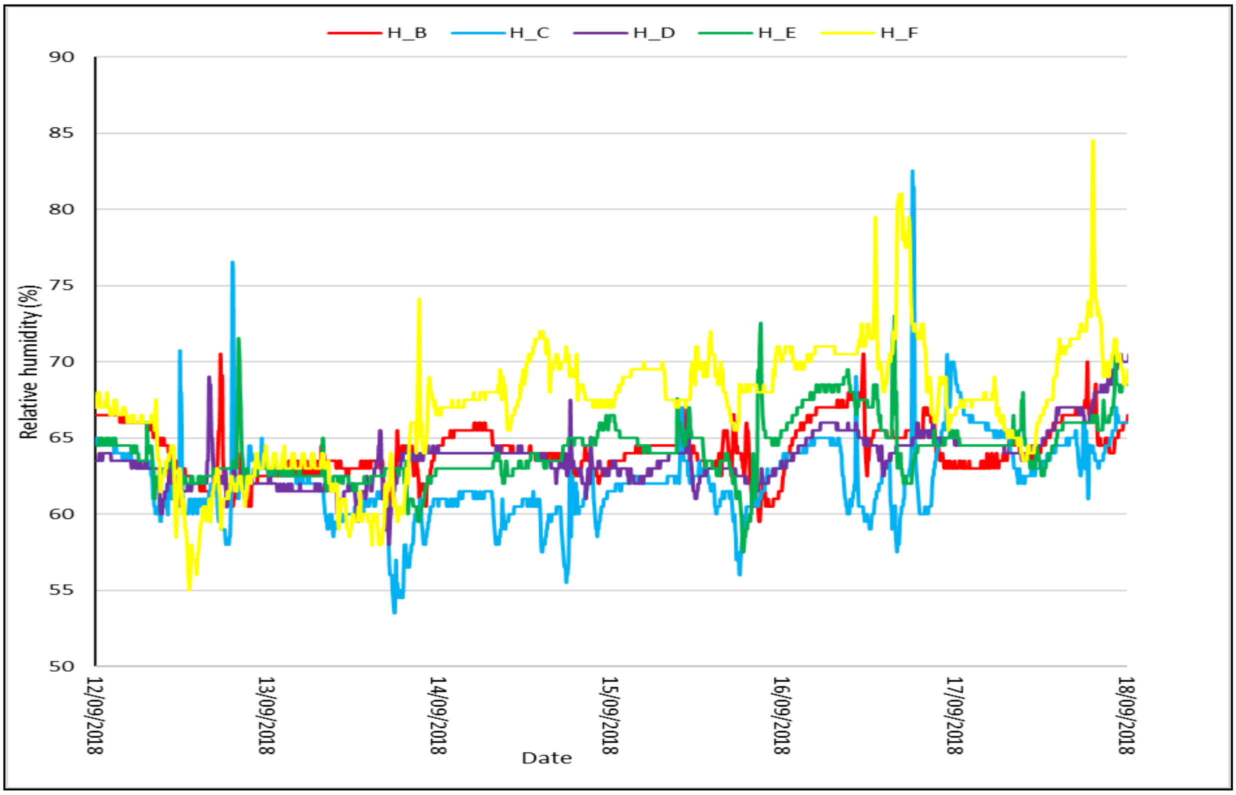
Appendices

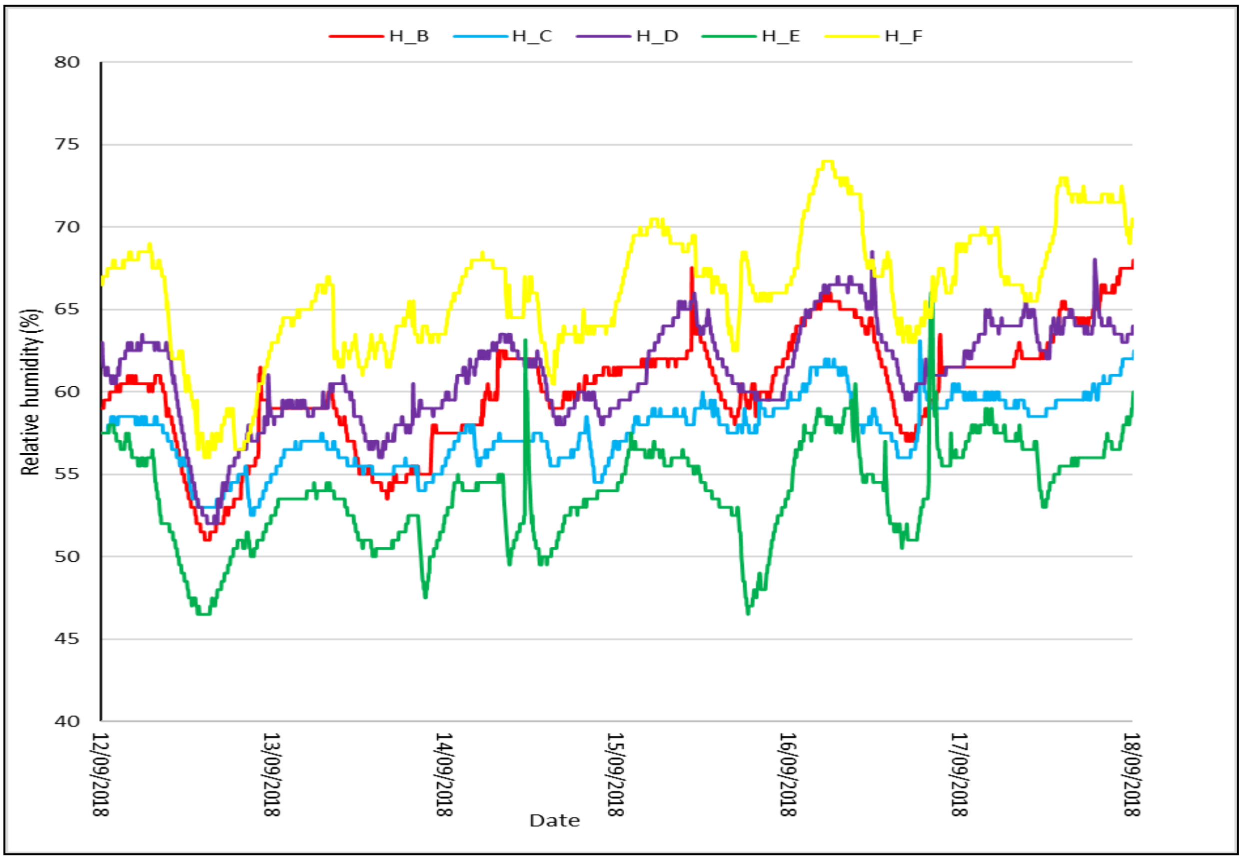
Appendix A –Layout and sensors location of the houses in Pilot Study



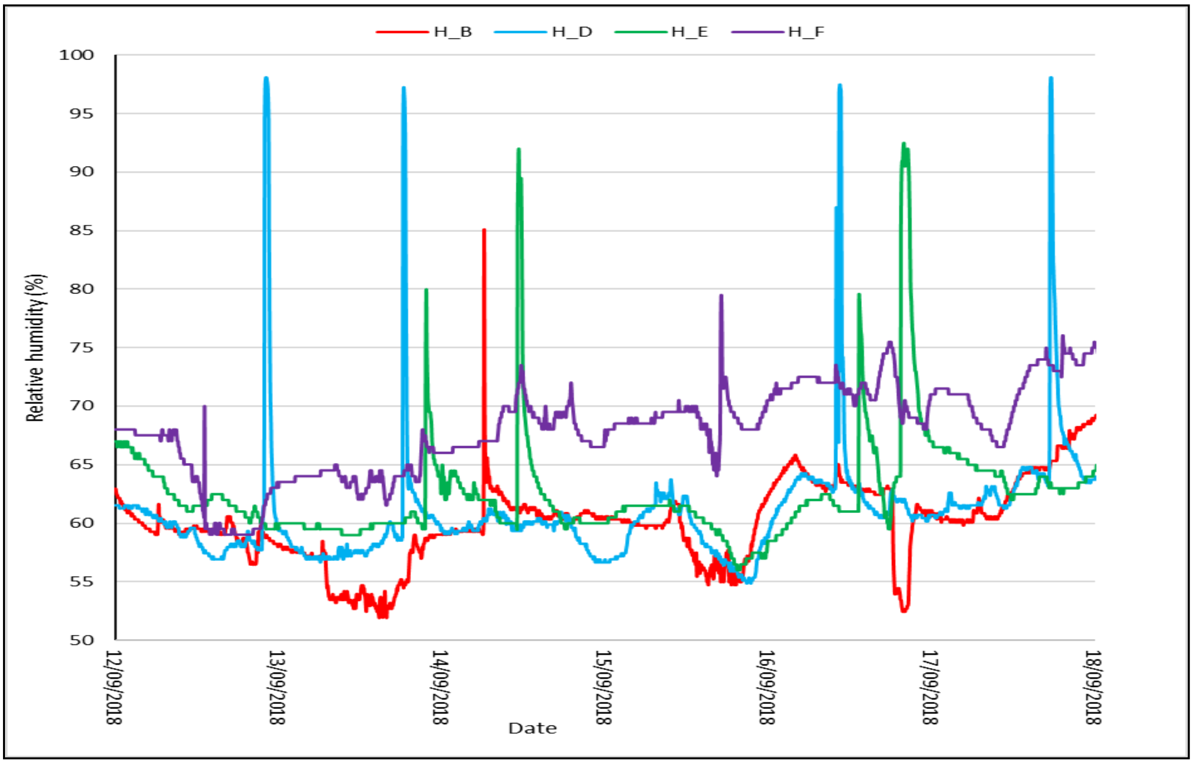
Appendix B –Results from Pilot Study



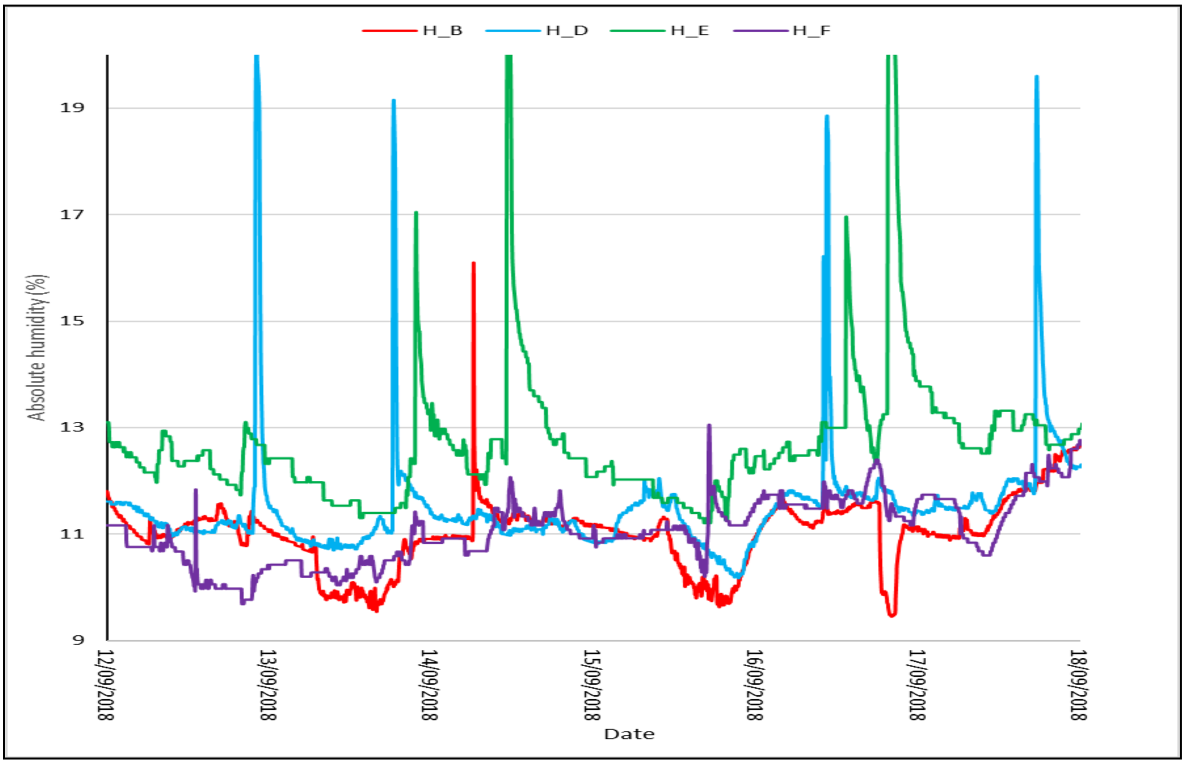
RH trends in kitchens of different family homes in Pilot Study



RH trends in Master bedroom of different family homes in Pilot Study



RH trends in bathroom of different family homes in Pilot Study



Variation of absolute humidity in bathroom in Pilot study

Appendix C –Primary analysis and data table example of one house

Season	House no	H. ref	H.Ref	Orientation	Occupancy	House Type	Working/stay at home	Advice	Area	Month	Month ref.	Mean Temperature	SD	Min Temp	Max Temp	T<18	T>25	Mean RH	SD	Min RH	Max RH	RH>60	RH>80	Mean CO2	SD	Min CO2	Max CO2	CO2>1000 <1500	CO2>1500
Spring	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	Living Room	Apr	a	20.37	1.81	18.20	24.20		0	47.73	2.70	29.00	56.00	0		664.00	224.00	315.00	2506.00	7.6	0.87
Summer	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	Living Room	May	b	20.47	0.59	18.90	22.80		0	49.33	4.05	35.00	68.00	0.9		630.00	199.00	322.00	2307.00	3.6	0.35
Summer	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	Living Room	Jun	c	21.98	0.81	20.30	24.50		0	51.67	4.25	39.00	65.00	0.27		710.00	244.00	212.00	1758.00	16.68	0.02
Summer	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	Living Room	Jul	d	23.79	0.68	21.90	26.00		4	52.34	3.95	41.00	65.00	0.47		618.00	173.00	356.00	1758.00	3.2	0.08
Autumn	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	Living Room	Aug	e	23.07	0.89	20.00	26.70		2.56	55.42	3.98	41.00	67.00	12.92		668.00	219.00	399.00	2201.00	7.43	0.39
Autumn	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	Living Room	Sept	f	21.92	0.84	20.40	25.50		0.66	51.70	3.06	36.00	60.00	0		658.00	214.00	397.00	1568.00	7.94	0.1
Spring	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	Kitchen	Apr	a	21.32	1.94	19	28.4		1.86	45.7	3.3	33	75	0.9		702.4	221.5	375	2887	7.7	1.38
Summer	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	Kitchen	May	b	21.7	0.8	20.1	27.5		0.44	47.05	4.4	34	77	0.4		658	195.85	375	3202	2.82	0.53
Summer	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	Kitchen	Jun	c	22.97	1.1	22	29		5.3	49.97	8.5	38	77	0.3		749	272	370	2431	17	0.31
Summer	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	Kitchen	Jul	d	24.9	1.02	21.3	29.9		40.5	49.8	4.39	36	79	0.38		565	174	358	2534	2	0.5
Autumn	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	Kitchen	Aug	e	24.08	0.74	22.1	28.7		8.9	52.7	3.9	42	74	3.12		605	178	382	2249	1.84	0.61
Autumn	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	Kitchen	Sept	f	22.8	0.7	20.8	29.4		1.03	49.6	3.6	37	83	0.74		594	198	386	2842	2.08	1.1
Spring	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	Master Bed	Apr	a	20.8	1.9	18.7	26.4		1.9	50.4	4.2	37	61	0.02		1020	315	396	2186	19	13.8
Summer	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	Master Bed	May	b	21.4	1.19	19.2	26.9		0.9	49.49	5.3	30	68	1.27		914	346	385	2574	34	3.7
Summer	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	Master Bed	Jun	c	22.4	1.2	20	26.3		3.46	52.1	3.9	39	64	0.15		883	348	274	2105	30.8	5.56
Summer	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	Master Bed	Jul	d	24	1	22.3	28.2		17.11	51.3	4.48	37	73	2.62		507	211	250	2051	1.27	0.77
Autumn	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	Master Bed	Aug	e	23.3	1.11	20.9	27.8		7.2	54.5	4.3	42	69	8.6		647	238	304	1843	6.4	1.37
Autumn	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	Master Bed	Sept	f	21.5	1.04	19.9	26.3		1.65	52	4.43	37	77	3.1		659.7	213	392	1987	4.2	0.94
Spring	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	econd Bedroom	Apr	a	21.07	1.14	19.9	24.2		0	49.7	2.22	42	56	0		1429	317	708	2931	64.7	25
Summer	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	econd Bedroom	May	b	20.8	0.76	18.9	23.7		0	50.19	3.55	40	59	0		938	380	426	2904	35.8	3.55
Summer	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	econd Bedroom	Jun	c	22.22	0.93	20.7	25.6		0.5	53.27	4.8	43	64	6.66		904	313	376	2529	32.66	2.98
Summer	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	econd Bedroom	Jul	d	23.9	0.71	21.8	25.8		6.1	52.08	3.8	44	60	0		606	154	329	1248	2.82	0
Autumn	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	econd Bedroom	Aug	e	22.9	0.83	20.7	25.3		0.3	55.4	3.87	48	66	12.7		630	172	398	1989	3.3	0.2
Autumn	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	econd Bedroom	Sept	f	21.2	0.52	20	23.2		0	52.77	3.02	45	62	0.59		608	180	367	1975	1.55	0.99
Spring	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	En-suite	Apr	a	21.6	1.2	20.1	25.5		0.27	49.9	3.3	41	88	0.91	0.1						
Summer	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	En-suite	May	b	21.12	0.8	19.6	23.7		0	51.1	4.86	40	87	2.11	0.62						
Summer	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	En-suite	Jun	c	22.1	1	20.2	25.1		0.05	54.47	3.61	44	86	2.9	0.09						
Summer	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	En-suite	Jul	d	23.9	0.5	22.5	26.8		3.68	53.89	4.86	45	88	6.28	0.24						
Autumn	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	En-suite	Aug	e	23.1	0.7	21.3	25.5		0.7	56.9	4.57	48	86	18.83	0.3						
Autumn	18	A1	A1-SW3E5	SW	5	End Terrace	NW	Change	En-suite	Sept	f	21.5	0.6	20.2	25		0	55.1	5	46	91	8.4	0.62						

Appendix D -Typical Blower Test Result

atbec ltd
air tightness & building energy consultants ltd

Details of Test

Building tested:		Nett Floor Area, A_F:	50.5 m²
		Envelope Area, A_E:	347.0 m²
On behalf of:		Env. Calc Prepared by:	
Test Date:	24th July 2018	Env. Calc Verified by:	
Certificate Date:	24th July 2018	Certificate no	17-04-2966 U40 T1

Test Conditions and Temporary Sealing at the Time of Test

	Response
All external doors and windows closed	Yes
All internal doors open	Yes
All extracts sealed (inc. kitchen and bathroom(s) extracts and the oven hood)	Yes
Temporary seals to drains, plugs, or overflows	No
Combustion appliances turned off (if inside the conditioned space of the dwelling. Temporary seal air supply / flue.	Yes
Trickle vents temporary sealed	No
Fireplace temporary sealed.	No
All building works completed to the air boundary envelope:-	Yes

Deviation(s) from ATTMA TSL1

None.

Test Result and Performance Characteristics

This is to certify that the above named building has been tested for air permeability in accordance with ATTMA TSL1 undertaken with the conditions stated above.

The Key Leakage Characteristics of the dwelling are:

Air Permeability Rate, Q_{50}:	**1.98 m³/(hr.m²) @ 50 Pa**
Effective Leakage Area:	343.0cm² @ 50 Pa
Correlation of results, r^2:	0.989
Slope, n:	0.64

Signed: ______________________

atbec ltd, 213 Cushendall Road, Ballymena, BT43 6PP Tel 028 2568 9108 www.atbecltd.com e: info@atbecltd.com

Appendix E - Typical Part L (2008, 2011) Conformity Report

Part L Specification

SUMMARY FOR PART L CONFORMANCE (Applies to TGD L 2008/2011 for new dwellings only)

BER Number		Building Regulations	2011 TGD L
BER Result	A2	Energy Value kWh/m²/yr	49.61
CO2 emissions [kg/m²/yr]	8.96	Total compliance with Part L in DEAP?	Pass
EPC	0.328	EPC Pass/Fail	Pass
CPC	0.287	CPC Pass/Fail	Pass

PART L CONFORMANCE - Fabric

Conformity with Maximum avg U-value requirements	U-value [W/m²K]	Pass / Fail	Conformity with Maximum U-value requirements	U-Value [W/m²K]	Pass / Fail
Pitched roof insulated on ceiling	0.11	Pass	Roofs	0.18	Pass
Pitched roof insulated on slope	0.00	Pass	Walls	0.15	Pass
Flat Roof	0.18	Pass	Floors	0.12	Pass
Floors with no underfloor heat	0.12	Pass	External doors / windows / rooflights	1.50	Pass
Floors with underfloor heat	0.00	Pass			
Walls	0.15	Pass			
Percentage of opening areas [%]	23.0	Pass			
Average U value of openings	1.40				
Permeability test carried out and meets guidelines in TGD L					Complies

PART L CONFORMANCE – Renewables (individual heating system)

Type of renewable	Total contribution [kWh/y]	Part L renewable contribution [kWh/m²/y]
Solar water heating system	0.00	0.00
Heat pump as main space heating system	0.00	0.00
Heat pump as secondary space heating system	0.00	0.00
Heat pump as main water heating system	0.00	0.00
Wood/Biomass heater as main space heating system	0.00	0.00
Wood/Biomass heater as secondary heating system	0.00	0.00
Wood/Biomass heater as main water heating system	0.00	0.00
Contribution from CHP	0.00	0.00
2.43 kWp PV Panels	1805.98	13.58
	0.00	0.00
	0.00	0.00
Total thermal	0.00	0.00
Total electrical	1805.98	13.58
Total thermal equivalent	4514.95	33.95
Does total thermal equivalent meet part L requirement?	Pass	

Appendix F – Descriptive summary of houses at Location 1

(For different seasons and different day times)
Overall - whole day
Morning time – 6am to 10am
Mid-day – 10am to 5pm
Evening – 5pm to 12midnight
Nighttime – 12midnight to 6am

Summary of overall

April 20

	co2 (N = 127514)	humidity (N = 153430)	temparature (N = 144004)
Kitchen			
min	189	23	15.5
max	4009	95	31
mean (sd)	650.07 ± 232.17	48.64 ± 6.51	20.89 ± 1.85
median (iqr)	606.00 (492.00, 742.00)	48.00 (45.00, 51.00)	21.00 (19.50, 22.20)

Summary of overall

April 20

	humidity (N = 115680)	temparature (N = 110450)
Ensuite		
min	33	15
max	96	28.2
mean (sd)	51.96 ± 7.90	20.38 ± 1.85
median (iqr)	51.00 (47.00, 56.00)	20.70 (19.30, 21.70)

Summary of overall

April 20

	co2 (N = 187100)	humidity (N = 187099)	temparature (N = 18709[illegible]
Living room			
min	220	29	14.5
max	4961	82	28.7
mean (sd)	709.63 ± 303.19	51.61 ± 7.12	19.83 ± 1.93
median (iqr)	631.00 (489.00, 836.00)	51.00 (47.00, 55.00)	19.70 (18.30, 21.30)
Master bedroom			
min	137	34	12.8
max	3735	94	30.1
mean (sd)	857.95 ± 437.32	56.05 ± 7.06	19.02 ± 2.22
median (iqr)	754.00 (523.00, 1,079.00)	55.00 (52.00, 60.00)	19.00 (17.20, 20.60)
Second bedroom			
min	44	0	-1002.1
max	4535	86	26.5
mean (sd)	781.19 ± 451.71	54.43 ± 7.05	18.89 ± 3.10
median (iqr)	646.00 (469.00, 938.00)	54.00 (50.00, 58.00)	18.80 (17.40, 20.40)

Summary of Evening time

April 20

	co2 (N = 47232)	humidity (N = 32317)	temparature (N = 42752)
Living room			
min	98	30	16.2
max	3258	83	26.8
mean (sd)	865.92 ± 348.35	49.90 ± 5.33	20.79 ± 1.39
median (iqr)	799.00 (615.00, 1,048.25)	50.00 (47.00, 53.00)	20.80 (20.00, 21.80)

Summary of Midday time

April 20

	co2 (N = 40687)	humidity (N = 30548)	temparature (N = 33927)
Master bedroom			
min	26	30	15.6
max	2731	79	27
mean (sd)	606.86 ± 250.80	49.54 ± 6.69	20.30 ± 1.76
median (iqr)	542.00 (440.00, 704.00)	49.00 (45.00, 53.00)	20.30 (19.10, 21.40)

Summary of Midday time

April 20

	co2 (N = 37215)	humidity (N = 44877)	temparature (N = 42002)
Kitchen			
min	211	23	15.6
max	3269	95	30.7
mean (sd)	666.92 ± 259.10	48.14 ± 7.13	21.07 ± 1.84
median (iqr)	618.00 (500.00, 765.00)	47.00 (44.00, 51.00)	21.20 (19.70, 22.40)

Summary of Midday time

April 20

	humidity (N = 33800)	temparature (N = 32351)
Ensuite		
min	34	15
max	94	26.7
mean (sd)	52.14 ± 8.43	20.26 ± 1.78
median (iqr)	51.00 (47.00, 56.00)	20.50 (19.20, 21.60)

Summary of Midday time

April 20

	co2 (N = 40581)	humidity (N = 38759)	temparature (N = 50452)
Second bedroom			
min	11	32	15.1
max	2539	75	26
mean (sd)	621.27 ± 307.60	48.28 ± 5.93	20.32 ± 1.66
median (iqr)	538.00 (442.00, 690.00)	47.00 (45.00, 50.00)	20.30 (19.10, 21.50)

Summary of Midday time

April 20

	co2 (N = 49784)	humidity (N = 34132)	temparature (N = 45033)
Living room			
min	42	28	16.1
max	2955	80	27.3
mean (sd)	714.01 ± 291.21	48.72 ± 5.70	20.72 ± 1.47
median (iqr)	649.00 (502.00, 861.00)	49.00 (45.00, 52.00)	20.80 (19.70, 21.70)

Summary of Morning time

April 20

	co2 (N = 24223)	humidity (N = 18161)	temparature (N = 20163
Master bedroom			
min	175	34	15.3
max	3306	80	25.4
mean (sd)	890.58 ± 484.83	52.18 ± 7.22	20.14 ± 1.73
median (iqr)	748.00 (545.00, 1,097.00)	51.00 (48.00, 55.00)	20.20 (19.00, 21.30)

Summary of Morning time

April 20

	co2 (N = 22198)	humidity (N = 26724)	temparature (N = 25069)
Kitchen			
min	189	32	15.5
max	2229	80	30.1
mean (sd)	581.75 ± 167.42	48.66 ± 5.95	20.54 ± 1.81
median (iqr)	560.00 (461.00, 664.00)	48.00 (45.00, 51.00)	20.70 (19.10, 21.90)

Summary of Morning time

April 20

	humidity (N = 20085)	temparature (N = 19174)
Ensuite		
min	33	15
max	96	26.3
mean (sd)	52.37 ± 8.59	20.28 ± 1.90
median (iqr)	51.00 (47.00, 56.00)	20.50 (19.20, 21.60)

Summary of Morning time

April 20

	co2 (N = 24180)	humidity (N = 23036)	temparature (N = 30029)
Second bedroom			
min	106	35	14.9
max	2959	75	25.1
mean (sd)	773.02 ± 390.19	49.79 ± 5.82	19.86 ± 1.57
median (iqr)	649.00 (500.00, 909.00)	49.00 (46.00, 52.00)	19.90 (18.70, 21.00)

Summary of Morning time

April 20

	co2 (N = 29678)	humidity (N = 20357)	temparature (N = 26857)
Living room			
min	21	32	16
max	2300	74	25.7
mean (sd)	618.12 ± 214.10	49.43 ± 4.76	20.15 ± 1.41
median (iqr)	576.00 (461.00, 716.00)	49.00 (47.00, 52.00)	20.20 (19.20, 21.00)

Summary of Night time

April 20

	humidity (N = 29727)	temparature (N = 28306)
Ensuite		
min	37	15.1
max	94	25
mean (sd)	51.55 ± 6.81	20.38 ± 1.82
median (iqr)	51.00 (47.00, 55.00)	20.70 (19.30, 21.70)

Summary of Night time

April 20

	co2 (N = 35761)	humidity (N = 34069)	temparature (N = 44253)
Second bedroom			
min	257	35	15
max	2812	75	24.9
mean (sd)	871.41 ± 458.24	49.59 ± 5.47	20.01 ± 1.57
median (iqr)	736.00 (532.00, 1,058.00)	49.00 (46.00, 52.00)	20.00 (18.80, 21.20)

Summary of Night time

April 20

	co2 (N = 35757)	humidity (N = 26777)	temparature (N = 29836
Master bedroom			
min	216	35	15.4
max	3341	78	27.7
mean (sd)	1,096.03 ± 515.97	52.28 ± 6.85	20.32 ± 1.80
median (iqr)	1,102.00 (665.00, 1,345.00)	51.00 (48.00, 55.00)	20.40 (19.10, 21.60)

Summary of Night time

April 20

	co2 (N = 43992)	humidity (N = 30276)	temparature (N = 39927)
Living room			
min	58	34	16.1
max	2438	67	24.2
mean (sd)	606.06 ± 201.92	49.63 ± 4.58	20.09 ± 1.30
median (iqr)	560.00 (469.00, 684.00)	49.00 (47.00, 52.00)	20.10 (19.30, 21.00)

Summary of Night time

April 20

	co2 (N = 32755)	humidity (N = 39306)	temparature (N = 37002)
Kitchen			
min	236	36	15.6
max	1735	91	26
mean (sd)	569.10 ± 141.76	48.90 ± 5.80	20.50 ± 1.71
median (iqr)	546.00 (466.00, 641.00)	48.00 (45.00, 51.00)	20.60 (19.20, 21.80)

Summary of overall

January 20

	co2 (N = 187100)	humidity (N = 187099)	temparature (N = 18709[illegible]
Living room			
min	220	29	14.5
max	4961	82	28.7
mean (sd)	709.63 ± 303.19	51.61 ± 7.12	19.83 ± 1.93
median (iqr)	631.00 (489.00, 836.00)	51.00 (47.00, 55.00)	19.70 (18.30, 21.30)
Master bedroom			
min	137	34	12.8
max	3735	94	30.1
mean (sd)	857.95 ± 437.32	56.05 ± 7.06	19.02 ± 2.22
median (iqr)	754.00 (523.00, 1,079.00)	55.00 (52.00, 60.00)	19.00 (17.20, 20.60)
Second bedroom			
min	44	0	-1002.1
max	4535	86	26.5
mean (sd)	781.19 ± 451.71	54.43 ± 7.05	18.89 ± 3.10
median (iqr)	646.00 (469.00, 938.00)	54.00 (50.00, 58.00)	18.80 (17.40, 20.40)

Summary of overall

January 20

	humidity (N = 244454)	temparature (N = 238582)
Ensuite		
min	32	12.9
max	99	28.9
mean (sd)	56.88 ± 9.86	19.40 ± 2.47
median (iqr)	56.00 (50.00, 62.00)	19.40 (17.30, 21.40)

Summary of overall

January 20

	co2 (N = 247402)	humidity (N = 247402)	temparature (N = 247400)
Kitchen			
min	123	28	14.2
max	5000	97	31.6
mean (sd)	657.83 ± 254.55	51.29 ± 7.18	20.38 ± 2.10
median (iqr)	599.00 (483.00, 759.00)	50.00 (47.00, 55.00)	20.30 (18.80, 22.00)

Summary of Evening time

Jan 20

	co2 (N = 72946)	humidity (N = 72946)	temparature (N = 72944)
Living room			
min	277	30	14.5
max	4961	82	27.2
mean (sd)	868.15 ± 349.32	52.11 ± 7.24	20.36 ± 1.97
median (iqr)	813.00 (624.00, 1,036.00)	51.00 (47.00, 56.00)	20.40 (18.80, 21.90)

Summary of Midday time

January 20

	co2 (N = 71841)	humidity (N = 71841)	temparature (N = 71841)
Living room			
min	247	30	14.5
max	3519	83	28.7
mean (sd)	655.54 ± 269.45	51.71 ± 7.19	19.60 ± 1.91
median (iqr)	588.00 (455.00, 766.00)	51.00 (47.00, 55.00)	19.40 (18.10, 21.00)

	co2 (N = 72797)	humidity (N = 72797)	temparature (N = 72797)
Master bedroom			
min	137	34	12.9
max	3343	94	28.4
mean (sd)	646.94 ± 289.41	55.63 ± 6.96	18.71 ± 2.04
median (iqr)	560.00 (452.00, 760.00)	55.00 (51.00, 60.00)	18.70 (17.00, 20.20)

	co2 (N = 71780)	humidity (N = 71780)	temparature (N = 71780)
Kitchen			
min	183	28	14.2
max	3838	96	31.6
mean (sd)	628.75 ± 242.33	51.37 ± 7.35	20.22 ± 2.08
median (iqr)	575.00 (459.00, 722.00)	50.00 (47.00, 54.00)	20.00 (18.60, 21.70)

	humidity (N = 71099)	temparature (N = 69390)
Ensuite		
min	32	13.1
max	99	28.9
mean (sd)	57.01 ± 10.40	19.11 ± 2.37
median (iqr)	56.00 (49.00, 62.00)	19.10 (17.10, 21.10)

	co2 (N = 74437)	humidity (N = 74437)	temparature (N = 74437)
Second bedroom			
min	45	36	12
max	4588	85	25.3
mean (sd)	613.36 ± 277.35	54.26 ± 6.87	18.66 ± 1.89
median (iqr)	536.00 (439.00, 710.00)	54.00 (50.00, 58.00)	18.60 (17.20, 20.10)

Summary of Morning time

Jan 20

	co2 (N = 41276)	humidity (N = 41276)	temparature (N = 41276)
Master bedroom			
min	174	36	12.8
max	3516	90	25.9
mean (sd)	969.43 ± 472.81	56.59 ± 7.13	18.97 ± 2.15
median (iqr)	864.00 (620.00, 1,186.00)	56.00 (52.00, 61.00)	19.10 (17.20, 20.60)

Summary of Morning time

Jan 20

	co2 (N = 41032)	humidity (N = 41032)	temparature (N = 41032)
Kitchen			
min	123	31	14.3
max	2900	83	27.5
mean (sd)	581.94 ± 170.94	50.52 ± 6.80	20.06 ± 2.02
median (iqr)	551.00 (459.00, 656.00)	49.00 (46.00, 54.00)	20.00 (18.50, 21.60)

Summary of Morning time

Jan 20

	humidity (N = 40249)	temparature (N = 39281)
Ensuite		
min	34	13
max	98	27
mean (sd)	56.84 ± 10.06	19.30 ± 2.41
median (iqr)	56.00 (50.00, 61.00)	19.30 (17.10, 21.30)

Summary of Morning time

Jan 20

	co2 (N = 42347)	humidity (N = 42347)	temparature (N = 42347)
Second bedroom			
min	116	34	11.9
max	4074	86	26.5
mean (sd)	873.36 ± 546.50	54.81 ± 7.63	18.79 ± 1.98
median (iqr)	698.00 (514.00, 993.00)	54.00 (50.00, 59.00)	18.70 (17.40, 20.20)

Summary of Morning time

Jan 20

	co2 (N = 40912)	humidity (N = 40912)	temparature (N = 40912)
Living room			
min	223	29	14.5
max	2264	79	26.2
mean (sd)	584.42 ± 175.03	50.95 ± 6.97	19.42 ± 1.86
median (iqr)	540.00 (459.00, 655.00)	51.00 (47.00, 54.00)	19.20 (18.00, 20.70)

Summary of Night time

Jan 20

	co2 (N = 61915)	humidity (N = 61915)	temparature (N = 6191
Master bedroom			
min	164	35	12.8
max	3735	89	30.1
mean (sd)	1,104.34 ± 477.36	56.87 ± 6.91	19.06 ± 2.18
median (iqr)	1,063.00 (786.00, 1,324.00)	56.00 (53.00, 61.00)	19.10 (17.30, 20.60)

Summary of Night time

Jan 20

	co2 (N = 61473)	humidity (N = 61473)	temparature (N = 61472)
Kitchen			
min	152	36	14.3
max	3962	84	26.9
mean (sd)	593.73 ± 195.49	51.16 ± 6.58	20.11 ± 1.95
median (iqr)	554.00 (471.00, 661.00)	50.00 (47.00, 54.00)	20.00 (18.70, 21.70)

Summary of Night time

Jan 20

	humidity (N = 60747)	temparature (N = 59282)
Ensuite		
min	34	12.9
max	99	26.5
mean (sd)	56.48 ± 8.82	19.41 ± 2.41
median (iqr)	55.00 (50.00, 61.00)	19.50 (17.30, 21.40)

Summary of Night time

Jan 20

	co2 (N = 63326)	humidity (N = 63326)	temparature (N = 6332(
Second bedroom			
min	148	34	12
max	3962	85	26.4
mean (sd)	961.97 ± 556.55	55.05 ± 7.39	18.92 ± 1.97
median (iqr)	825.00 (532.00, 1,183.00)	54.00 (50.00, 59.00)	18.80 (17.50, 20.40)

Summary of Night time

Jan 20

	co2 (N = 61543)	humidity (N = 61543)	temparature (N = 61542)
Living room			
min	220	30	14.5
max	4070	80	25
mean (sd)	649.56 ± 249.92	51.66 ± 6.95	19.54 ± 1.77
median (iqr)	589.00 (490.00, 719.00)	51.00 (47.00, 55.00)	19.50 (18.20, 20.90)

Summary of overall

July 19

	humidity (N = 314093)	temparature (N = 314093)
Ensuite		
min	40	17.5
max	98	27.9
mean (sd)	58.75 ± 6.98	23.35 ± 1.05
median (iqr)	58.00 (54.00, 62.00)	23.40 (22.70, 24.00)

Summary of overall

July 19

	co2 (N = 318729)	humidity (N = 318729)	temparature (N = 318727)
Kitchen			
min	224	29	18.7
max	3988	95	35
mean (sd)	573.00 ± 180.06	57.76 ± 5.48	23.41 ± 1.05
median (iqr)	529.00 (456.00, 631.00)	58.00 (54.00, 61.00)	23.40 (22.70, 24.10)

Summary of overall

July 19

	co2 (N = 239669)	humidity (N = 239668)	temparature (N = 239668)
Living room			
min	209	35	19.7
max	2889	81	29.8
mean (sd)	604.35 ± 214.12	58.34 ± 5.14	22.99 ± 1.00
median (iqr)	541.00 (464.00, 673.00)	58.00 (55.00, 61.00)	22.90 (22.30, 23.60)
Master bedroom			
min	162	37	18.7
max	3531	92	30.1
mean (sd)	706.96 ± 367.75	55.90 ± 5.72	23.70 ± 1.23
median (iqr)	582.00 (454.00, 864.00)	56.00 (52.00, 59.00)	23.70 (22.90, 24.50)
Second bedroom			
min	0	37	19.3
max	65535	82	27.7
mean (sd)	723.17 ± 1,917.30	56.14 ± 5.55	23.48 ± 1.04
median (iqr)	534.00 (449.00, 764.00)	56.00 (53.00, 59.00)	23.50 (22.80, 24.20)

Summary of Evening time

July 19

	co2 (N = 89173)	humidity (N = 89172)	temparature (N = 89171)
Living room			
min	221	34	19.9
max	2807	81	30
mean (sd)	687.99 ± 259.07	58.47 ± 5.45	23.15 ± 0.96
median (iqr)	628.00 (498.00, 811.00)	58.00 (55.00, 62.00)	23.10 (22.50, 23.80)

Summary of Evening time

July 19

	co2 (N = 89173)	humidity (N = 89172)	temparature (N = 89171)
Living room			
min	221	34	19.9
max	2807	81	30
mean (sd)	687.99 ± 259.07	58.47 ± 5.45	23.15 ± 0.96
median (iqr)	628.00 (498.00, 811.00)	58.00 (55.00, 62.00)	23.10 (22.50, 23.80)

Summary of Midday time

July 19

	co2 (N = 94150)	humidity (N = 94150)	temparature (N = 94150)
Living room			
min	241	37	18.6
max	2889	81	28.8
mean (sd)	574.21 ± 204.43	57.44 ± 5.32	23.15 ± 1.02
median (iqr)	510.00 (444.00, 634.00)	57.00 (54.00, 61.00)	23.10 (22.50, 23.80)

Summary of Morning time

July 19

	co2 (N = 54403)	humidity (N = 54403)	temparature (N = 54403)
Master bedroom			
min	206	37	19.2
max	3531	92	30.1
mean (sd)	770.32 ± 405.03	56.68 ± 5.61	23.50 ± 1.28
median (iqr)	652.00 (511.00, 911.00)	56.00 (53.00, 60.00)	23.40 (22.60, 24.20)

Summary of Morning time

July 19

	humidity (N = 52772)	temparature (N = 52772)
Ensuite		
min	42	19.9
max	97	27.9
mean (sd)	59.26 ± 7.31	23.25 ± 1.04
median (iqr)	58.00 (54.00, 63.00)	23.30 (22.60, 23.90)

Summary of Morning time

July 19

	co2 (N = 55480)	humidity (N = 55480)	temparature (N = 55480)
Second bedroom			
min	2	0	-1002.1
max	65532	82	27.4
mean (sd)	753.73 ± 1,541.69	56.91 ± 5.34	23.20 ± 4.47
median (iqr)	589.00 (473.00, 802.00)	56.00 (54.00, 59.00)	23.20 (22.60, 23.90)

Summary of Morning time

July 19

	co2 (N = 53536)	humidity (N = 53536)	temparature (N = 53536)
Kitchen			
min	241	36	19.7
max	3988	95	28.8
mean (sd)	554.00 ± 149.16	57.87 ± 4.98	23.15 ± 0.93
median (iqr)	521.00 (459.00, 606.00)	58.00 (55.00, 61.00)	23.20 (22.50, 23.80)

Summary of Morning time

July 19

	co2 (N = 53735)	humidity (N = 53735)	temparature (N = 53735)
Living room			
min	209	35	17.9
max	2561	81	28.8
mean (sd)	571.13 ± 172.55	58.59 ± 4.74	22.70 ± 0.99
median (iqr)	523.00 (464.00, 628.00)	58.00 (56.00, 61.00)	22.60 (22.10, 23.20)

Summary of Night time

July 19

	co2 (N = 83101)	humidity (N = 83101)	temparature (N = 83101)
Master bedroom			
min	282	43	19.7
max	3447	77	27.4
mean (sd)	949.45 ± 447.93	57.15 ± 5.34	23.55 ± 1.17
median (iqr)	896.00 (635.00, 1,129.00)	57.00 (53.00, 60.00)	23.60 (22.80, 24.30)

Summary of Night time

July 19

	co2 (N = 81501)	humidity (N = 81501)	temparature (N = 81501)
Kitchen			
min	257	42	19.9
max	2725	86	27.7
mean (sd)	549.44 ± 124.23	58.32 ± 4.86	23.19 ± 0.92
median (iqr)	525.00 (466.00, 599.00)	58.00 (55.00, 61.00)	23.20 (22.60, 23.80)

Summary of Night time

July 19

	humidity (N = 80841)	temparature (N = 80841)
Ensuite		
min	44	18.4
max	97	27
mean (sd)	58.59 ± 6.23	23.26 ± 1.03
median (iqr)	58.00 (54.00, 62.00)	23.30 (22.60, 24.00)

Summary of Night time

July 19

	co2 (N = 84412)	humidity (N = 84412)	temparature (N = 84412)
Second bedroom			
min	0	44	19.3
max	65534	82	26.1
mean (sd)	862.36 ± 1,220.90	57.22 ± 5.53	23.30 ± 0.97
median (iqr)	739.00 (500.00, 995.00)	56.00 (54.00, 60.00)	23.40 (22.70, 24.00)

Summary of Night time

July 19

	co2 (N = 82041)	humidity (N = 82041)	temparature (N = 82041)
Living room			
min	221	38	19.7
max	2059	79	27.9
mean (sd)	572.58 ± 168.03	59.08 ± 4.64	22.65 ± 0.92
median (iqr)	531.00 (471.00, 618.00)	59.00 (56.00, 62.00)	22.60 (22.00, 23.20)

Summary of overall

March 20

	humidity (N = 283682)	temparature (N = 283651)
Ensuite		
min	29	13.7
max	99	28.1
mean (sd)	53.42 ± 9.85	19.70 ± 2.41
median (iqr)	52.00 (47.00, 58.00)	19.60 (17.90, 21.50)

Summary of overall

March 20

	co2 (N = 288628)	humidity (N = 288628)	temparature (N = 288628)
Kitchen			
min	212	20	14.1
max	6474	97	33.4
mean (sd)	694.44 ± 263.01	48.49 ± 7.19	20.59 ± 1.95
median (iqr)	636.00 (515.00, 802.00)	47.00 (44.00, 52.00)	20.60 (19.10, 22.00)

Summary of overall

March 20

	co2 (N = 233434)	humidity (N = 233434)	temparature (N = 23343
Living room			
min	256	24	15.2
max	4754	84	29.4
mean (sd)	752.99 ± 318.15	48.66 ± 7.00	20.09 ± 1.82
median (iqr)	675.00 (526.00, 890.00)	48.00 (44.00, 52.00)	20.20 (18.70, 21.40)
Master bedroom			
min	163	31	13.5
max	7001	91	28.2
mean (sd)	949.45 ± 567.78	52.08 ± 7.40	19.48 ± 2.19
median (iqr)	816.00 (584.00, 1,167.00)	51.00 (47.00, 56.00)	19.50 (17.80, 21.00)
Second bedroom			
min	95	30	14.1
max	4589	80	26.6
mean (sd)	834.25 ± 455.93	50.64 ± 6.56	19.28 ± 1.85
median (iqr)	706.00 (508.00, 983.00)	50.00 (46.00, 54.00)	19.30 (17.90, 20.70)

Summary of Evening time

March 20

	co2 (N = 82909)	humidity (N = 82909)	temparature (N = 8290
Living room			
min	285	27	15.4
max	3649	82	28.4
mean (sd)	913.58 ± 357.66	49.43 ± 7.15	20.57 ± 1.80
median (iqr)	856.00 (669.00, 1,085.00)	48.00 (45.00, 53.00)	20.70 (19.30, 21.90)

Summary of Midday time

March 20

	co2 (N = 81223)	humidity (N = 81223)	temparature (N = 81221)
Living room			
min	246	24	15.3
max	4754	84	29.4
mean (sd)	740.92 ± 314.83	48.29 ± 7.09	20.14 ± 1.79
median (iqr)	674.00 (519.00, 872.00)	47.00 (44.00, 51.00)	20.20 (18.70, 21.50)

Summary of Morning time

March 20

	co2 (N = 47168)	humidity (N = 47168)	temparature (N = 47168
Master bedroom			
min	258	33	13.5
max	6981	89	25.9
mean (sd)	1,113.24 ± 694.67	53.21 ± 7.41	19.27 ± 2.12
median (iqr)	967.00 (695.00, 1,291.00)	53.00 (48.00, 57.00)	19.30 (17.70, 20.80)

Summary of Morning time

March 20

	humidity (N = 46288)	temparature (N = 46288)
Ensuite		
min	33	13.7
max	98	26.7
mean (sd)	53.40 ± 9.98	19.53 ± 2.36
median (iqr)	52.00 (47.00, 57.00)	19.40 (17.70, 21.40)

Summary of Morning time

March 20

	co2 (N = 48486)	humidity (N = 48486)	temparature (N = 48486)
Second bedroom			
min	199	36	14.1
max	3981	80	25.5
mean (sd)	937.81 ± 556.00	51.29 ± 6.82	19.04 ± 1.86
median (iqr)	768.00 (539.00, 1,109.00)	50.00 (46.00, 55.00)	19.00 (17.60, 20.40)

Summary of Morning time

March 20

	co2 (N = 47050)	humidity (N = 47050)	temparature (N = 47050)
Kitchen			
min	262	28	14.8
max	2511	97	27.3
mean (sd)	608.51 ± 176.01	47.76 ± 6.72	20.15 ± 1.89
median (iqr)	571.00 (479.25, 693.00)	47.00 (43.00, 51.00)	20.10 (18.70, 21.50)

Summary of Morning time

March 20

	co2 (N = 46922)	humidity (N = 46922)	temparature (N = 46922)
Living room			
min	256	29	15.2
max	2902	78	25.3
mean (sd)	613.17 ± 194.86	48.10 ± 6.63	19.61 ± 1.79
median (iqr)	566.00 (471.00, 696.00)	47.00 (44.00, 51.00)	19.60 (18.20, 20.80)

Summary of Night time

March 20

	co2 (N = 77744)	humidity (N = 77744)	temparature (N = 77744
Master bedroom			
min	289	32	13.6
max	6370	80	28.2
mean (sd)	1,209.96 ± 641.20	53.10 ± 7.21	19.46 ± 2.16
median (iqr)	1,131.00 (828.00, 1,419.00)	52.00 (48.00, 57.00)	19.50 (17.80, 21.00)

Summary of Night time

March 20

	co2 (N = 77291)	humidity (N = 77291)	temparature (N = 77291)
Kitchen			
min	247	34	14.9
max	2633	86	26
mean (sd)	614.56 ± 179.86	48.48 ± 6.46	20.28 ± 1.83
median (iqr)	576.00 (496.00, 682.00)	48.00 (44.00, 52.00)	20.30 (18.90, 21.70)

Summary of Night time

March 20

	humidity (N = 75507)	temparature (N = 75507)
Ensuite		
min	33	13.8
max	97	27.2
mean (sd)	53.13 ± 8.94	19.72 ± 2.39
median (iqr)	52.00 (47.00, 58.00)	19.70 (17.90, 21.60)

Summary of Night time

March 20

	co2 (N = 79867)	humidity (N = 79867)	temparature (N = 79867)
Second bedroom			
min	210	35	14.3
max	3912	79	24.6
mean (sd)	990.75 ± 536.35	51.43 ± 6.66	19.23 ± 1.80
median (iqr)	848.00 (582.00, 1,249.00)	51.00 (47.00, 55.00)	19.20 (17.90, 20.60)

Summary of Night time

March 20

	co2 (N = 77138)	humidity (N = 77138)	temparature (N = 77138)
Living room			
min	278	30	15.3
max	3450	79	24.5
mean (sd)	670.32 ± 246.15	48.88 ± 6.59	19.75 ± 1.69
median (iqr)	609.00 (509.00, 756.00)	48.00 (45.00, 52.00)	19.80 (18.50, 21.00)

Summary of overall

November 19

	humidity (N = 232464)	temparature (N = 267022)
Ensuite		
min	33	12.16557
max	100	28.9
mean (sd)	57.86 ± 9.14	19.34 ± 2.58
median (iqr)	57.00 (51.00, 63.00)	19.50 (17.40, 21.30)

Summary of overall

November 19

	co2 (N = 235517)	humidity (N = 235515)	temparature (N = 270068)
Kitchen			
min	222	25	8.976182
max	5410	96	35.6
mean (sd)	673.20 ± 265.81	52.97 ± 7.34	20.40 ± 2.31
median (iqr)	605.00 (489.00, 780.00)	52.00 (48.00, 57.00)	20.40 (18.62, 22.00)

Summary of overall

November 19

	co2 (N = 138374)	humidity (N = 138374)	temparature (N = 172933
Living room			
min	275	31	14.58506
max	5211	87	28
mean (sd)	696.64 ± 296.04	53.24 ± 7.26	19.98 ± 2.18
median (iqr)	609.00 (479.00, 829.00)	53.00 (49.00, 57.00)	20.00 (18.30, 21.50)
Master bedroom			
min	3	30	12.3
max	65534	92	29.3
mean (sd)	881.42 ± 692.42	57.39 ± 7.15	19.30 ± 2.44
median (iqr)	750.00 (532.00, 1,072.00)	57.00 (53.00, 62.00)	19.20 (17.60, 20.81)
Second bedroom			
min	154	34	12.6
max	4987	85	28.4
mean (sd)	836.24 ± 518.24	56.12 ± 6.66	19.21 ± 2.28
median (iqr)	685.00 (492.00, 1,001.00)	55.00 (52.00, 60.00)	19.16 (17.50, 20.70)

Summary of Evening time

Nov 19

	co2 (N = 68870)	humidity (N = 68869)	temparature (N = 78827)
Living room			
min	275	32	14.9
max	4702	87	28
mean (sd)	856.81 ± 349.10	53.62 ± 7.28	20.51 ± 2.14
median (iqr)	808.00 (595.00, 1,032.00)	53.00 (49.00, 58.00)	20.70 (18.80, 22.05)

Summary of Midday time

November 19

	co2 (N = 70065)	humidity (N = 70065)	temparature (N = 80144)
Living room			
min	260	31	14.58506
max	5211	86	27.1
mean (sd)	653.67 ± 267.99	53.18 ± 7.24	19.68 ± 2.09
median (iqr)	580.00 (456.00, 775.00)	53.00 (49.00, 57.00)	19.60 (18.10, 21.10)

Summary of Morning time

November 19

	co2 (N = 39561)	humidity (N = 39561)	temparature (N = 45320)
Master bedroom			
min	255	37	12.3
max	5893	88	26.44214
mean (sd)	1,021.69 ± 614.97	57.93 ± 7.05	19.08 ± 2.36
median (iqr)	869.00 (645.00, 1,209.00)	58.00 (53.00, 62.00)	19.00 (17.40, 20.70)

Summary of Morning time

November 19

	co2 (N = 39567)	humidity (N = 39567)	temparature (N = 45327)
Kitchen			
min	292	34	13.8
max	2413	93	26.7
mean (sd)	613.60 ± 197.62	52.31 ± 7.00	20.06 ± 2.27
median (iqr)	567.00 (476.00, 686.00)	51.00 (48.00, 56.00)	20.10 (18.30, 21.50)

Summary of Morning time

November 19

	humidity (N = 38872)	temparature (N = 44632)
Ensuite		
min	36	12.16557
max	100	26.5
mean (sd)	57.94 ± 9.31	19.20 ± 2.51
median (iqr)	57.00 (51.00, 63.00)	19.40 (17.40, 21.00)

Summary of Morning time

November 19

	co2 (N = 40897)	humidity (N = 40897)	temparature (N = 46657)
Second bedroom			
min	161	34	12.6
max	5007	85	27
mean (sd)	939.93 ± 596.40	56.67 ± 6.98	18.97 ± 2.15
median (iqr)	773.00 (557.00, 1,110.00)	56.00 (52.00, 61.00)	18.90 (17.50, 20.40)

Summary of Morning time

November 19

	co2 (N = 39512)	humidity (N = 39512)	temparature (N = 45272)
Living room			
min	292	32	14.8
max	2211	84	25.2
mean (sd)	595.76 ± 189.25	52.82 ± 7.04	19.45 ± 2.04
median (iqr)	540.00 (462.00, 667.00)	52.00 (48.00, 57.00)	19.40 (17.90, 20.80)

Summary of Night time

Nov 19

	co2 (N = 57056)	humidity (N = 57055)	temparature (N = 65815
Master bedroom			
min	274	30	12.4
max	5477	89	29.3
mean (sd)	1,150.55 ± 601.08	58.14 ± 7.16	19.25 ± 2.39
median (iqr)	1,048.00 (787.00, 1,368.00)	58.00 (54.00, 63.00)	19.30 (17.60, 20.80)

Summary of Night time

Nov 19

	co2 (N = 57174)	humidity (N = 57173)	temparature (N = 65929)
Kitchen			
min	276	37	8.976182
max	3679	91	27.2
mean (sd)	600.70 ± 187.47	52.89 ± 6.81	20.16 ± 2.18
median (iqr)	559.00 (477.00, 663.00)	52.00 (48.00, 57.00)	20.20 (18.50, 21.63)

Summary of Night time

Nov 19

	humidity (N = 57005)	temparature (N = 65765)
Ensuite		
min	36	12.5
max	98	28.1
mean (sd)	57.61 ± 8.27	19.35 ± 2.49
median (iqr)	57.00 (52.00, 63.00)	19.70 (17.60, 21.20)

Summary of Night time

Nov 19

	co2 (N = 59355)	humidity (N = 59355)	temparature (N = 68115)
Second bedroom			
min	163	36	12.7
max	4910	84	26.8
mean (sd)	1,022.52 ± 612.15	56.81 ± 6.89	19.19 ± 2.13
median (iqr)	909.00 (563.50, 1,253.50)	56.00 (52.00, 61.00)	19.20 (17.70, 20.60)

Summary of Night time

Nov 19

	co2 (N = 57044)	humidity (N = 57043)	temparature (N = 65804)
Living room			
min	294	32	14.9
max	2759	83	26.1
mean (sd)	633.29 ± 228.39	53.53 ± 6.98	19.62 ± 1.96
median (iqr)	570.00 (481.00, 696.00)	53.00 (49.00, 57.00)	19.70 (18.10, 20.90)

Appendix G – Mind Map

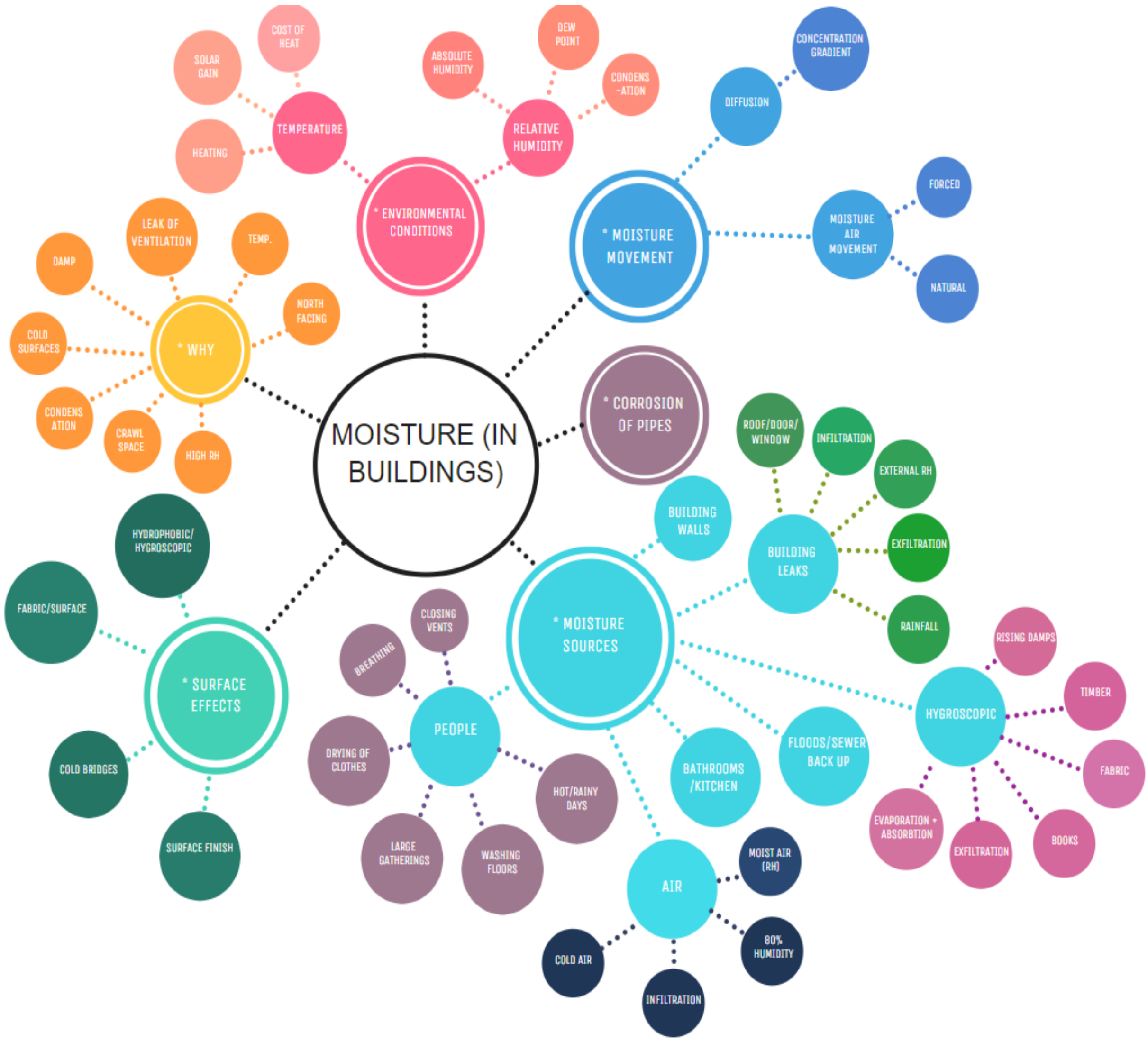


Figure A-1 Mind map to analyse the moisture in buildings

Appendix H - Typical advisory report sample for Location 1 residents

(Prepared by the Author)

AMBER Assessment Methodology Building Energy Ratings

IES

Trinity College Dublin
Coláiste na Tríonóide, Baile Átha Cliath
The University of Dublin

6-Month House Report for O'Cualann Development

Thank you again for allowing the AMBER team to have access to the data from your A-rated home. We now have six months of data on three parameters (temperature, relative humidity and CO_2 levels) on your house in five rooms – the living room, kitchen, ensuite bathroom, main and second bedroom. To re-state, nobody else in the project will be given this data and anything we publish will be anonymised.

In giving you your data, you should know that we compare the levels of these three parameters against international norms as laid down in codes and standards. For comparison for occupant comfort and health reasons, in Ireland we expect your living room will have an average temperature between 20 and 22^oC in Winter and 23 and 25^oC in Summer and your bedrooms to have between 17 and 19^oC average in Winter and 23 and 25^oC in Summer. The relative humidity should, on average, typically be between 40 and 50%, but any values below 60% are usually deemed acceptable. Relative humidity above 80% for prolonged periods can result in mould growth on walls and on any unventilated surfaces, such as behind curtains, blinds, wardrobes, etc. Levels of humidity can also affect the occupant's feeling of well-being, for example, low levels of humidity can lead to drying of the eyes and nose and throat irritations, particularly for those who are susceptible to such conditions. For Carbon Dioxide (CO_2), a gas which can make us feel lethargic and drowsy if too high, below 1,000 parts per million (ppm) is quite normal, while up to 1,500 ppm can make us less alert, and above 1500 ppm can have an effect on energy and concentration levels. In the context of these figures, here are the average and peak values for your home (note the percentages are the highest monthly values, while the averages and maxima are over 6 months):

	TEMPERATURE			RELATIVE HUMIDITY				CARBON DIOXIDE			
Room	**Avg. Temp**	**Max Temp**	**% > 25°C**	**Avge RH**	**Max RH**	**>60% RH**	**> 80% RH**	**Avge CO_2**	**Max CO_2**	**1000 to1500**	**>1500**
Living	21.29	25.4	4.44%	69.16	84	99.98%	0.26%	840	2656	39.5%	11%
Kitchen	21.54	26.4	14.12%	68.82	95	100%	2%	802	2354	42%	4.88%
Master Bed	22.8	28.5	73.15%	67.7	78	99.98%	0%	1652	4851	29.65%	66.39%
En-Suite	21.9	26.8	21.9%	69.23	79	100%	0%	-	-	-	-
2nd Bed	22.15	26.7	41.14%	68.3%	82	99.63%	12.81	1252	3711	48.55%	51.74%

Data evaluation and comments

The obtained values of indoor air temperature, relative humidity and CO_2 in this house are shown in the table above. The minimum measured indoor air temperature was 15°C indicating that the recommended indoor air temperature in the house was less than the optimal temperature (18°C) in April. The maximum value of indoor air temperature was 29.2°C. The indoor air temperature in the master bedroom exceeded 28.5°C for a total of 73% of the time in the month of July.

The levels of relative humidity were high for most of the time. In this house, the peak relative humidity values were 80% - 95% in most of the areas. The levels of relative humidity were even higher than 80% in bedroom, which can result in mould growth on walls and other surfaces.

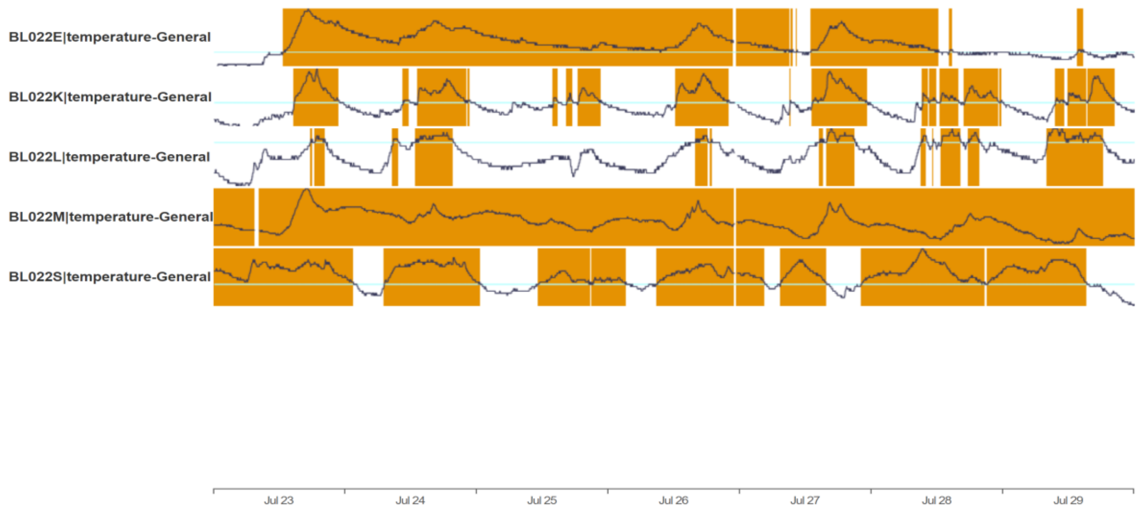
High levels of CO_2 were recorded for 50 to 67% of the time in both bedrooms. As per the observed measurements, the quality of indoor air was good only for 13 to 20% of the time. Based on an inspection by the maintenance team, it can be assumed that high CO_2 and humidity levels are possibly caused by closed trickle vents and Aereco ventilation system. Examples of temperature, humidity and CO_2 with exceedances in your house are shown in Figures 1 to 3.

Recommendations

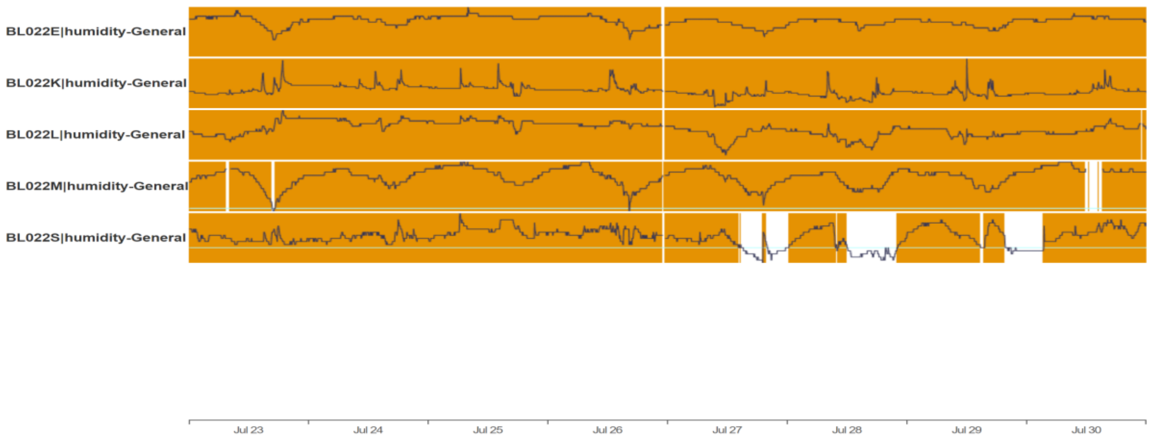
- The ventilation rate plays an important role in indoor environmental conditions, particularly in A-Rated homes. Properly operating ventilation systems tend to reduce the extreme conditions which may expose occupants to symptoms such as irritations and difficulties in concentration. Thus, the sealing of the ventilation slots is not recommended at any time as it can affect the health of occupants particularly in A-rated houses.
- Before you start cooking, it is recommended that you turn on the extractor fan, this will help to prevent extra moister build-up in the kitchen.

- Proper air exchange is recommended to avoid high levels of relative humidity and CO_2 levels in house. So, ensure the ventilation is working and not turned off or sealed.

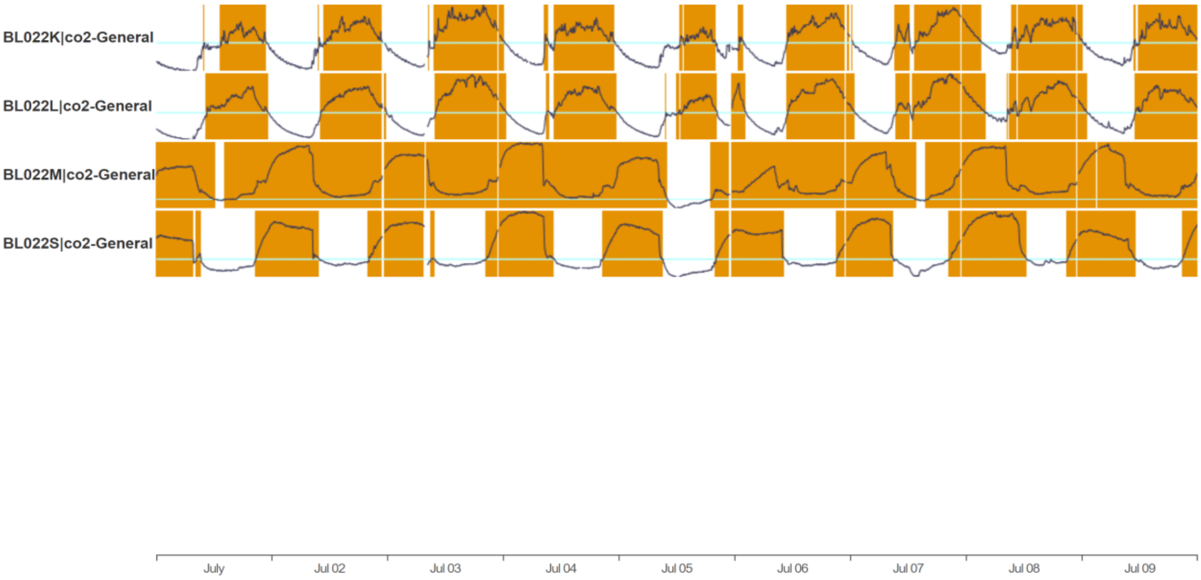
Appendix



Overheating and exceedances of temperature more than 25^{0}C (in orange)



Relative humidity exceedances in orange



CO_2 exceedances in orange

Appendix I - Resident's Questionnaire

(Jointly prepared by all AMBER project partners)

I.. agree to engage with the SEAI RD&D funded project, AMBER (Assessment Methodology for Building Energy Ratings), coordinated by IES R&D with partners Trinity College Dublin, RIAI and O'Cualann. I agree to allow my gas and electricity meter readings to be used for this project. I also agree to have sensors placed in my home, which will monitor Indoor Environmental Conditions.

Please fill out the following with as much information as you can and please sign and date :

Contact Details:

Name: ____

Address: ____

Email: ____

Phone Number: ____

MPRN (Meter Point Reference Number): ______________________

GRPN (Gas Point Reference Number): _______________________

Number of people in your home and ages: ____________________

____

What time does your heating come on at and how long does it stay on for? __________

____

__________(e.g. 6am-8am and 5pm-9pm)

Do you use your emersion often, if so roughly how much? _______________

What time does the first person in your house get up at and the last person at night go to bed at?

____

How many TVs do you have? ___________________________

How many computers do you have? ______________________

How many times a week would you eat out or order a take away (i.e. not use your hob for cooking):

____

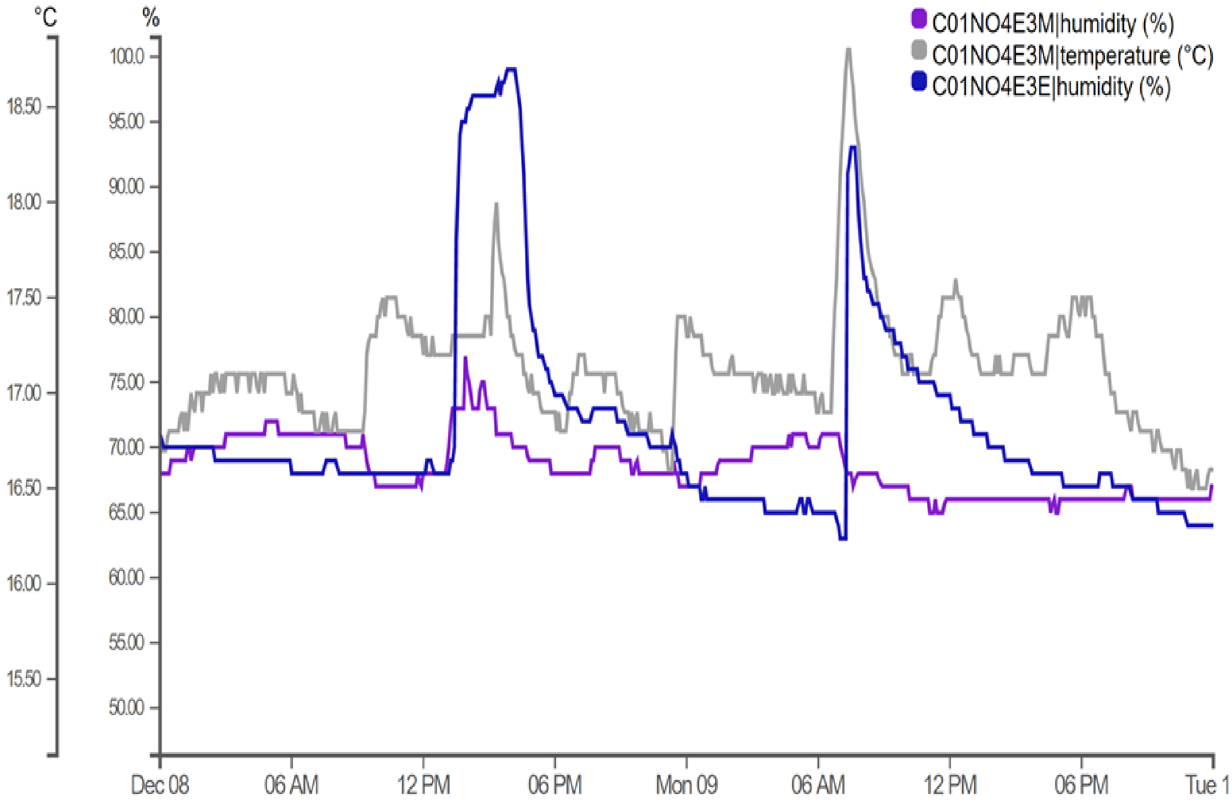
Name: ____________________

Signed: ____________________

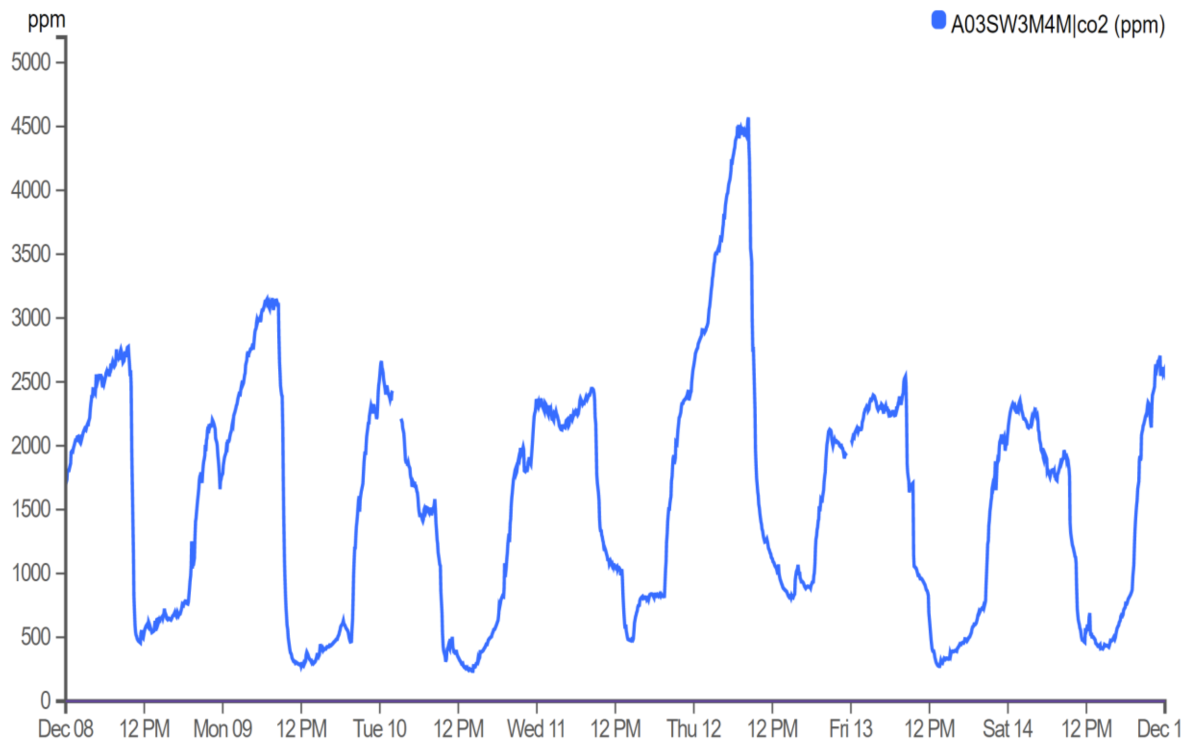
Date: ____________________

All personal data is confidential and shall be kept in compliance with IES GDPR and ISO27001 guidelines. This information will only be used for the purposes of the SEAI RD&D funded AMBER project.

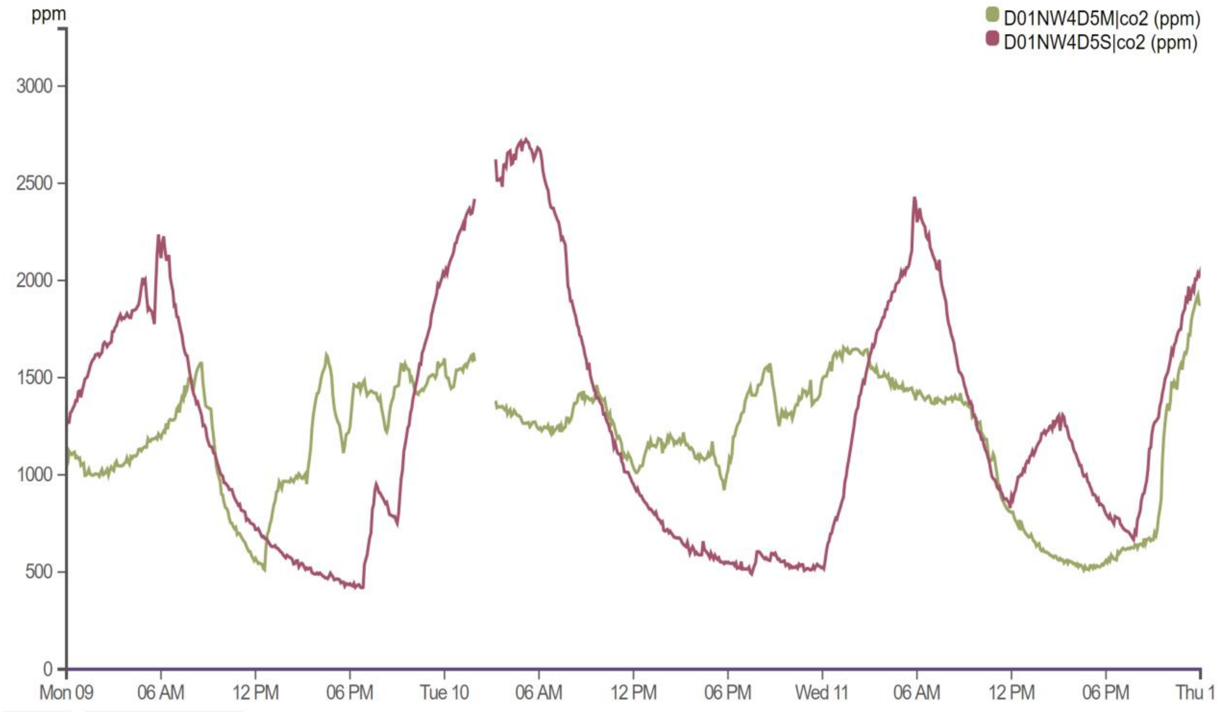
Appendix J- IAQ examples



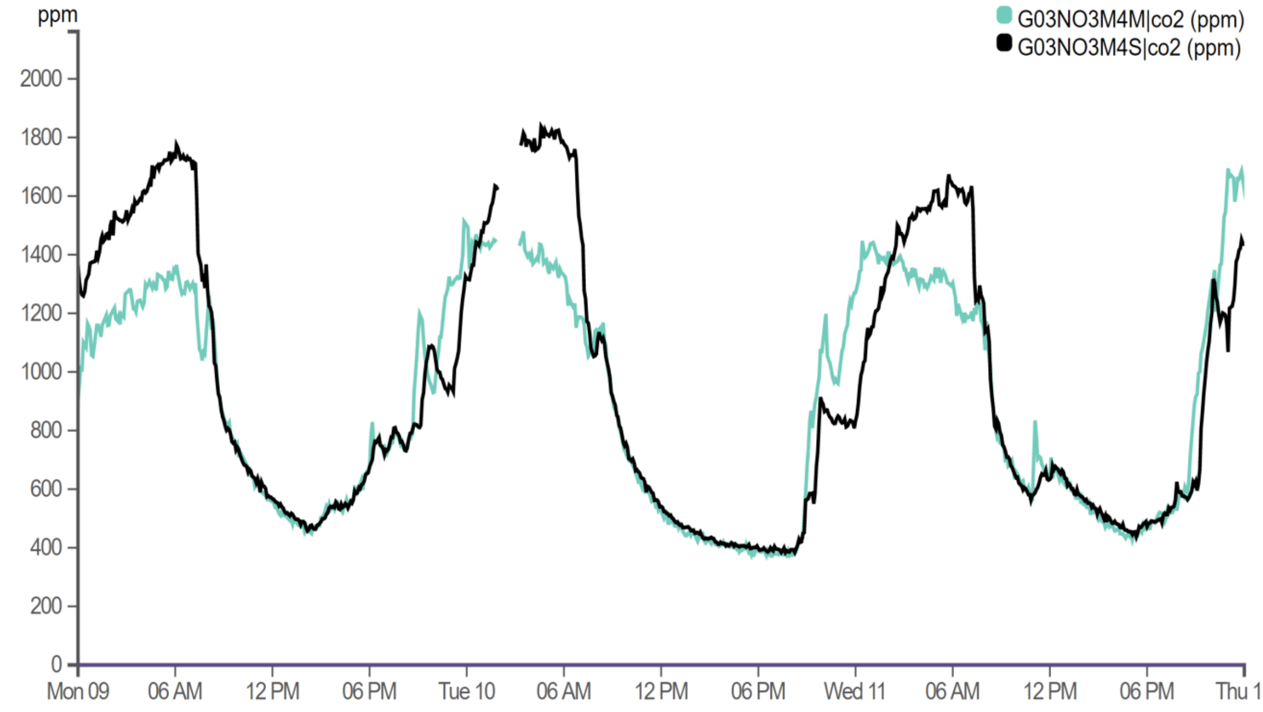
Effect of ventilation on humidity after shower



High CO_2 in Master Bed



High CO_2 in second bed compared to master bed



High CO_2 in second bed compared to master bed

Appendix K- User operational guide jointly prepared by the AMBER project partners

DOMESTIC OPERATIONAL GUIDE

As homes become more energy efficient, innovative systems and construction processes will be deployed as part of your home. This has caused the need for your home to be operated more efficiently to ensure you use your energy efficient home as initially designed. This guide provide simple tips and hints to reduce your energy consumption and to improve the environmental quality of your home. These guidelines apply to all homeowners, whether existing, new or retrofitted.

Advice will be given in the following areas which affect energy consumption:	*Advice will be given in three key areas which affect occupant comfort*
Heating Energy	Thermal Comfort (Heating)
Heat Pumps	Relative Humidity (moisture conditions)
Appliances (Electricity)	Carbon Dioxide in the air
Ventilation Systems (Energy Use)	Ventilations System (Air circulation)

Each tip is labelled as the following: Operational Improvement Tips

Heating

On average Irish homes use 61% of their energy on space heating each year. New building regulations have incentivized the adoption of heating systems with high levels of efficiency meaning if these systems are used to their design intent by improving the operation it can considerably reduce your energy consumption.

Only use your heating for 2 hours per day to reduce costs

Turn down your room thermostats and adjust the temperature of your water heater

If possible reduce temperature on the radiators in bedrooms, bathroom and kitchen and maintain living room and home office should be the ones with higher temperatures in rooms that you stay in for a long time, in stationary positions

Close doors to unused rooms

Do not open window when heating is on

Thermal Comfort (Heating Continued):

Indoor temperature is a measure of the warmth or coldness inside a building. This recording is critical to your own internal comfort with in your home. You may, of course, operate your home at any temperature you wish, but be mindful that if the temperature is high, this (a) is going to cost you more and (b) may lead to a less healthy environment and (c) will produce higher carbon emissions.

Turn down the thermostat even by 1°C which has been shown to translate into an energy saving up to 10%.

Opening windows at night in summers can help in preventing overheating.

Keep doors fully closed in heated rooms. However, do not block the gap under the doors as these are needed to supply fresh air to the room.

Leave blinds/curtains open during sunny days and let the sun rays enter to benefit from solar gain and save on heating. Keep the blinds/curtains fully closed during cold nights to stop warm air escaping.

Check the running times of your heating system to better align with the times you actually need heat. Turn off heating well before going to bed as the insulation should keep the space warm enough.

If your heating is on, and if a room is too hot, turn down the thermostat and open a door to the rest of the house rather than open a window as that will help heat the whole house which will help keeping it warmer for longer.

If you tend to feel the cold more, it is better to consider adding an extra layers (such as a jumper or knee rug) to keep warm instead of putting on the heating for a short

Overheating refers to the accumulation of heat within a building which can lead to discomfort for building occupants or can impact the productivity and the activities done in your home.

Cold homes can be bad for your health, lead to illness and can contribute to damp and cold patches.

Recommended guideline temperatures in your home are:

- Living Rooms: 20 °C to 22 °C in winter and 20 °C to 25 °C in summer
- Bedrooms: 17 °C to 19 °C in winter and 20 °C to 25 °C in summer.

AMBER

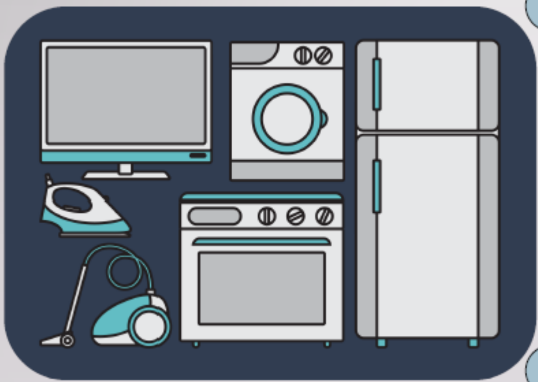
Heat Pumps

Heat-pumps convert energy from the air outside of your home into heat and are becoming more commonplace in Ireland due to the minimal electricity needed to run.

- Don't set your heat pump to the maximum – it won't heat the room any quicker, but it will use more energy.
- Use the timer function to heat the space 15 minutes before you use it
- Keep the setting low (18°C or - 20°C) to reduce the energy used
- If there is access, clean your heat pump filter regularly
- Turn off your heat pump when it's not in use. It can run for as long as you need, but make sure you switch it off when you're not using it

Appliances

Due to new regulations, appliances are becoming more efficient but as technology advances small electrical loads are increasing in homes. This compounded by the adoption of more smart devices (laptops, phones, tablets). These electrical devices are also occupational in nature meaning when a house is designed it is difficult to quantify how much electricity will be used in the home.



- Run your dishwasher on low temperature
- Run your washing machine on a cooler or eco cycle
- Turn off all appliances at night
- Change old lightbulbs to LED and add smart plugs to switch things off and monitor consumption
- Don't leave the fridge door open while getting food. The longer the door is open the more energy it uses
- Turn off lights when you are leaving a room or when you do not need them.
- Do not use personal plug-in electric heaters

Ventilation Systems

Intermittent fans

This system comprises of background ventilators such as trickle ventilators fitted to windows, or standard hole-in-the-wall ventilators, with extract fans fitted in certain rooms in your home. The background ventilators act to supply air to your home, while manual extract fans provide ventilation removing odors and excessive humidity from your home.

Do not turn off the ventilation system as they are important to the operation of your home and use minimal energy

Demand Control Ventilation.

Demand-controlled ventilation (DCV) automatically regulates ventilation based on actual demand using a suitable sensor. The difference between DCV and basic intermittent ventilation is that DCV operates automatically, without requiring any manual user intervention.

Continuous Mechanical Supply & Extract with Heat Recovery.

Mechanical Ventilation with Heat Recovery (MVHR) continually removes stale moist air from wet rooms, while supplying a balanced amount of outside air directly to habitable rooms. The difference between MVHR and other ventilation systems is that with MVHR, the heat energy carried by the stale air is used to partially heat the fresh intake air through a heat exchanger. This reduces the demand on the building's heating system and minimizes the loss of heat to the outside atmosphere while maintaining fresh clean air.

Do not block vents. Vents should be left open, however where you might wish to close a vent, remember to open it again when the room becomes unoccupied.

Relative Humidity (% RH)

Relative Humidity (or RH) is a measure (in percent) of the amount of moisture in the air and it varies with temperature. The higher the space temperature in a room, the more water that air can absorb. 100% RH means the air cannot hold any more water without it condensing, in other words, forming water droplets on colder surfaces. This is why in your bathroom, for instance, moisture can be seen on the window, mirror glass or the tiled walls. Excess RH for prolonged periods can encourage mould growth.

Prolonged periods of RH above 80% could result in mould growth and damp.

Prolonged periods of RH below 30% can lead to an uncomfortable home due to dryness and it can cause irritation to people with respiratory conditions.

- In the summer open windows to dissipate moisture from cooking, showering and sleeping. In winter, windows should not be opened for any significant length of time.
- Make sure your humidity extraction vent and fan is switched on and functioning
- Close the door of the en-suite or bathroom if you're using the shower – this avoids moisture laden air travelling into the adjoining rooms.
- If you find mould growth, you should ventilate the space and removing the water source.
- Gas heaters should not be used as they create a high moisture content.
- Keep kitchen doors closed while cooking to prevent transfer of moisture from the kitchen to other rooms.
- Dry wet clothes outside or make sure windows are slightly open to allow moisture to escape.
- After taking a shower/bath, leave the door to the bathrooms open all day to help reduce the concentration of the moisture throughout the house.
- Leave the doors of occupied bedrooms open during the day - this will disperse the night moisture in the air throughout the house.
- Always use an extractor in the kitchen, during any cooking involving boiling water. This will help to prevent extra moisture build-up in the kitchen.
- Ensure that your window trickle vents are left open
- Never block vents or gaps underneath internal doors.

Carbon Dioxide (CO2)

Carbon Dioxide (CO2) is an invisible gas which is naturally generated by many human activities. While not important in small concentrations, higher concentrations have been shown to adversely affect humans through signs of tiredness, lower concentration levels and even sleepiness. Groups of people assembling in rooms will drive this level higher, but for short periods, this is not considered harmful. Person or persons gathering for long periods or sleeping in poorly ventilated rooms is a regular cause of high carbon dioxide levels. CO2 occurs naturally in the atmosphere and is different from carbon monoxide which is toxic and is produced from incomplete combustion of fossil fuels.

- Maintain ventilation systems regularly including cleaning of filters, HVAC ducting and vents.
- If a group of people is assembled in a room, consider opening or partially opening a window in summer to dissipate the CO2.
- Ensure your window trickle vents or wall vents are fully operational and open, particularly in rooms where long occupation periods can apply, such as living rooms, kitchen or bedrooms.
- In occupied bedrooms which have an ensuite bathroom, leave the joining door open or partially open to reduce the overnight build-up of CO2.
- Free-standing gas heaters should not be used as they create high amounts of dangerous carbon monoxide gas in the air.
- Keep trickle vents (which are located on windows and doors) on the recommended setting. However, in winter, if the trickle vent is closed, remember to open it again when the room is unoccupied.

CO2 is measured in **CO2 Parts Per Million (PPM).** The different levels and affects of CO2 in your home would be:

Less than 400 PPM: Optimal Level

400 -1000 PPM: OK but not Optimal Level

1000 - 1500 PPM: Affects Alertness of Occupants

More than 1500 PPM: Affects Energy and Concentration of Occupants

Appendix L – Occupant's guidelines – jointly prepared by the AMBER project partners

AMBER

Running Your Modern Energy-Efficient Home

As homes become more energy-efficient, you may find that newer and less familiar systems and construction techniques have been used.

This guide provides simple tips to help you use your energy-efficient home as designed.

Not only reducing your energy consumption and saving you money, but also helping you make your home healthier and more comfortable.

Contents

Project Partners

Trinity College Dublin

IES

Ó CUALANN

AMBER

Energy Advice

Heating Energy

New building regulations have increased the use of highly efficient heating systems. If used correctly they can considerably reduce your energy consumption and costs.

Improvement Tips

Reduce the temperatures of the radiators in bedrooms, bathrooms and kitchen.

The living room and home office should have higher temperatures as you are likely to stay stationary in these for a longer time.

Only use your heating as much as you comfortably need per day.

Turn down your room thermostats and adjust the temperature of your water heater.

Do not open windows when heating is on.

Close doors to unused rooms.

Did you know?

On average Irish homes use about 60% of their energy on heating spaces each year.

AMBER

Comfort & Health Advice

Indoor Temperature

Did you know?

Overheating refers to the accumulation of heat within a building which can lead to discomfort for occupants and can impact on your productivity and the activities done in your home.

Cold homes can be bad for your health, leading to illness. They can also contribute to damp and cold patches.

Recommended Indoor Temperatures

Living Rooms

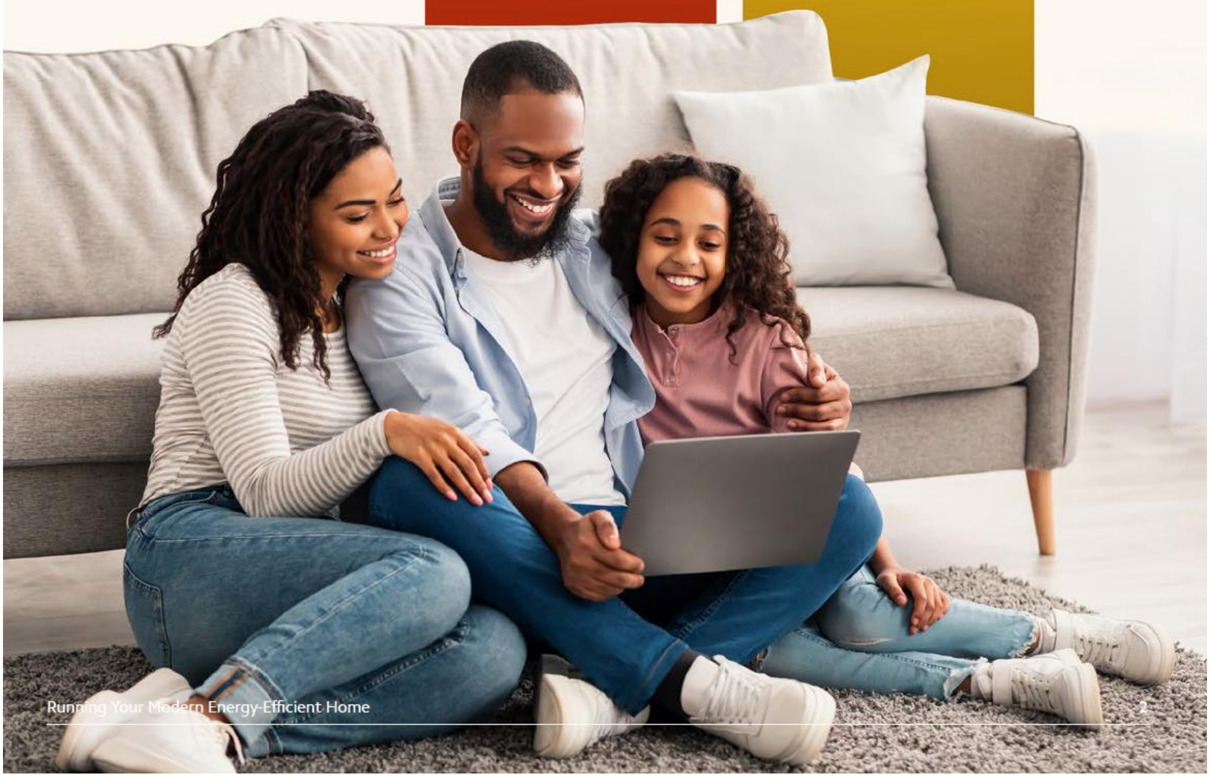
20 °C to 22 °C in winter.

Try not to use heating in summer unless necessary.

Bedrooms

17 °C to 19 °C in winter.

Try not to use heating in summer unless necessary.



AMBER

Comfort & Health Advice

Indoor Temperature

Improvement Tips

Indoor temperature is a measure of the warmth or coldness inside a building. This value is critical to your own comfort and will vary from person to person.

When choosing what temperature to operate your home at, be mindful that if it is high, this is

(a) going to cost you more

(b) may lead to a less healthy environment and

(c) will increase your carbon footprint.

Turn down your thermostat Even a reduction of 1°C can save up to 10% in energy use,

Open windows at night in summer to help prevent overheating.

Keep doors fully closed in heated rooms. However, do not block the gap under the doors as these are needed to supply fresh air to the room.

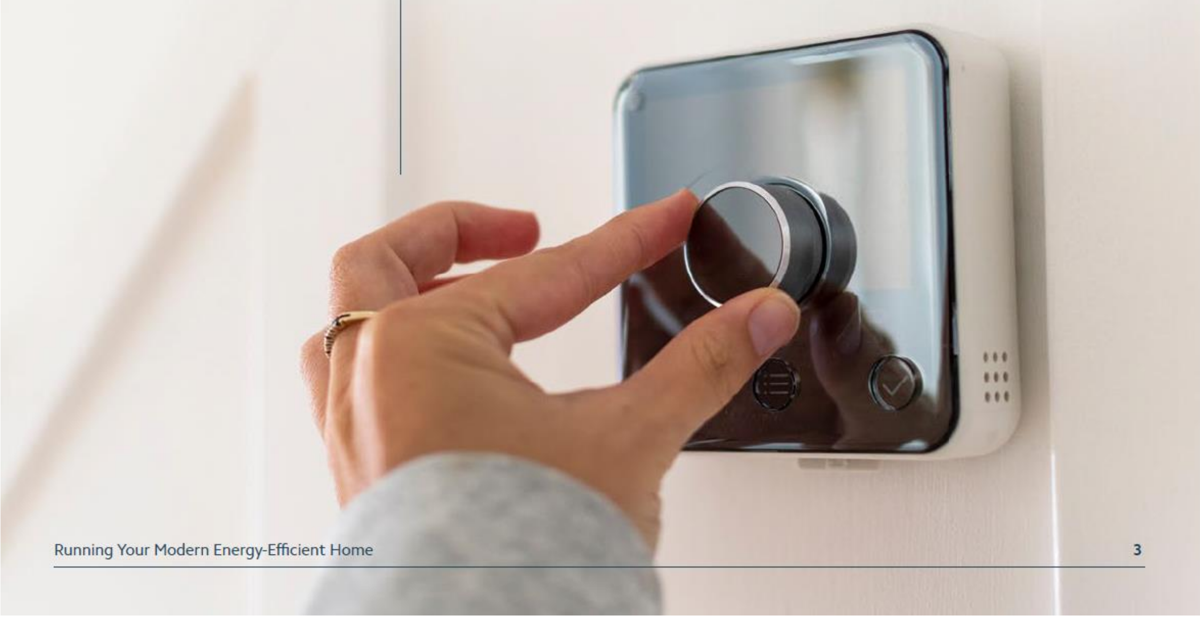
If a room is too hot **open a door to the rest of the house rather than open a window.** This will help heat the whole house keeping it warmer for longer.

Leave blinds/curtains open during sunny days to let the sun rays enter the rooms so you benefit from solar heat gain and save on heating.

Check the running times of your heating system and adjust them to when you actually need heat. Turn off heating well before going to bed as the insulation should keep the space warm enough for long enough.

Keep the blinds/curtains fully closed during cold nights to stop warm air escaping, even in unoccupied and unheated rooms.

If you tend to feel the cold more, it is better to **add extra layers (such as a jumper or knee rug) to keep warm instead** of putting the heating on for a short time.



Energy Advice

Appliance Electricity Use

New regulations have made appliances more energy efficient, but as technology advances a larger number of small electrical items, such as smart home devices, laptops, phones, and tablets, are also being used in homes.

When a home is designed it is difficult to accurately calculate how much electricity these devices will use.

However, this also means that you have a lot of control over this energy use.

Improvement Tips

- Run your dishwasher on **low temperature**
- Run your washing machine **on a cooler or eco cycle**
- **Do not leave the fridge door open for long** while getting food. The longer the door is open the more energy it uses
- **Change old lightbulbs to LED** and add smart plugs to switch things off and monitor consumption
- **Turn off lights** when you are leaving a room or when you do not need them
- **Minimise the use** of personal plug-in electric heaters
- **Turn off all appliances** at night

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Energy Advice

Heat Pumps

Heat-pumps convert energy from the air or ground outside your home into heat and are becoming more commonplace in Ireland due to the minimal electricity needed to run them.

Improvement Tips

Don't set your heat pump to the maximum – it won't heat the room any quicker, but will use more energy.

Use the timer function to heat the space 15 minutes before you use it.

Keep the setting low (18°C or 20°C) to reduce the energy used.

If there is access, **clean your heat pump filter regularly**.

Turn off your heat pump when it's not in use. It can run for as long as you need, but make sure you switch it off when you're not using it.

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Improvement Tips

Do not turn off the ventilation system as it is important to the operation (particularly air quality) of your home and it uses minimal energy.

Do not block vents – they should be left open permanently. However, where you might wish to close a vent, if there is a cold draught remember to open it again when the room becomes unoccupied.

Energy Advice

Ventilation Systems

Intermittent Fans

This system is made up of trickle vents located in windows and doors, and extractor fans fitted in certain rooms of your home, usually bathrooms and kitchens. The trickle vents supply fresh air to your home, while manual extractor fans remove odours, carbon dioxide and excessive moisture from your home.

Demand Control Ventilation

This type of system automatically regulates ventilation based on what is needed, using sensors. For example, an extractor fan that is triggered by high humidity, in combination with trickle vents. The difference between Demand Control and basic Intermittent ventilation is that it operates automatically, without requiring any manual use.

Continuous Mechanical Supply and Extract with Heat Recovery

Mechanical Ventilation with Heat Recovery (MVHR) continually removes stale moist air from rooms, while supplying a balanced amount of outside air directly to habitable rooms. The difference between MVHR and other ventilation systems is that with MVHR, the heat energy carried by the stale air is used to partially heat the fresh intake air through a heat exchanger. This reduces the energy use of the building's heating system and minimizes the loss of heat to the outside atmosphere while maintaining fresh clean air.

AMBER

Comfort & Health Advice

Ventilation – Carbon Dioxide Levels

Carbon Dioxide (CO_2) is an invisible gas which is naturally generated by many human activities.

While not important in small concentrations, higher concentrations have been shown to affect humans by making them tired, decreasing their level of concentration and even causing sleepiness.

Groups of people gathering for long periods or sleeping in poorly ventilated rooms is a common cause of high CO_2 levels.

Regularly Maintain Ventilation Systems Clean filters, ducts and vents.

If a group of people is assembled in a room, **open a window in summer** to dissipate the CO_2.

Free-standing gas heaters should not be used as they create high amounts of dangerous carbon monoxide gas.

In bedrooms which have an en-suite bathroom, **leave the joining door open** to reduce the overnight build-up of CO_2.

Ensure your window trickle vents or wall vents are fully operational and open, particularly in rooms that are occupied for long periods, such as living rooms, kitchen or bedrooms.

Keep trickle vents open and on the recommended setting. However, in winter, if the trickle vent must be closed, remember to open it again when you leave the room.

CO_2 is measured in CO_2 Parts Per Million (PPM)

The different levels and affects of CO_2 in your home are, typically:

Less than 400 PPM
Optimal level

1000 - 1500 PPM
Affects alertness of occupants

400 -1000 PPM
OK but not optimal level

More than 1500 PPM
Affects energy and concentration of occupants

Did you know?

Carbon Dioxide occurs naturally in the atmosphere and is different from Carbon Monoxide which is toxic and is produced from incomplete combustion of fossil fuels.

AMBER

Comfort & Health Advice

Damp & Condensation

Relative Humidity (or RH), is also known more simply as condensation. It is a measure (in percent) of the amount of moisture in the air and it varies with temperature.

The higher the temperature in a room, the more water that air can absorb.

100% RH means the air cannot hold any more water without it condensing, in other words, forming water droplets on colder surfaces. This is why in your bathroom, for instance, moisture can be seen on the window, mirror glass or the tiled walls.

Excess RH for prolonged periods can encourage mould growth.

Did you know?

Prolonged periods of **RH below 30%** can lead to an uncomfortable environment due to dryness and it can cause irritation to people with respiratory conditions.

Improvement Tips

In the summer, open windows to remove moisture from cooking, showering and sleeping. In winter, only open windows for short periods.

Close the door of the en-suite or bathroom if you're using the shower – this avoids moisture laden air travelling into the adjoining rooms.

Never block vents or gaps underneath internal doors

Ensure your window trickle vents are left open

Gas heaters should not be used as they create high moisture content.

Make sure **humidity extraction vents and fans are switched on** and functioning

Keep kitchen doors closed while cooking to prevent transfer of moisture to other rooms.

Dry your wet clothes outside or make sure windows are slightly open to allow moisture to escape.

Always use an extractor fan in the kitchen when doing anything with boiling water. This will help to prevent extra moisture build-up.

Leave the doors of occupied bedrooms open during the day - this will disperse the night moisture in the air throughout the house.

After taking a shower/bath, leave the door to the bathrooms open all day to help reduce the concentration of the moisture in that and adjacent rooms.

If you find mould growth, you should **ventilate the space and remove the water source** if possible.

Did you know?

Prolonged periods of **RH above 80%** could result in mould growth and damp.

Appendix M – Data sheets

➢ Lorawan ERS CO_2 wireless Sensors

Datasheet
Publish Date: 20.08.2019

ERS CO_2

ELSYS.se
LoRaWAN Wireless Sensor

Description

ERS CO_2 is a sensor for measuring the indoor environment. It is enclosed in a room sensor box and is designed to be wall mounted. ERS CO_2 is completely wireless and powered by two 3.6V AA lithium batteries. Inside you will find internal sensors for measuring indoor CO_2 levels, temperature, humidity, light, and motion.

Applications

- Indoor environment measuring
- Smart buildings
- Workplace management
- Room occupancy

Product features

- LoRaWAN Certified CM
- CO_2 sensor
- Temperature sensor
- Humidity sensor
- Light sensor
- Motion detection sensor (PIR)
- NFC for configuration
- Configuration over the air

Device Specifications

Mechanical specifications	
Weight	80 g excluding batteries / 120 g including batteries
Dimensions	86 x 86 x 27 mm
Enclosure	Plastic, PC/ABS

Operating conditions	
Temperature	0 to 50 °C
Humidity	0 to 85% RH (non-condensing)

Device Power Supply	
Battery Type	2 x 3.6V AA Lithium Batteries
Expected Battery Life	<10 years (Depending on configurations and environment)

Device Logging Function	
Sampling Interval	Configurable via NFC and downlink configuration
Data Upload Interval	Configurable via NFC and downlink configuration

Radio / Wireless	
Wireless Technology	LoRaWAN® 1.0.3
Wireless Security	LoRaWAN® End-to-End encryption (AES-CTR), Data Integrity Protection (AES-CMAC)
LoRaWAN Device Type	Class A/C (configurable) End-device
Supported LoRaWAN® features	OTAA, ABP, ADR, Adaptive Channel Setup
Supportet LoRaWAN® regions	US902 – 928, EU863 – 870, AS923, AU915 – 928, KR920 – 923, RU864, IN865
Link Budget	137 dB (SF7) to 151 dB (SF12)
RF Transmit Power	14 dB / 20 dB (Region specific)

Data types			
Type value	*Type*	*Data size*	*Comment*
0x01	Temperature	2	-3276.5 °C → 3276.5 °C (Value of: 100 → 10.0 °C)
0x02	Humidity	1	0 – 100 %
0x04	Light	2	0 – 65535 Lux
0x05	Motion (PIR)	1	0 – 255 (Number of motion counts)
0x06	CO_2	2	0 – 2000 ppm (Extended: 0 – 10000 ppm)
0x07	VDD (Battery voltage)	2	0 – 65535 mV
0x3D	Debug information	4	Data depends on debug information
0x3E	Sensor settings	n	Sensor setting sent to server at startup (first package). Sent on Port+1.

Sensors

Temperature

Resolution: 0.1 °C

Accuracy: ±0.2 °C (See figure 1)

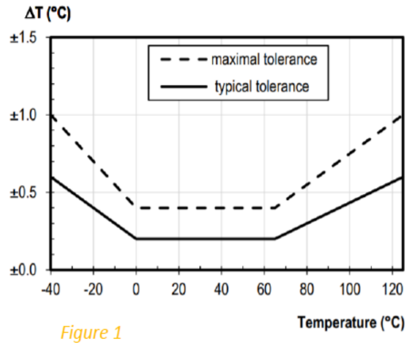


Figure 1

Humidity

Resolution: 0.1 % RH

Accuracy at 25 °C: ± 2 % RH (See figure 2)

Accuracy of humidity over temperature: See figure 3

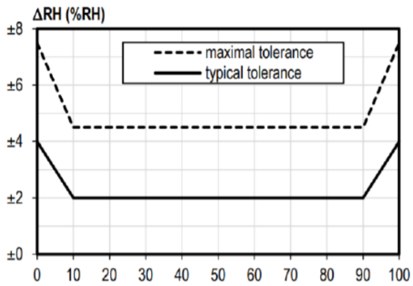


Figure 2

Light

Range: 4 – 2000 LUX

Resolution: 1 LUX

Accuracy: ± 10 LUX

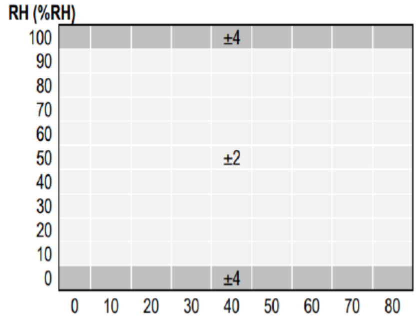
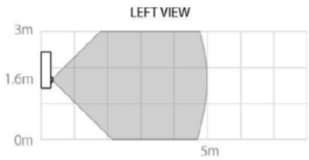


Figure 3

Motion (PIR)



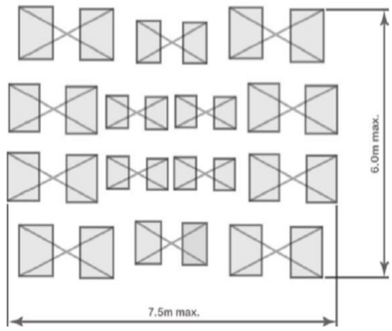
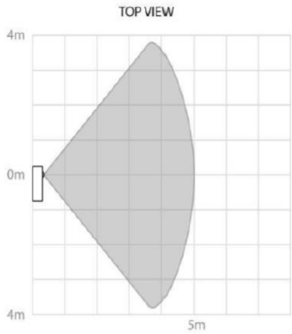


Figure 4 - Detection pattern



Note:
There is a blanking time of 30 seconds of the PIR triggering after each PIR trig and after each transmission. This is to reduce the risk of self-triggering from internal events that could disturb the high sensitivity PIR circuits.

CO_2

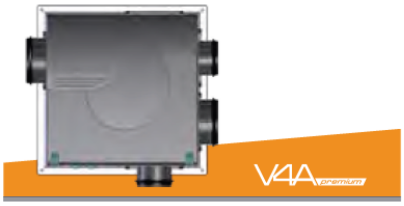
Range, calibrated: 0 – 2000 ppm
Range, extended: 0 – 10000 ppm
Accuracy, calibrated: ± 50 ppm / ± 3% of reading
Accuracy, extended: ± 10% of reading

Accuracy is met at 10 – 40°C, 0 – 60%RH, after minimum three (3) performed Automatic Baseline. Corrections, preferably spanning eight (8) days in-between, or a successful zero-calibration

Noise: 14 ppm at 400 ppm / 25 ppm at 1000 ppm

Note:
The CO2 sensor has an internal automatic calibration routine. This routine calibrates the sensor to set 400 ppm to the lowest value that has been read in the last period of approximately 8 days. This means that in an 8 day period, the sensor must be exposed to fresh (well ventilated) air at least once for the calibration to work. The sensor can also be manually calibrated.

➢ DCV Fan

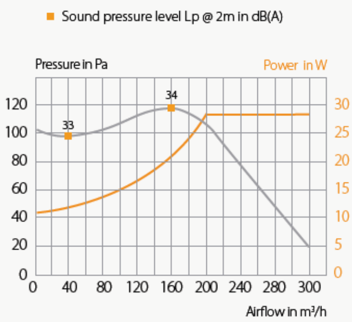


Acoustic fan		V4A Premium 100V	V4A Premium 230V
Standard code		V4A199	V4A336
Airflow characteristics			
Max. airflow @ 100 Pa	m³/h	210	210
Max. pressure	Pa	118	118
Acoustics			
Sound pressure level Lp @ 40 m³/h (r = 2m)	dB(A)	33	33
Sound pressure level Lp @ 160 m³/h (r = 2m)	dB(A)	34	34
Electrics			
Power supply		100 VAC / 50 Hz	230 VAC / 50 Hz
Motor type		Electronic commutation	Electronic commutation
Consumption @ 40 m³/h	W	12.5	12.5
Consumption @ 160 m³/h	W	22	22
IP degrees of protection		IP30	IP30
Characteristics			
Weight	kg	6.7	6.7
Colour		grey	grey
Material (envelope)		PS	PS
Dimensions	mm	450 x 450 x 219	450 x 450 x 219
Installation			
Max. available connections		4	4
Max. connectable extract units (airflow capacity)		4	4
Inlet*	mm	ø100 or ø125	ø100 or ø125
Outlet	mm	ø125	ø125
Installation in inhabitable place (cupboard, ceiling, etc)		■	■
Installation in protected non-inhabitable place (attic, etc)		■	■
Installation on wall or ceiling		■	■
Installation on the floor		■	■
Maintenance			
Removable filter		-	-
Easily dismountable propeller		■	■
Easily openable cover (no tools needed)		■	■
Removable electrical part (motor change without taking off the fan)		■	■
Working			
Direct driven propeller		■	■
Speed	RPM	1350	1350
Other fonctions			
12 VAC output for 4 boost airflow extract units supply		■	■

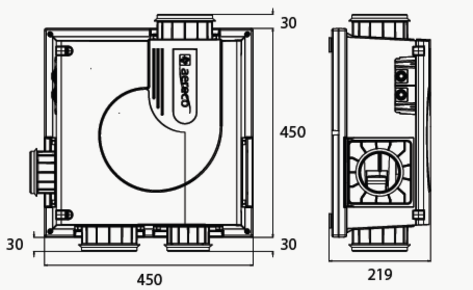
* Not supplied, available as accessories

■ : standard

Airflow characteristics



Dimensions in mm



- Demand controlled exhaust unit

BXC
DEMAND CONTROLLED EXHAUST UNIT FOR MEV

Exhaust unit

A multifunctional exhaust unit to optimise indoor air quality and energy efficiency in MEV applications

The BXC incorporates all of the functions one could want in an air exhaust unit: various activation modes, such as humidity sensitive, presence detection, switch, and even CO_2 are available to adapt the ventilation to occupants' needs. The exhaust airflow is automatically modulated, in silent operation. The range of variable airflows can be set at installation to meet special needs, or to compensate for a lack of pressure; commissioning is also facilitated by the presence of a pressure plug, which allows measurement and easy calculation of the airflow.

Airflow '+': airflow can be set at time of installation (1)

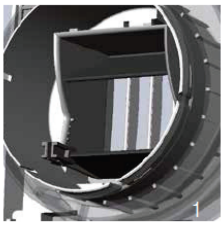
The BXC lets you set the airflow according to the pressure available or to specific regulation requirements. The fixed shutter can be set to 6 positions, with an average step of +10 m^3/h (maximum = +50 m^3/h).

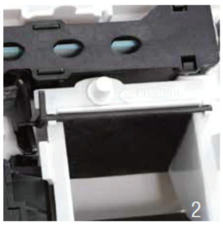
Pressure plug to help commissioning (2)

The built-in pressure plug makes it easy to measure the pressure using a manometer, then calculate airflow using a table in the installation instructions.

Advanced special versions (3)

The BXC was the first exhaust unit in the world offering the possibility of having built-in CO_2 and VOC sensors, for example. These innovations are especially well suited to applications in schools, offices, gymnasiums, mobile homes, etc. A remote control version is also available.





Humidity sensitive, presence detector and switch versions: modulates the airflow according to the various needs of the dwelling.

Airflow '+': possibility of setting the airflow levels at installation: up to + 50 m^3/h on the max. airflow.

Advanced special versions: CO_2, VOC, and remote control versions.

Silent working: silent auxiliary airflow activation.

Battery indicator: buzzer to indicate low battery level.

Pressure plug: allows pressure measurement to determine the airflow.

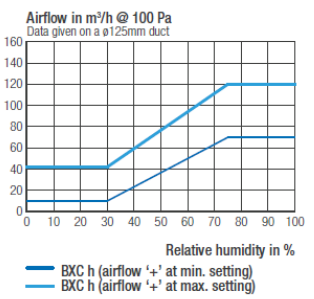
Easy to maintain: removable shutter case and front cover for easy cleaning.

for technical data, see page 82

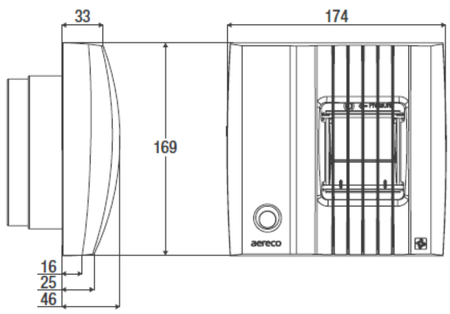
BXC Exhaust unit for MEV

		BXC h	BXC p	BXC hi	BXC hp	BXC pd
Standard code		BXC273	BXC276	BXC215	on request	BXC299
Airflow characteristics						
Humidity sensitive		■	-	■	■	-
Boost airflow		-	■	■	■	■
Boost airflow activated by switch		-	-	■	-	-
Boost airflow activated by presence detection		-	■	-	■	■
Other activation modes		-	-	-	-	-
Airflow @ 100 Pa (min.-max.) (1)	m³/h	12-70	12-70	12-70	12-70	12-70
Airflow '+' - maximum available airflow @ 100 Pa (2)	m³/h	120	120	120	120	120
Acoustics						
Sound pressure level Lp @ 2 m, 100 Pa, 80 m³/h, min. airflow '+' setting	dB(A)			28.3		
Dn,e,w (C, Ctr) Acoustic insulation, RH = 65 %, min. airflow '+' setting	dB	57 (-2 ; -4)	-	57 (-2 ; -4)	57 (-2 ; -4)	-
Power supply						
2 x 1.5 V AAA LR03 batteries (not supplied)		-	⊠	⊠	⊠	⊠
Buzzer (low battery charge)		-	■	■	■	■
12 VAC supply with specific transformer (ref. CAL261)		-	⊠	⊠	⊠	⊠
Characteristics						
Colour		white	white	white	white	white
Material (main)		PS / ABS	PS / ABS	PS / ABS	PS / ABS	PS / ABS
Installation						
Round duct compatibility with integrated spigot	mm	ø125	ø125	ø125	ø125	ø125
Round duct compatibility with accessory spigot (3)	mm	ø100	ø100	ø100	ø100	ø100
Round duct compatibility - bracket version (min.-max.)	mm	ø85 - ø90	ø85 - ø90	ø85 - ø90	ø85 - ø90	ø85 - ø90
Rectangular duct compatibility - bracket version (min.-max.)	mm	67 x 60 - 67 x 66	67 x 60 - 67 x 66	67 x 60 - 67 x 66	67 x 60 - 67 x 66	67 x 60 - 67 x 66
Other functions						
60" delay to activate the presence boost airflow		-	-	-	-	■
Pressure plug		■	■	■	■	■

Airflow characteristics



Dimensions in mm



BXC hpd	BXC co_2	BXC voc	BXC hrc	BXC rc	BFX	BXC s
BXC275	BXC401	BXC402	BXC406	BXC404	BXC371	BXC403
■	-	-	■	-	-	-
■	■	■	■	■	-	■
-	-	-	-	-	-	☒
■	-	-	-	-	-	-
-	CO_2 level	VOC level	remote control	remote control	-	BXC CO_2 or VOC
12-70	12-80	12-80	12-80	12-80	12 / 120 (4)	12-80
120	130	130	130	130	120	130
			28.3			
57 (-2 ; -4)	-	-	57 (-2 ; -4)	-	-	-
☒	-	-	☒	☒	-	☒
■	-	-	■	■	-	☒
☒	■ (CAL included)	■ (CAL included)	☒	☒	-	■
white	white	white	white	white	white	white
PS / ABS	PS / ABS	PS / ABS	PS / ABS	PS / ABS	PS / ABS	PS / ABS
ø125	ø100	ø100	ø100	ø100	ø125	ø100
ø100	ø125	ø125	ø125	ø125	ø100	ø125
ø85 - ø90	ø85 - ø90	ø85 - ø90	ø85 - ø90	ø85 - ø90	ø85 - ø90	ø85 - ø90
67 x 60 - 67 x 66	67 x 60 - 67 x 66	67 x 60 - 67 x 66	67 x 60 - 67 x 66	67 x 60 - 67 x 66	67 x 60 - 67 x 66	67 x 60 - 67 x 66
■	-	-	-	-	-	-
■	■	■	■	■	■	■

Note: airflows given for a ø125 mm duct

■ standard / included - ☒ compatible

(1) Default setting.

(2) Airflow '+' : the airflow can be increased from +10 m^3/h to + 50 m^3/h (6 available positions). This function can be used to adapt to lower pressures or to specific regulations imposing higher airflows. Standard is position 0 (minimum airflow = 12 m^3/h @ 100 Pa).

(3) Delivered in specific versions or available as accessory (A4260: 100mm adaptor for BXC; AEA317: 125mm adaptor for BXC).

(4) Total of 18 configurations available for airflow setting for BFX version.

AERECO

NEW

EMM^2

Humidity sensitive air inlet for windows

- **Slim design: only 31 mm thickness.**
- **Humidity sensitive system: modulates the airflow according to the local relative humidity.**
- **Directional airflow (horizontal) as accessory.**
- **Manual closing and opening device in option.**
- **Additional airflow sleeve available as an accessory.**
- **Slim profile for easy installation on windows.**
- **Easy to maintain: no adjustment, simple yearly dusting.**

Slim design for perfect integration

With its slim design (only 31 mm thickness), the EMM^2 is optimised to discreetly integrate on all types of windows. Its humidity sensitive sensor modulates the airflow according to the ambient humidity level. The EMM^2 has specific accessories to increase the airflow or to adapt the air direction if necessary. The range is composed of 2 humidity sensitive versions and 4 different colors; its single-part front cover facilitates painting. Installed with a specific canopy, it provides an acoustic attenuation of 37 dB.

Directional airflow (1)

The standard version offers an oblique airflow, which can be modified with the accessory O-EMM^2 to adjust the air jet horizontally in case of close proximity of windows reveals or ceilings. Therefore, the airjet is always optimal and the airflow guaranteed.

Additional airflow sleeve (2)

The E-EMM^2 sleeve, available as an accessory, enables an increase in airflows for the different versions of the EMM^2 to satisfy regulatory requirements or to decrease the number of air inlets in some rooms.

A manual closing and opening device (3)

This option, available on the 5-35 humidity sensitive version, allows you to choose between 3 modes: minimum, automatic (humidity sensitive) or maximum to adapt the airflow to the occupant's needs.