Assessment of spatial and temporal distribution of thermal comfort and IAQ in low energy houses

Maria del Carmen Bocanegra-Yanez *[1], Paul Strachan[1], Paul Tuohy[1], Jon Hand[1], Tim Sharpe[2]

[1] *ESRU, University of Strathclyde*
75 Montrose Street
Glasgow, Scotland

[2] *MEARU, Glasgow School of Art*
167 Renfrew Street
Glasgow, Scotland

**Corresponding author: maria.bocanegra-yanez@strath.ac.uk*

ABSTRACT

According to the International Energy Agency, buildings represent over one-third of total final energy consumption. Thus, a more sustainable future begins with low energy buildings which must combine comfort and function using passive systems and new evolving technologies. Policies to reduce building energy consumption and carbon emissions have been developed worldwide during the last decades. As a consequence, Building Regulations and Standards require more insulated and air tight buildings which may lead to indoor environment issues when not designed appropriately or systems are not used as designed. Detailed building modelling and simulation can provide an indication of building performance and furthermore, it can be used to assess indoor environment issues. Although there have been several previous studies of the indoor environmental quality in low energy buildings, this research is focused on the variability of overheating risk and poor indoor air quality (IAQ) at different locations in the building at different times. The impact that different occupancy profiles and ventilation strategies has on the distribution of thermal comfort levels and IAQ in low-energy houses has been assessed using the detailed thermal simulation program, ESP-r.

The first part of the research involved developing a model of a low energy house in accordance with the Passivhaus (PH) standard. Comparison of modelling results and the results from the Passive House Planning Package (PHPP) confirmed that the modelling results were in good agreement with the PH Standard in terms of monthly heat gains and losses of the building. Secondly, more realistic assumptions were formulated so modelling results could be compared with measured data in terms of temperature, humidity and CO_2 distribution within various rooms of the building. Then a number of scenarios were formed, varying occupancy numbers and profiles with different ventilation regimes, which included natural ventilation, mechanical ventilation and mechanical ventilation with heat recovery options. These parametric variations were compared in terms of energy demand, plus temporal variation of indoor environment metrics (thermal comfort and IAQ).

The general conclusion arising from the analysis is that, contrary to the usual assumption of even distribution of the indoor environmental conditions, there can be significant variations in the internal distribution. Important factors are number and location of occupants and the movement of air within the building. Although this study was focused on climate representative of conditions in Scotland, similar variations would be expected in other climates.

KEYWORDS

Thermal Comfort, Indoor Air Quality, Passivhaus, Modelling

1 INTRODUCTION

Policies to reduce building energy consumption and carbon emissions have been developed worldwide during the last decades. In Europe the policy that started the path to energy efficiency in buildings was the European Directive 2002/91/EC (The European Parliament and the Council of the European Union, 2003) completed by the Directive 2010/31/EU (The European Parliament and the Council of the European Union, 2010) which established the

European targets for reducing energy consumption by 20 % by 2020 through improved energy efficiency and integration of renewable energy in buildings.

Many energy performance standards have arisen to promote energy consumption reduction in buildings through different measures. Passivhaus is probably the most worldwide known low energy building standard since its appearance in Germany in the early 1990s (Building Research Establishment, 2011). The PH standard is based on reducing the energy demand needed for heating and cooling by the use of passive measures such as high levels of insulation, air tightness and control of solar gains.

Apart from its obvious benefits reducing energy consumption and environment impact of buildings, the PH standard can lead to health risks due to noise from installations, poor IAQ or overheating according to (Hasselaar, 2008). An example can be found in the Dormont Park Passivhaus Development situated close to Lockerbie, Scotland. This development consists of eight dwellings built to the PH standard. Indoor environmental conditions (temperature, relative humidity and CO_2 concentration) were monitored for two years in the living room, kitchen and main bedroom of the dwellings. In addition, occupants were interviewed regarding the thermal comfort showing that the main concern, common to all the dwellings, was the overheating during warm periods (MEARU, 2015).

Figure 1 shows that the temperatures in the South-facing bedrooms ranged from 20 to 35 °C, oscillating mainly around 25 °C during summer. However, the overheating frequency (when indoor temperature rises above 25 °C) calculated by PHPP (Passive House Institute, 2012) was only 0.2 % (MEARU, 2015), which highlights the limitations of PHPP overheating calculation under certain circumstances. This is clearly stated in the Certified European Passive House Designer Course (CEPH-Developing Group, 2013), indicating that the "accuracy is not very high for values above and below 10 %". Therefore, in those cases, dynamic simulation is needed if risk of overheating was to be avoided when designing a new PH.

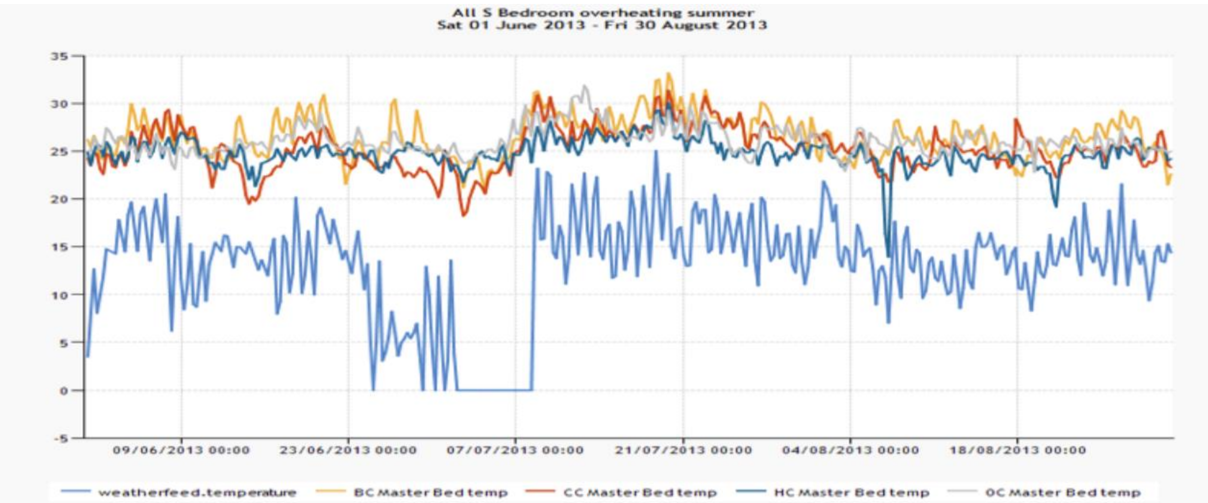

Figure 1. Temperature (in °C) in the south-facing bedrooms and ambient temperature for the summer period (June 1st to 26th August 2013) (MEARU, 2015)

Regarding the IAQ, monitored data shows that the 3-bedroom houses (with 4-5 occupants) have poor air quality issues in the main bedroom. Figure 2 shows that CO_2 concentration was above the acceptable range 50 % of the time in winter since windows remain generally closed. This fact also leads to Relative Humidity (RH) issues with levels below 40 % which can cause health problems.

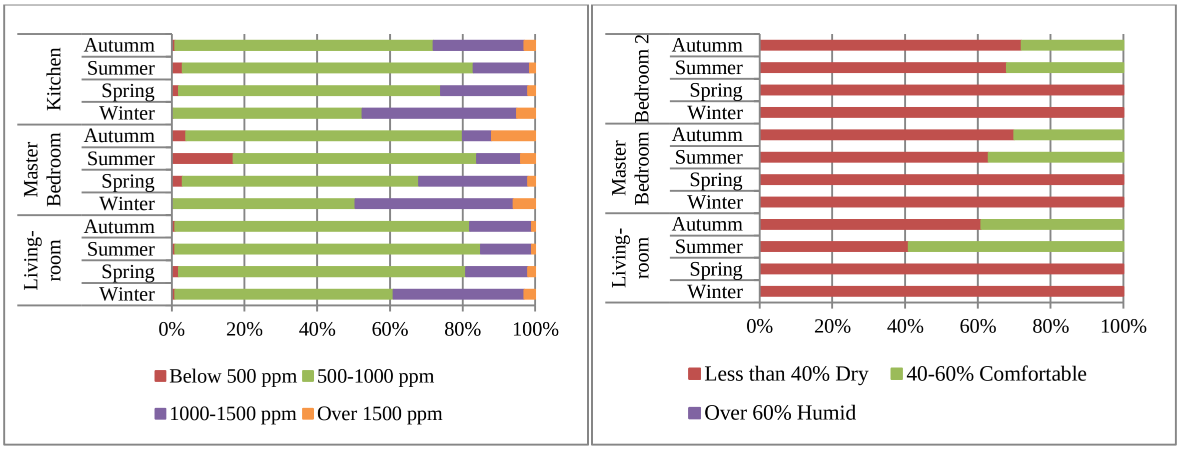

Figure 2. CO_2 concentrations by season for one of the 3-bedroom PH in Dormont (left) and Relative Humidity for one of the 2-bedroom PH (MEARU, 2015)

2 AIM

The aim of this study is to assess the impact that different occupancy profiles and ventilation strategies have on the distribution of thermal comfort levels and IAQ in a low energy house using the detailed thermal simulation program, ESP-r (ESRU, 2015). This program has been selected for its capability to simulate dynamic variations of indoor environmental conditions, in particular, temperature, relative humidity and CO_2 concentrations, in different zones within a building. Moreover, it has been extensively validated (Strachan et al, 2008).

3 MODELLING

This section describes the main characteristics of the model built using ESP-r, which will determine the thermal behaviour of the building. They are divided according to the following categories: Location and climate, Geometry and shading, Materials and constructions and Heating system. The house was chosen to represent a typical detached house in the UK, modified to conform to the PH standard. Once the model was built, it was crucial to investigate the results obtained to verify the model and make sure it was reasonable. This was done by a comparison between the results obtained using PHPP and ESP-r in terms of monthly heat gains and losses of the building.

PHPP is the official tool that is used for certifying that a house complies with the PH standard, and it has been validated and proved against measured data (Passivhaus Institut, 2014). However, PHPP has limitations. It follows the quasi-steady monthly method included in the European Standard 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. For that reason, the use of dynamic simulation tools is recommended when more accurate results are required.

Once the ESP-r model is shown to be in good agreement with the PH Standard, further modification of the ventilation options and the occupancy profile will allow extending the conclusions to other low-energy houses.

3.1 Model Description

The house modelled is situated in Dundee, East of Scotland. The climate is typically mild, with temperatures ranging from -6.1 to 24 °C, and prevailing southwest winds with maximum speed of 19.7 m/s. The dwelling comprises two floors and ten rooms. The first floor includes a hall, living-room, dining-room, kitchen and equipment room, while the second floor consists of a hall, three 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 3 and the constructions used are detailed in
Table 1.

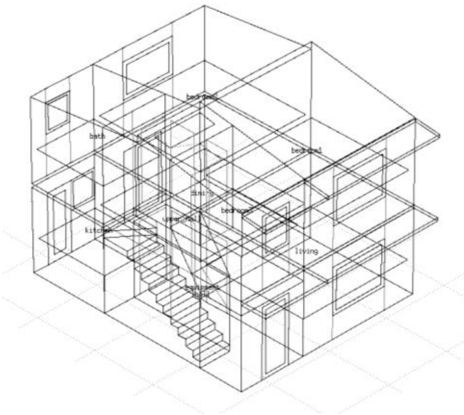

Figure 3. ESP-r Low Energy House Model

Table 1. Main construction details

Construction	U-value (W/m^{2}K)	Insulation		
		Thickness (mm)	Thermal Conductivity (W/mK)	Type
External Wall	0.075	500	0.04	Mineral fibre
Ground Floor	0.085	400	0.04	XPS
Roof	0.097	400	0.04	Glasswool
Window/Door:				
Glazing	0.490	-	-	-
Frame	0.800	-	-	-

Regarding control of solar gains, two types of shading devices are used, overhangs and blinds. Overhangs are designed in all south-facing windows to avoid overheating during summer when solar altitudes are greater, but allowing passive heating during winter when the direct solar incidence is more perpendicular to the windows. The blinds are assumed to be used in all south-facing windows when the indoor temperature rises over 23 °C in winter and 25 °C in summer.

Finally, the system that provides the heating demand to the dwelling needs to be defined. There are several ways to heat a PH to keep the indoor temperature at 20 °C. In this case, heating is supplied by a post-air heating unit as part of the Mechanical Ventilation Heat Recovery (MVHR) system. This unit senses the temperature in the hall downstairs and supplies warm air when the temperature drops below 20 °C. The maximum temperature of the supply air is set to 50 °C, slightly below the maximum set point imposed by the PH standard, which is 52 °C, to avoid dust burning inside the ventilation ducts.

3.2 Model Verification

Once the model is built, it is crucial to investigate the results obtained to verify the model and make sure it is reasonable. This has been done by a comparison between the results obtained using PHPP, ESP-r and monitored data. For the PHPP – ESP-r comparison, the model built using ESP-r has been simplified using PHPP assumptions, such as constant internal heat gains (IHG), constant monthly ambient temperatures, etc. Table 2 shows good agreement in terms of heat gains and losses for the month of January. The only variable that differs from one program to the other is the available solar heat gains. This can be explained by the impossibility of setting constant monthly irradiation values in the ESP-r climate file to match those in PHPP. For this reason, a further comparison has been made looking at annual heat gains and losses. In that case, available solar heat gains obtained from ESP-r only differ by 6 % from that obtained from PHPP, which proves the acceptability of the model.

Table 2. Comparison between the results obtained for January using PHPP and ESP-r

Unit: kWh	**PHPP**	**ESP-r**	**Difference (%)**
Infiltration losses	32.7	33.3	-2.0%
Ventilation losses	24.7	25.2	-2.0%
Available Solar Heat Gains	96.0	126.7	-32.0%
Internal Heat Gains	133.0	131.7	1.0%
Heating Demand	228.0	190.7	16.4%

3.3 Scenarios

The scenarios considered are divided in two categories: ventilation strategy and occupancy profile.

Ventilation strategy

Design options regarding the ventilation system are MVHR, mechanical ventilation without heat recovery and natural ventilation.

I. MVHR:
The PH Standard requires the use of a heat recovery unit with a minimum efficiency of 75 %. More efficient units are available in the market and efficiencies around 90 % are common practice. In this case, the efficiency was assumed to be 92 %.

II. Mechanical Ventilation:
This represents the case of a fault occurring in the heat recovery unit during the cold months or the use of summer bypass to avoid overheating during summer.

III. Natural Ventilation:
This situation applies when fans are turned off and ventilation naturally occurs due to temperature and pressure differences between the inside and the outside of the house. Since the heating was supplied by a post-air heating unit in the MVHR system, this scenario requires another heating system to keep the house at 20 °C, for example, radiators in the different rooms. To control the ventilation in this case, it is assumed that occupants will open the windows of a room when it is occupied and the indoor temperature rises over 23 °C in winter and 25 °C in summer. In the case of bedrooms, windows remain closed during the sleeping hours.

Occupancy profile

The IHG of a building account for the heat generated by the occupants, the lighting and the appliances within each zone. For the present analysis, two different profiles have been considered:

A. 3-member family with PHPP appliance use assumptions
B. 5-member family with typical UK use of appliances

To calculate the heat generated by the occupants, an occupancy profile needs to be defined. This has been done assuming a typical three member-family and five member-family behaviour, differentiating between weekdays, Saturdays and Sundays, based on data from the UK Time Use Survey (TUS) 2000 (Flett, 2014), (ONS, 2003). The total heat load due to the use of the appliances has been calculated using the IHG sheet from PHPP for Scenario A, and a more realistic model based on typical UK use of appliances (Richardson et al, 2010) for Scenario B.

4 RESULTS AND DISCUSSION

This section analyses the modelling results obtained for the different scenarios described in the previous section. Each scenario has been assigned with a code (see Table 3) to facilitate the later result discussion.

Table 3. Scenario codes

Code	Scenario
A1	3-member family profile with PHPP appliance use assumptions and MVHR
A2	3-member family profile with PHPP appliance use assumptions and mechanical ventilation without heat recovery
A3	3-member family with PHPP appliance use assumptions and natural ventilation
B1	5-member family with typical UK use of appliances and MVHR
B2	5-member family with typical UK use of appliances and mechanical ventilation without heat recovery
B3	5-member family with typical UK use of appliances and natural ventilation

The results gathered for each scenario are the operative temperature, CO_2 concentration and relative humidity in every room, and the total heating demand for the whole building. Simulations were run for a winter period (January 1st to March 31st) and a summer period (June 1st to August 31st) using a time step of 15 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). These categories are shown in Table 4 and have been chosen to match the ranges used in the Building Performance Evaluation (BPE) of the Dormont Park Passivhaus Development.

Table 4: Categories for the indoor environmental parameters in this study (Mackintosh Environmental Architecture Research Unit (MEARU), 2015)

Variable	Factor	Winter		Summer	
		Other rooms	Bedrooms	Other rooms	Bedrooms
Temperature (°C)	Cold	<16°C	<16°C	<16°C	<16°C
	Cool	16-18°C	16-17°C	16-18°C	16-19°C
	Comfortable	18-22°C	17-19°C	18-23°C	19-23°C
	Warm	22-23°C	19-24°C	23-25°C	23-25°C
	Hot	23-28°C	24-26°C	25-28°C	25-26°C
	Overheating	>28°C	>26°C	>28°C	>26°C
CO_2 Concentration (ppm)	Ambient	<500 ppm			
	Ideal	500-1000ppm			
	Poor	1000-1500ppm			
	Very poor	>1500ppm			
Relative Humidity (%)	Dry	<40%			
	Comfortable	40-60%			
	Humid	>60%			

4.1 Heating demand

Figure 4 shows the heating demand during the winter period simulated for the different scenarios. As expected, results show greater heating requirements for the models with mechanical ventilation without heat recovery. However, the scenarios with natural ventilation present a lower heating demand than those with the MVHR system, which was not anticipated. These results are due to a very low ventilation rate in the case of the natural ventilation scheme as a result of the assumption of occupants opening the windows of a room only when this is occupied and the indoor temperature rises over 23 °C in winter or 25 °C in summer. This low ventilation rate led to overheating and IAQ issues as discussed in Section 4.2.

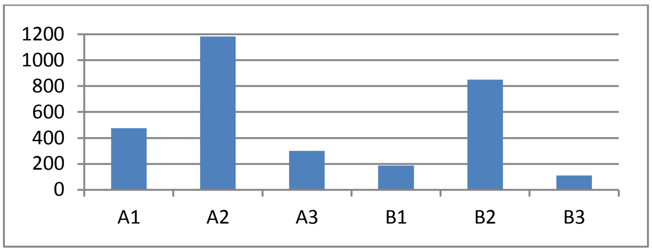

Figure 4. Heating demand (kWh) for the different scenarios

4.2 Overheating

Temperature results during the winter period show similar trends for all the scenarios considered. As an example, Figure 5 shows the result summary for Scenario A1. The temperature throughout the dwelling mainly stays in the comfortable and warm ranges, except for the kitchen, where it is hot 20 % of the time due to the use of cooking facilities. This can be seen more clearly by looking at the daily variation of indoor temperatures for a typical winter week (Figure 6).

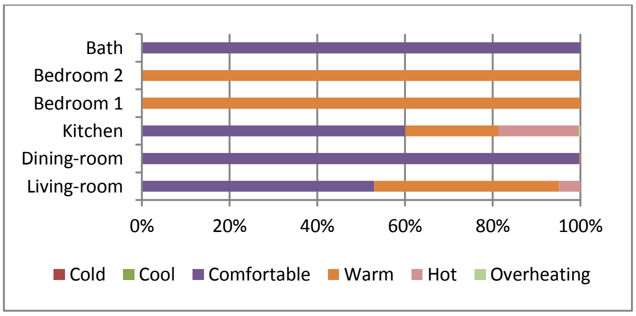

Figure 5. Temperature results for Scenario A1 for the winter period

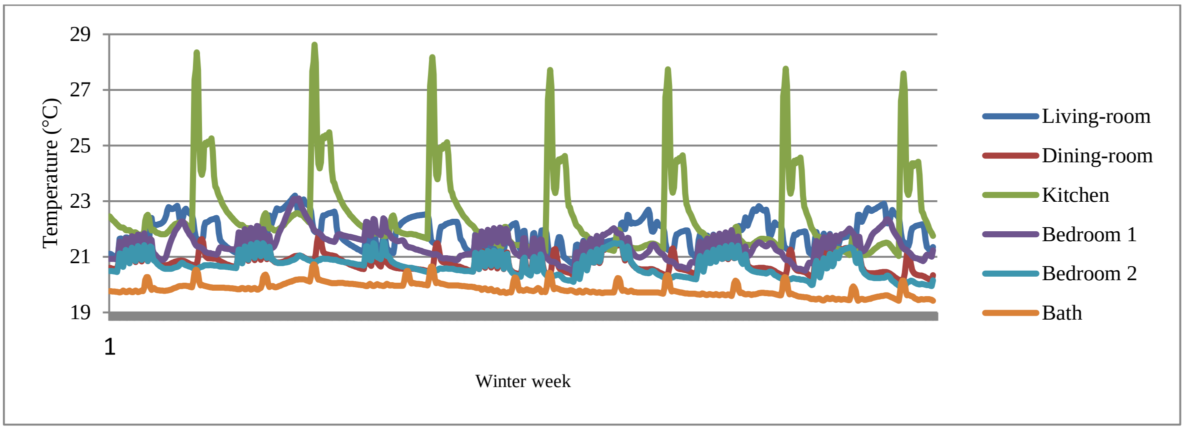

Figure 6. Indoor temperatures during a typical winter week for Scenario A1

For the summer period, differences between the scenarios considered are noticeable. There is more overheating in the 5-member family scenarios due to the higher level of IHG, as may be expected. Figure 7 shows the result summary for Scenario B1, B2 and B3, where overheating is an issue in all rooms for the MVHR and natural ventilation strategies. The use of summer bypass reduces the frequency of overheating but it is not enough to secure comfortable temperatures during summer as shown in Figure 8. Therefore, other strategies should be considered, like the use of hybrid ventilation or boost ventilation when needed.

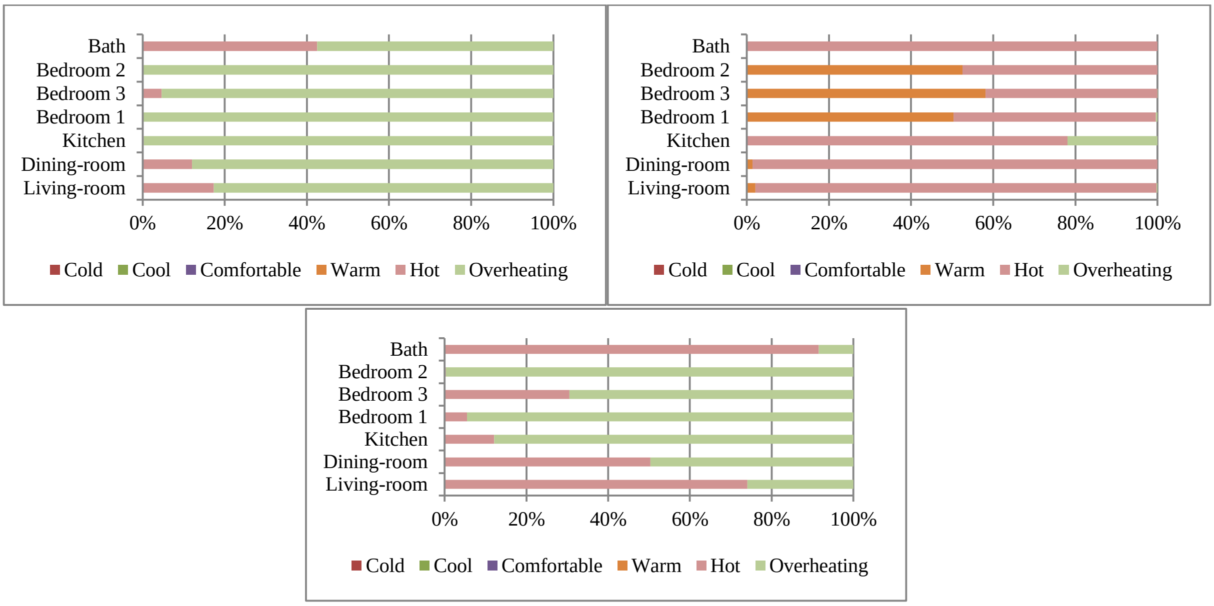

Figure 7. Temperature results for the summer period for Scenario B1 (top-left) , B2 (top-right) and B3 (down)

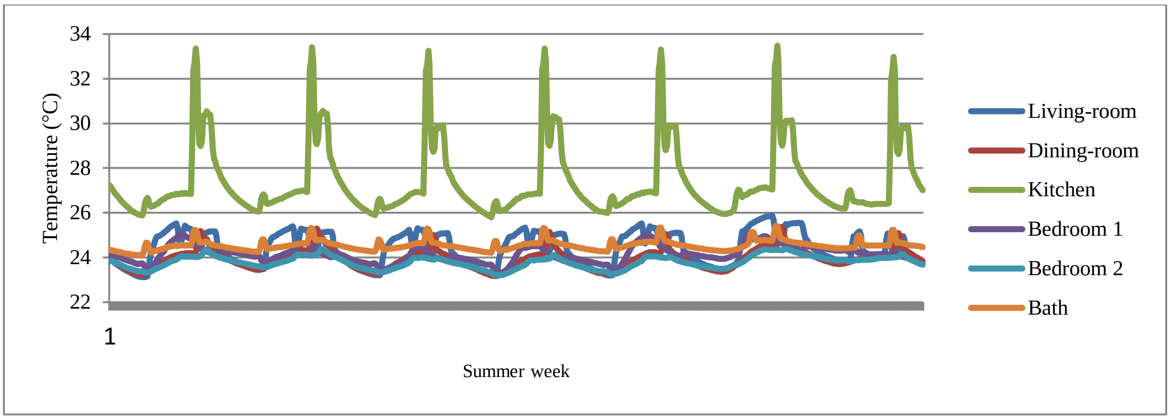

Figure 8. Indoor temperatures during a typical summer week for Scenario A2

4.3 CO_2 concentration

Predicted CO_2 levels show higher concentrations for the 5-member family scenarios as was expected. However, differences are not excessive. Hence, comparisons will be made between the mechanical and natural ventilation strategies. Figure 9 shows the CO_2 concentration frequencies for Scenarios B1/B2 and B3. As previously mentioned, it can be noticed that the assumption of occupants opening the windows of a room when this is occupied and the indoor temperature rises over 23 °C in winter and 25 °C in summer, does not lead to an adequate ventilation rate to keep good IAQ conditions inside the house, and this could lead to serious health problems in the long term. Further investigation should consider the impact of using trickle vents continuously so that a basic ventilation rate is guaranteed.

Beside the clear benefit of using mechanical ventilation in terms of IAQ, results in Figure 9 show that CO_2 levels remain too high for 50 % of the time in the living-room and 30 % of the time in the bedrooms, which represents essentially all the occupied time. A possible solution could be the use of boost ventilation when the CO_2 concentration rises above 1000 ppm.

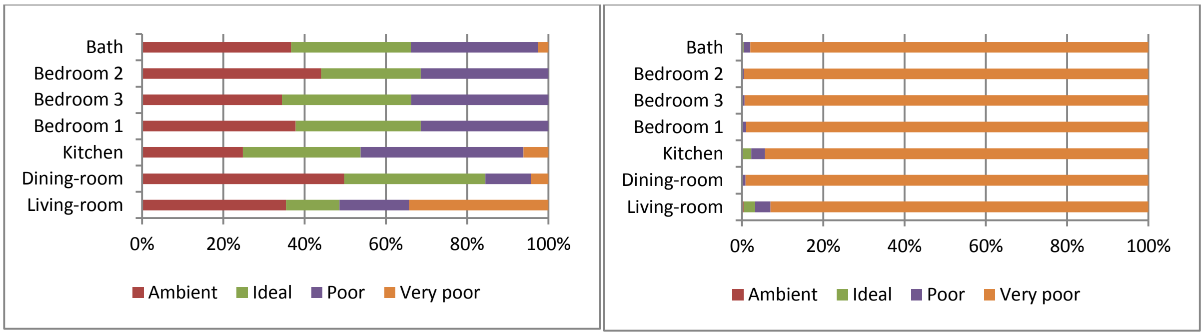

Figure 9. Temperature results for the winter period for Scenario B1/B2 (left) and B3 (right)

4.4 Relative Humidity

Relative Humidity (RH) should be in the range from 40 to 60 % according to CIBSE recommendations (CIBSE, 2006), in order to avoid mould growth and health issues. Results gathered from the simulation of the different scenarios show large discrepancies between the mechanical and natural ventilation strategies. Again, due to the low ventilation rate in the natural ventilation scheme, humidity is not released to the ambient and therefore, high levels of RH are found in all rooms, being slightly worse during winter (shown in Figure 10).

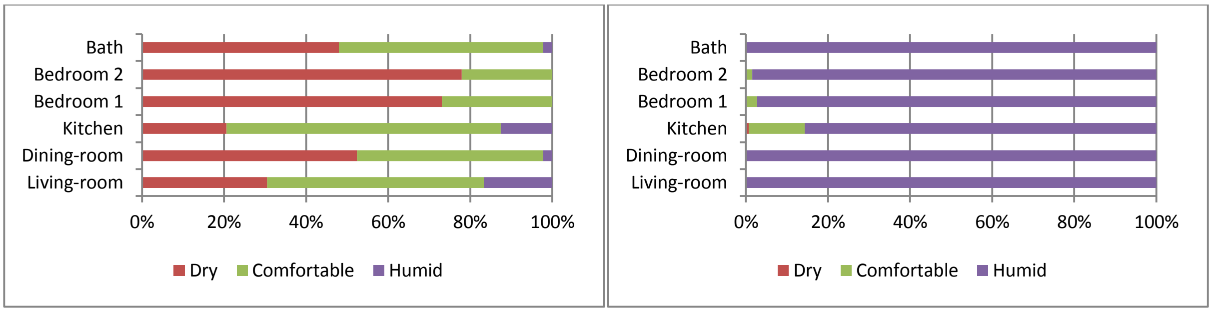

Figure 10. Temperature results for the winter period for Scenario A1/A2 (left) and A3 (right)

On the other hand, the use of mechanical ventilation may lead to very low levels of RH, mainly during the winter period. Results in Figure 10 show RH ranged from dry levels to comfortable levels in all rooms, with the frequency of dry air greater than 70 % in the bedrooms. Thus, moisture content of the incoming air should be controlled to keep the indoor conditions within the comfort range under different circumstances.

5 CONCLUSIONS AND FURTHER WORK

The main conclusion arising from the analysis is that, contrary to the usual assumption of even distribution of the indoor environmental conditions, there can be significant variations in the internal distribution. Important factors are the use of appliances in different rooms within the building at different times, and the ventilation strategy used.

From the scenarios analysed, it can be concluded that natural ventilation, which requires the action of the inhabitants opening windows, may lead to serious problems of overheating and poor IAQ, with high levels of CO_2 and humidity. However, mechanical ventilation strategies do not achieve ideal indoor environment conditions in all cases. The use of the heat recovery unit during summer led to unacceptable levels of overheating throughout the house with temperatures ranging from hot to overheating in all the rooms. This issue can be improved by the use of summer bypass. However, the risk of hot temperatures still remains very high: 50 % of the time for the bedrooms and almost all the time for the other rooms. Regarding IAQ and RH, although the use of mechanical ventilation showed better results than natural ventilation, CO_2 levels remain too high during 50 % of the time in the living-room and 30 % of the time in the bedrooms, which represents almost all the occupied hours. RH ranged from dry levels to comfortable levels in all rooms during winter, with the frequency of dry air greater than 70 % in the bedrooms.

As further work, additional scenarios should be simulated to investigate the impact of hybrid ventilation, with trickle vents continuously opened, or boost ventilation controlled by temperature and CO_2 concentration simultaneously. Also, new occupancy profiles could be defined in order to check the impacts of high occupancy levels, like inhabitants holding a party, children playing in a bedroom or intensive use of appliances like electronic devices throughout the house. The research should lead to recommendations for the design of appropriate ventilation systems and a better understanding of variations in the indoor environment.

6 ACKNOWLEDGEMENTS

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