# MODELLING INDOOR ENVIRONMENTAL QUALITY IN LOW ENERGY HOUSING

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## Abstract

The aim of this paper is to assess the impact that pollutant sources and ventilation strategies have on thermal comfort levels and indoor air quality (IAQ) in low energy houses through a case study using the detailed thermal simulation program, ESP-r. $CO_2$ is commonly used as a proxy for IAQ, but a novelty of this research is the integrated analysis of distribution for other pollutants, specifically formaldehyde. A model was created based on monitored data from a low energy house. Acceptance criteria for calibrating the model were defined, addressing the current absence of specific guidelines for model calibration based on the monitored indoor environment. Then, a review of current literature of indoor pollutants was undertaken and three time-dependent models were implemented in ESP-r to model formaldehyde emissions. Different scenarios were defined to investigate specific design questions and common ventilation issues regarding the indoor environmental quality (IEQ). The results demonstrate that detailed modelling and simulation can predict IEQ issues and help to design ventilation strategies in low energy houses.

## Introduction

To reduce building energy consumption and carbon emissions, Building Standards require more insulated and airtight buildings, which may lead to a poor quality indoor environment if the ventilation provision is not designed appropriately.

An example can be found in the Dormont Park Passivhaus Development in Scotland, UK, where significant overheating was recorded, even during winter periods. However, the overheating frequency calculated by the Passive House Planning Package (PHPP) was only 0.2 % (MEARU 2015). PHPP is the official tool that is used for certifying that a house complies with the Passivhaus (PH) standard, and it has been validated against measured data (Passivhaus Institut 2014). However, PHPP has limitations. PHPP, as well as other simplified tools, models the entire house as one single zone, where the air is well mixed and the internal heat gains are constant and evenly distributed within the building. This simplification decreases the accuracy of the model when the heat gains are highly localised in certain areas, such as cooking appliances in the kitchen or a number of electronic devices in the living room. Therefore, dynamic simulations are recommended when designing large and complex buildings (Passivhaus Trust 2016). In addition, PHPP follows the quasi-steady monthly method included in the European Standard EN ISO 13790:2008 for the calculation of energy use for space heating and cooling in buildings (Passive House Institute 2012). Therefore, PHPP is focused on estimating annual energy performance, but it does not account for variation in the indoor environmental conditions in different parts of the house at different times.

In addition to overheating, poor indoor air quality (IAQ) in low energy buildings is a concern, not only as a result of reduced ventilation rates, but also due to the increased number of materials used in modern building construction (Raw 1992). These materials, together with cleaning products and occupants' activities, emit pollutants to the indoor environment and can lead to health problems if the ventilation is insufficient.

Detailed building modelling and simulation can be used to design appropriate ventilation systems by predicting the risk of overheating and poor IAQ at different locations in the building at different times. The aim of this study was to assess the impact that pollutant sources and ventilation strategies have on the distribution of thermal comfort levels and IAQ in low energy houses through a case study based on the Dormont Park houses.

## Modelling

A model was created based on the available constructional information, monitored data of the external and internal conditions over a 2-year period, plus detailed occupant diaries. To calibrate the model, a ranking of the sources of uncertainty according to their participation in the indoor environment was done.

In this way, the categories that had a greater impact on the results were prioritised, and their related input variables were the focus of the sensitivity analysis. Thus, these parameters were modified within feasible limits to improve the fit between measurements and predictions. Calibration acceptance criteria were defined, addressing the current absence of specific guidelines for model calibration based on the indoor environment. Once the results were in acceptable agreement with measured data, a review of current literature on indoor pollutants was undertaken and three time-dependent models were implemented in ESP-r to model formaldehyde emissions. This program was selected for its capability to simulate dynamic variations of indoor environmental conditions, in particular, temperature, relative humidity (RH) and concentrations of different pollutants, in different zones within a building. Moreover, it has been extensively validated (Strachan et al. 2008).

The calibrated model was then modified according to different scenarios including mechanical ventilation with heat recovery (MVHR) with and without summer bypass, natural and hybrid ventilation, with different control strategies. These scenarios were defined to investigate specific design questions and common ventilation issues regarding the indoor environmental quality (IEQ).

**Model description**

The house modelled is situated in the Dormont Park Passivhaus Development in Lockerbie, Scotland. The climate is typically mild, with temperatures ranging from 0 to 18.5 °C. The dwelling comprises two floors and nine rooms. The first floor includes a hall, cloak-room, living room, kitchen and utility room, while the second floor consists of a hall, two bedrooms and a bathroom. Each room has been modelled as an independent zone to quantify its indoor conditions separately. A sketch of the model can be seen in Figure 1 and the constructions used are summarised in Table 1. These U-values are measured values for the external wall and the roof, and calculated values for the floor and window.

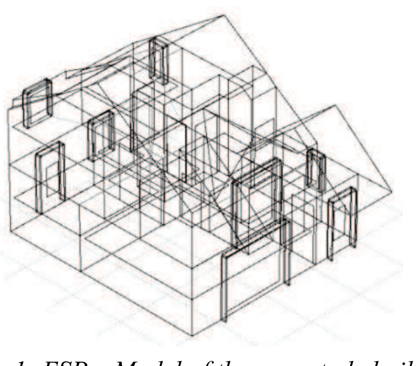

*Figure 1: ESP-r Model of the case study building*

*Table 1: Main construction details*

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

Heating is supplied by a post-air heating unit as part of the MVHR system. This unit senses the temperature in the kitchen and supplies warm air when the temperature drops below the set-point. The maximum temperature of the supply air is set to 50 °C to avoid dust burning inside the ventilation ducts, complying with the PH standard (Passive House Institute 2012).

**Model calibration**

Once the model is built, it is crucial to investigate the results obtained to make sure the model is reasonable and results are in good agreement with measured data. This is done by model calibration.

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

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

For the current case study, it is important that there is good correlation between measured data and the model in respect of the mean, the overall distribution and the variance of the results. To find the most suitable metrics, a review of some common metrics was undertaken and it was decided to assess the model acceptance using a percentile comparison (50 %, 75 % and 90 % percentiles) and the CV RMSE.

The European Standard EN 15251:2007 (CEN 2007) recommends categories of $CO_2$ concentrations above outdoor concentration for energy calculations and demand control ventilation. The minimum amplitude difference between these categories is 150 ppmv. Therefore, a maximum difference between the simulated and the measured percentile of 150 ppmv is considered acceptable for $CO_2$. According to the analysis by Nicol and Humphreys of the SCATs project database (Nicol & Humphreys 2002), where indoor conditions of 26 office buildings across Europe were measured, the range of temperatures at which discomfort will be acceptable is up to ± 2 °C from the comfort temperature. Therefore, a maximum difference between the simulated and the measured percentile of 2 °C is considered acceptable for temperature calibration.

To calibrate the model based on several parameters, a multi-objective function was defined as in (1), and this function needed to be minimised.

$$f = \sum_{zones} \Big( w_t CVRMSE(T) + w_{iaq} Max\big(CVRMSE(p_i)\big)\Big) \tag{1}$$

In the previous equation, $p_i$ is each of the pollutants used to calibrate the model (only $CO_2$ in this case); $w_t$ and $w_{iaq}$ are the weighting factors for the temperature and IAQ respectively. These weighting factors should be defined by the person responsible for the calibration and will depend on the main focus of the study. The sum of the weighting factors must be equal to 1. In this case, all weighting factors were given the same value as the objective was the assessment of temporal and spatial distribution of overheating and poor IAQ within the house, and both temperature and IAQ are considered equally important. Despite the current discussions about $CO_2$ being considered an indoor pollutant or not, there have been studies that found it may impact health at certain levels (Vural 2011; Satish et al. 2012). Therefore, in this study, $CO_2$ was considered an indoor pollutant and its concentration, together with formaldehyde, was used to determine the IAQ within the building.

### Formaldehyde emission model

A review of current literature on indoor pollutants was undertaken and it was decided to focus on formaldehyde as it is a recognised carcinogen (WHO Regional Office for Europe 2010; NTP (National Toxicology Program) 2016) and it can be easily found in common products such as cleaning fluids, wood furniture and carpets.

Currently, there are different tools available to assess IEQ. CONTAM (Dols & Polidoro 2015), for instance, is widely used for IAQ and ventilation analysis. However, this program is not a thermal simulation tool and it does not have the capability of calculating the spatial and temporal distribution of temperature within the building, which makes impossible the assessment of overheating risks under different conditions. In addition, temperature can also vary the pollutant emission rates, and therefore, IAQ.

There are detailed simulation tools, like EnergyPlus and ESP-r, that include both thermal and contaminant calculations. However, the contaminant modelling in these tools is limited. Therefore, a review of emission models for formaldehyde was carried and three time-dependent models from the PANDORA database (Abadie & Blondeau 2011) were implemented in ESP-r. These models are:

- Gas transient power law model:

$$S = a_1 \times t_p^{-a_2} \; if \; t \leq t_p \tag{2}$$

$$S = a_1 \times t^{-a_2} \; if \; t > t_p \tag{3}$$

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

- Gas transient discrete emission data model:

$$S = a_i \; at \; t = t_i, \qquad i \in \mathbb{N} \tag{4}$$

where S is the emission rate (mg/h) at different times $t_i$ (h).

- Gas transient peak model:

$$S = a_1 e^{-0.5\left(\frac{ln(t/t_p)}{a_2}\right)^2} \tag{5}$$

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

### Scenarios

Scenarios have been defined to investigate two typical design questions and the impact that common ventilation issues have on the indoor environment. The questions are the following:

1. Do trickle vents with Mechanical Extract Ventilation (MEV) supply enough ventilation for good IAQ? How does its performance compare with an MVHR system?

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

<u>Ventilation scenarios</u>

*Question 1*

MEV with trickle vents is by far the most common ventilation strategy in the UK (Adam-Smith 2014). Trickle vents are small openings located in the top part of the windows to provide background ventilation for good IAQ. However, some studies have found that this ventilation system does not provide enough ventilation (Sharpe et al. 2014; Sharpe et al. 2015). The scenarios defined to analyse this problem and seek possible solutions are as follows:

- Scenario 1A - Trickle vents with continuous MEV:

Trickle vents and mechanical extract fans were defined according to the Building Standards (Scottish Government 2015). Since the heating was supplied by a post-air heating unit in the MVHR system, this scenario requires another heating system to keep the temperature within comfort limits, for example, radiators in the different rooms.

- Scenario 1B - Trickle vents with boost MEV control:

In this case, a control based on RH is applied to the system to increase the ventilation rate of the fans when RH is above 60 %.

- Scenario 1C - Trickle vents with boost MEV control and window opening:

To control the ventilation in this case, it is assumed that beside the fans working in boost mode when the air is humid, occupants will open the windows of a room when the indoor temperature rises over the comfort temperature (see Table 5).

- Scenario 1D – MVHR:

In this case, ventilation is provided using a MVHR system only (with no trickle vents). The PH standard requires the use of heat recovery units with a minimum efficiency of 75 %. Units that are more efficient are available in the market and efficiencies around 90 % are common practice. In this case, the efficiency is 91 % according to the manufacturer specifications.

- Scenario 1E - MVHR with boost control:

In this case, a control based on RH and indoor temperature is applied to the system to increase the ventilation rate of the fans when RH is above 60 % or the indoor temperature rises over the comfort temperature shown in Table 5.

*Question 2*

There are some concerns that MVHR without summer bypass can lead to overheating issues. One example can be found in the Dormont Passivhaus Development, where no summer bypass was provided in the 2-bedroom houses and overheating was recorded even during winter periods (MEARU 2015). This is not a special case. Several studies have found that lack of summer bypass is a common shortcoming of MVHR systems in new buildings (Balvers et al. 2012; Sharpe et al. 2016). The scenarios defined to analyse this problem and search for possible solutions are as follows:

- Scenario 2A - MVHR
- Scenario 2B - MVHR with summer bypass
- Scenario 2C - MVHR with boost control
- Scenario 2D - MVHR with boost control and window opening available, where the boost option is switched off when windows are open.
- Scenario 2E – Same situation as Scenario 2D but incorporating summer bypass.

All the scenarios for Questions 1 and 2 were defined for two different situations, one assuming internal doors are open and another one assuming internal doors remain shut. The model assumes 15 mm door undercuts as an ideal case even though in real situations these may not exist or be blocked by carpets. In addition, the use of blinds were assumed when the indoor temperature rises over the comfort levels.

Pollutant scenarios for both Questions 1 and 2

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

*Table 2: Formaldehyde sources included in this study*

| Source and Location | Emission Model |
|---|---|
| Nylon carpet (Won & Shaw 2004) in living room, bedrooms, stairs and halls | Gas transient power law model<br>$a_1$=0.0455363 mg/m$^2$h<br>$a_2$=0.3634<br>$t_p$=36.235 h |
| Kitchen cabinet (countertop) - Melamine particleboard (Won & Shaw 2004) | Gas transient power law model<br>$a_1$=0.0059902 mg/m$^2$h<br>$a_2$=0.103<br>$t_p$ =36.035 h |
| Gypsum wallboard (vinyl-faced) (Won & Shaw 2004) in all rooms | Gas transient power law model<br>$a_1$=0.0023535 mg/m$^2$h<br>$a_2$=0.1793<br>$t_p$ =36.485 h |
| Kitchen cleaner - Carrefour éco-planète brand (Meme et al. 2013) | Gas transient discrete emission data model<br>$a_1$=25.8 µg/gh, $t_1$=0.5 h<br>$a_2$=4.5 µg/gh, $t_2$=1 h |

| | |
|---|---|
| Bleach – low cost (Meme et al. 2013) in the bathroom | Gas transient discrete emission data model<br>$a_1$=218.9 µg/gh, $t_1$=0.5 h<br>$a_2$=196.1, $t_2$=1 h |
| Television PDP (Plasma Display Panel) (Kurosawa et al. 2008) in the living room | Gas transient discrete emission data model<br>$a_1$=38 µg/h, $t_1$=0<br>$a_2$=30 µg/h, $t_2$=1 h<br>$a_3$=38 µg/h, $t_3$=3 h<br>$a_4$=30 µg/h, $t_4$=6 h<br>$a_5$=38 µg/h, $t_5$=8 h<br>$a_6$=30 µg/h, $t_6$=24 h |
| Desktop with CRT monitor (Nakagawa et al. 2003) in the living room | Gas steady state emission rate<br>S=0.0128 mg/h |
| New laptop – switched off (Funaki et al. 2003) in the main bedroom | Gas steady state emission rate<br>S=0.001 mg/h |
| Wooden chair (Roux 2013) in the living room | Gas transient discrete emission data model<br>$a_1$=128.8 µg/m$^2$h, $t_1$=24 h<br>$a_2$=96.6 µg/m$^2$h, $t_2$=72 h<br>$a_3$=50.6 µg/m$^2$h, $t_3$=672 h |
| Wooden table (Roux 2013) in the living room and kitchen | Gas transient discrete emission data model<br>$a_1$=19.1 µg/m$^2$h, $t_1$=24 h<br>$a_2$=20.8 µg/m$^2$h, $t_2$=72 h<br>$a_3$=14.9 µg/m$^2$h, $t_3$=672 h |
| Wooden wardrobe (Roux 2013) in the living room and bedrooms | Gas transient discrete emission data model<br>$a_1$=21.9 µg/m$^2$h, $t_1$=24 h<br>$a_2$=18.1 µg/m$^2$h, $t_2$=72 h<br>$a_3$=13.4 µg/m$^2$h, $t_3$=672 h |
| Kitchen cabinet - Melamine particleboard (Won & Shaw 2004) | Gas steady state emission rate<br>S=0.0362158 mg/m$^2$h |

Two different formaldehyde emission scenarios were considered: a low emission rate scenario and a high emission rate one. These scenarios were defined to represent actual formaldehyde levels measured in several houses in Scotland (Farren 2016). The low emission rate scenario is defined assuming materials are five years old. However, the model available for wooden furniture is a gas transient discrete emission data model and there is no information on the emission rate after 5 years. Hence, it has been assumed that the emission rate comes to steady state after the last emission data available (672 hours after the start of the emission). On the other hand, the high emission rate scenario assumes new materials. For both scenarios, it is assumed that cleaning products are used on Saturdays and the TV is used every evening when occupants are in the living room.

Finally, to generalise the analysis to a typical 3-member family, a representative behaviour, differentiating between weekdays, Saturdays and Sundays, has been assumed based on data from the UK Time Use Survey (TUS) 2000 (Flett & Kelly 2016; ONS 2003). The total heat load due to the use of the appliances has been calculated using the internal heat gain sheet from PHPP.

## Results

### Calibration results

After applying the calibration procedure, the maximum differences between simulated and measured percentiles are 174 ppmv and 1.7 °C for the $CO_2$ concentration and indoor temperature, respectively. Regarding the multi-objective function defined in (1), the values of CV RMSE that minimises it are shown in Table 3.

*Table 3: CV RMSE Results for the calibrated model*

| | LIVING | BED1 | BED2 |
|---|---|---|---|
| CV RMSE ($CO_2$) | 23.01 % | 25.28 % | 16.63 % |
| CV RMSE (T) | 10.60 % | 9.31 % | 10.62 % |

Finally, this calibration process gives the results shown in Table 4, where it can be seen that the simulated results are in good agreement with measured data in terms of average and standard deviation of indoor temperature and $CO_2$ concentrations in the living room and bedrooms.

*Table 4: Monitored and simulated results for winter*

| | | | LIV | BED1 | BED2 |
|---|---|---|---|---|---|
| Temperature (°C) | Average | Monitored | 21.1 | 22.9 | 22.5 |
| | | Simulated | 20.0 | 23.3 | 23.0 |
| | Standard dev. | Monitored | 1.7 | 1.5 | 1.4 |
| | | Simulated | 0.9 | 1.0 | 1.0 |
| $CO_2$ (ppmv) | Average | Monitored | 719 | 789 | 716 |
| | | Simulated | 686 | 685 | 658 |
| | Standard dev. | Monitored | 159 | 168 | 111 |
| | | Simulated | 118 | 115 | 67 |

## Scenario analysis results

The results gathered are the operative temperature, $CO_2$ concentration, RH and formaldehyde concentration in the living room and bedrooms. Simulations were run for a winter period (January 2nd to March 31st) for Question 1 and a summer period (June 1st to August 31st) for Question 2, using a time step of 10 minutes.

In order to compare these results, different categories were defined for each parameter using the recommendations in CIBSE Guide A (Chartered Institution of Building Services Engineers, 2006), LEED v4 (U.S. Green Building Council 2016) and World Health Organization (WHO Regional Office for Europe 2010). These categories are shown in Table 5.

*Table 5: Categories for the indoor environmental parameters in this study*

| TEMPERATURE (°C) | WINTER | | | SUMMER | | |
|---|---|---|---|---|---|---|
| | LIVING | KITCHEN | BEDROOMS | LIVING | KITCHEN | BEDROOMS |
| Cold | < 18 | < 16 | < 16 | < 18 | < 18 | < 16 |
| Cool | 18-22 | 16-17 | 16-17 | 18-23 | 18-21 | 16-19 |
| Comfortable | 22-23 | 17-19 | 17-19 | 23-25 | 21-23 | 19-23 |
| Warm | 23-25 | 19-25 | 19-24 | 25-26 | 23-25 | 23-25 |
| Hot | 25-28 | 25-28 | 24-26 | 26-28 | 25-28 | 25-26 |
| Overheating | > 28 | > 28 | > 26 | > 28 | > 28 | > 26 |

| $CO_2$ CONCENTRATION (ppmv) | | RELATIVE HUMIDITY (%) | | FORMALDEHYDE CONC. (mg/m$^3$) | |
|---|---|---|---|---|---|
| Ambient | < 400[1] | | | Ambient | < 0.0025[2] |
| Comfortable | 400-1000 | Dry | < 40 | Comfortable | 0.0025-0.034 |
| Poor | 1000-1500 | Comfortable | 40-60 | Poor | 0.034-0.1 |
| Very poor | > 1500 | Humid | > 60 | Very poor | > 0.1 |

[1] (ProOxygen 2016) [2] (WHO Regional Office for Europe 2010)

Regarding the formaldehyde categories in Table 5, it should be noted that even though the guideline value of 0.1 mg/m$^3$ is for short-term (30-minute), it will also prevent long-term health effects (WHO Regional Office for Europe 2010).

*Question 1*

Results show that, when trickle vents and MEV are used (Scenario 1A), $CO_2$ concentration is over 1000 ppmv for around 35 % of the occupied time in the living room and main bedroom (Bed1) and 24 % in the rear bedroom (Bed2). This situation gets clearly worse when the internal doors remain shut, with $CO_2$ levels exceeding 1000 ppmv around 80 % of the time in the living room and main bedroom and 70 % in the rear bedroom. Figure 2 shows the variation of $CO_2$ concentration during the winter period for this scenario (worst case). It can be seen that the maximum $CO_2$ concentration in the main bedroom, where two occupants were assumed, is almost six times above the comfortable level. The calculated average concentration during the sleeping hours is 1900 ppmv, which is slightly higher but in good agreement with the $CO_2$ concentration measured in natural ventilated bedrooms with closed windows and trickle vents open in 40 new houses in Scotland (Sharpe et al. 2015). Also, peak $CO_2$ concentration of 3425 ppmv for one occupant in a bedroom with closed windows and trickle vents open has been measured in a monitoring study of several new built houses in Scotland (Farren 2016) so these predictions are not unreasonable. Figure 3 shows a comparison of the $CO_2$ concentration results for the Scenario 1A with doors open and shut. The use of boost control based on RH does not make a significant difference in terms of $CO_2$ concentration. On the other hand, window opening or the use of a MVHR system decreases $CO_2$ levels but, in the living room, they still rise over the threshold 45 % of the time when doors are shut. Finally, the use of MVHR with boost control and window opening decreases the $CO_2$ concentration to comfortable levels when indoor doors are open but it still rises over the threshold 20 % of the time in the living room when doors are closed. Therefore, for this case study, MVHR can provide adequate ventilation, regarding $CO_2$ concentration, only when internal doors remain open.

Formaldehyde concentration remained below the 0.034 mg/m$^3$ recommended limit (U.S. Green Building Council 2016) when doors are open for all the scenarios. However, when doors are shut and the ventilation system involves trickle vents with MEV

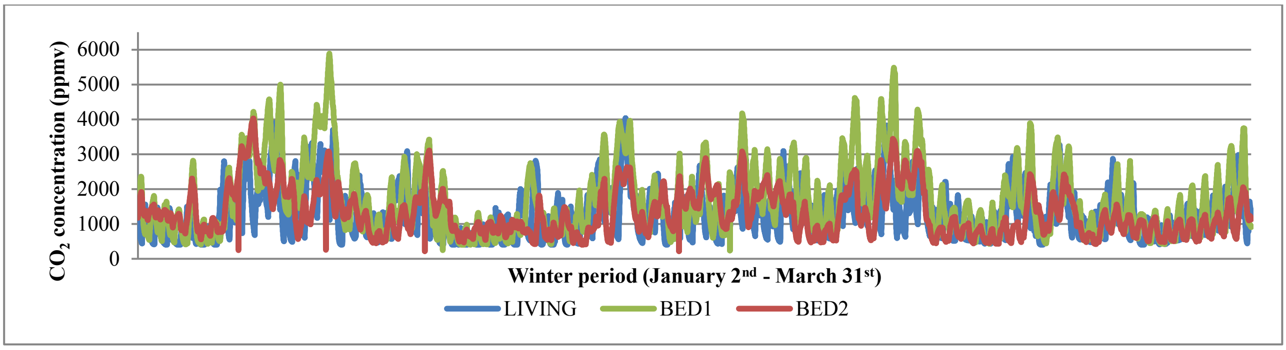


*Figure 2: $CO_2$ results for Scenario 1A with indoor doors shut (worst case)*

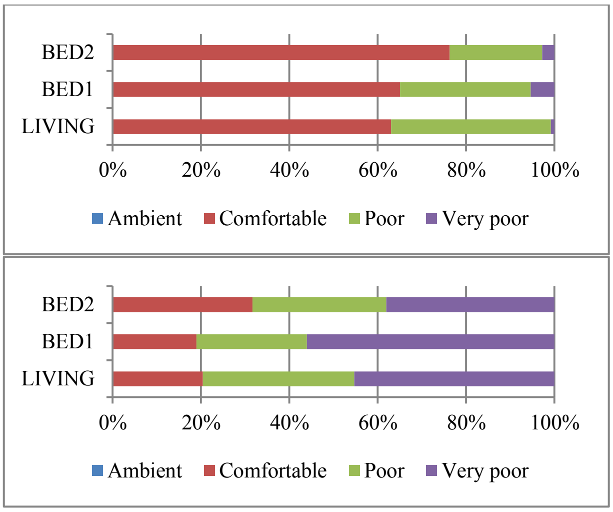


*Figure 3: Comparison of $CO_2$ results for Scenario 1A with doors open (top) and shut (bottom)*

with or without boost control (Scenario 1A and 1B), it rises over the threshold around 20 % of the time in both bedrooms for the low emission scenario and around 40 % for the high emission scenario (see Figure 4). Figure 6 shows the variation of formaldehyde concentration for Scenario 1A with doors shut assuming the high emission rate (worst case). Formaldehyde concentration improves slightly with the opening of windows and, when MVHR is used, it remains below the threshold, independent of the control implemented.

Regarding RH, opening or closing the indoor doors makes a significant difference to the results in the case of trickle vents and MEV system (Scenario 1A). When doors are open the air is dry around 40 % of the time, while it is humid between 40 and 50 % of the time when doors are closed. For the other scenarios, air becomes drier when applying boost control or window opening. Scenario 1E is the worst case with dry air around 80 % of the time in the living room and around 90 % of the time in the bedrooms. The scenario that provides more comfortable periods (around 50 % of the time) is the case of trickle vents and MEV system with boost control (Scenario 1B) if internal doors are open. Figure 5 shows a comparison of the RH results for Scenario 1B (best case) and Scenario 1E (worst case).

Finally, overheating is not an issue for any of the scenarios simulated in this case.

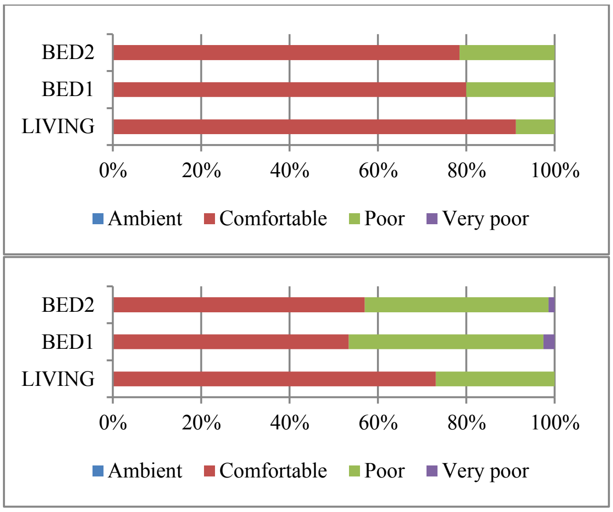


*Figure 4: Comparison of formaldehyde results for Scenario 1A with indoor doors shut – Low emission scenario (top) and high emission scenario (bottom)*

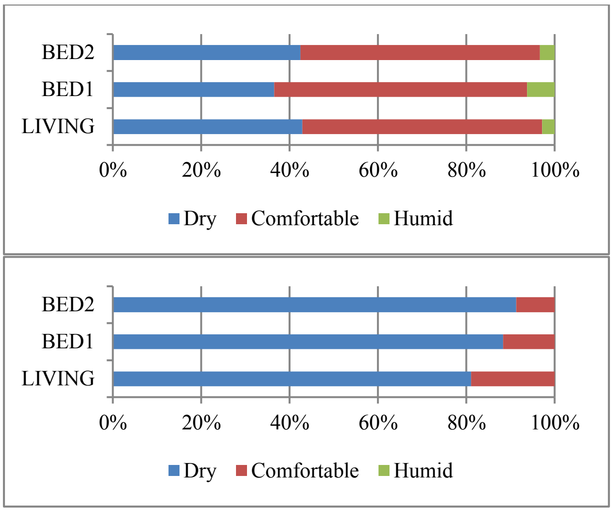


*Figure 5: Comparison of RH results for Scenario 1B with doors open (top) and Scenario 1E with doors open (bottom)*

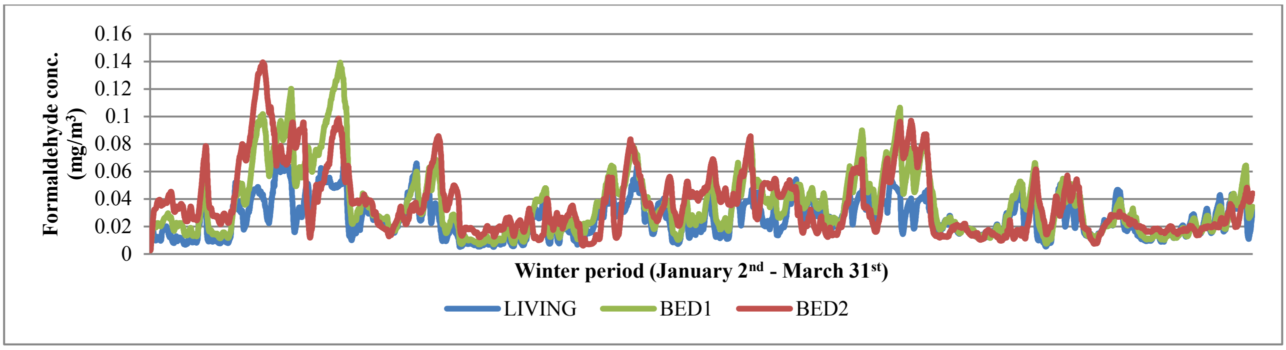


*Figure 6: Formaldehyde results for Scenario 1A with indoor doors shut – High emission scenario (worst case)*

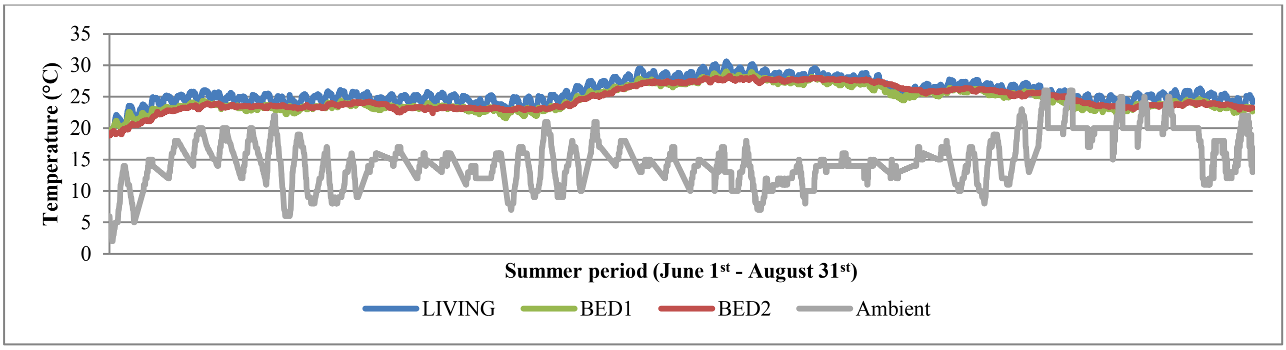


*Figure 7: Temperature results for Scenario 2A with internal doors open*

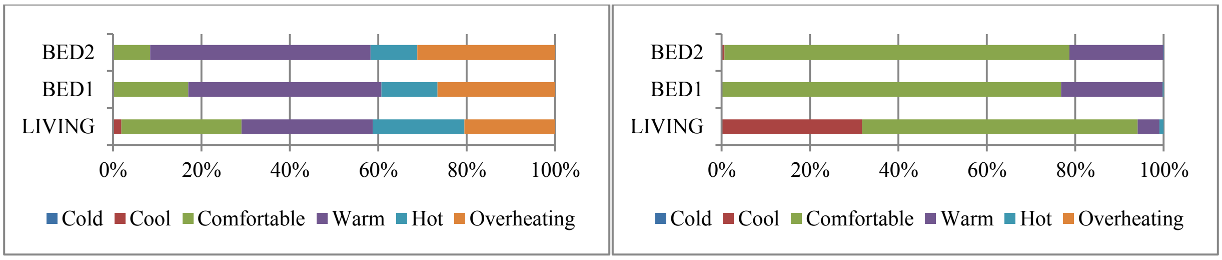


*Figure 8: Comparison of temperature results for Scenario 2A with indoor doors open (left) and Scenario 2E with indoor doors open (right)*

*Question 2*

Results show that MVHR without summer bypass and no window opening (Scenario 2A) can lead to overheating and hot periods for 40 % of the occupied time in the bedrooms and living room; with a maximum temperature of 30 °C (see Figure 7). Selecting boost ventilation when temperature rises over the comfort threshold does not make a significant difference. The use of summer bypass eliminates the overheating and reduces the hot periods to around 10 % of the time in the living room but does not solve the problem completely. MVHR with window opening (Scenario 2D) keeps the temperatures within the comfort range when doors remain open. However, the overheating problem persists when internal doors are shut, leading to hot and overheating periods for around 30 % and 40 % of the time in the living room and bedrooms, respectively. In this case, air velocity could improve thermal comfort as naturally ventilated buildings may have higher air velocities. Indicative air velocities were calculated using the air changes per hour and it was found that the maximum velocity was 1 m/s. Nevertheless, the air velocity was around 0.02 m/s for more than 84 % of the time. Therefore, air velocity is negligible in this case and will not have an impact on thermal comfort levels. The overheating problem is solved when MVHR with bypass is combined with window opening. Figure 8 shows a comparison of the temperature results for Scenario 2A with indoor doors open (worst case) and Scenario 2E with indoor doors open (best case).

Regarding IAQ, formaldehyde concentration remained below 0.1 mg/m$^3$ for all the scenarios. As mentioned previously for Question 1, $CO_2$ concentration in the living room is over 1000 ppmv around 42 % of the occupied time when there is no boost control for the MVHR and the doors are shut. This improves with the use of boost control and window opening but $CO_2$ level still remains over 1000 ppmv around 18 % of the time in the living room if the internal doors are closed. This is solved by opening the doors to let the air flow from the polluted rooms to the ambient through the extract fans.

Finally, RH stays within comfortable levels around 90 % of the time when MVHR is used. Conversely, the use of summer bypass with or without window opening leads to RH levels above 60 % (humid air) between 30 % and 40 % of the time.

## Conclusions

These results show that the model calibration resulted in acceptable agreement between simulated and measured data regarding the indoor environment.

From the scenarios analysed, it can be concluded that trickle vents with continuous MEV may lead to serious problems of poor IAQ, with high levels of formaldehyde and $CO_2$. However, mechanical ventilation strategies do not achieve ideal indoor environment conditions in all cases. Indoor doors should remain open for the $CO_2$ levels to be acceptable, however this may not be a practical solution in most households. In addition, door opening helps to avoid overheating when there is no summer bypass and windows are open to get the heat out of the house. The use of summer bypass without window opening can improve the risk of overheating but it does not solve the problem completely. Regarding RH, since the air is drier during winter, the best option is the use of trickle vents with MEV, while in summer, the air is more humid and better results are obtained with MVHR without summer bypass.

It should be noted that there is not an optimum ventilation strategy for all the indoor parameters considered. A compromise should be made between them in order to decide the most appropriate strategy. Despite this, these examples show how detailed integrated modelling and simulation can predict IEQ issues and help to design appropriate ventilation strategies in low energy houses.

Further work will include the implementation of more complicated emission models of formaldehyde (dependent on temperature and RH) as well as other pollutants, for example, PM2.5. Low energy houses in different climates will also be studied.

In addition, more scenarios will be defined to answer other design question regarding ventilation systems and IEQ in low energy houses. Some of these questions may include:

- What is the impact of switching off the MVHR system? What are the peak concentrations that could arise? How long after switching off is the IAQ threshold surpassed?
- Does continuous constant ventilation (not adapted to occupancy) lead to low levels of RH? If so, how may this be improved?
- Are controls based on RH enough to ensure good IAQ? How does this compare with other types of control?

The analysis of these and other questions should lead to recommendations for the design of appropriate ventilation systems and a better understanding of variations in the indoor environment.

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