Chapter 11
An Investigation of Indoor Air Quality in UK Passivhaus Dwellings

Gráinne McGill, Tim Sharpe, Lukumon Oyedele, Greg Keeffe and Keith McAllister

Abstract The adoption of the German Passivhaus Standard in the UK has grown rapidly in recent years. Stimulated by the shift towards energy efficient design and rising fuel costs, the concept is perceived as a potential means of meeting energy and carbon targets through an established, reliable methodology. However the performance of the Standard in terms of adequate indoor air quality and thermal comfort in a UK climate remains under-researched. This paper describes the use of the Passivhaus Standard in a UK context, and its potential implications on indoor environmental quality. A case study is presented, which included indoor air quality measurements, occupant diary, building survey and occupant interviews in a Passivhaus social housing project in Northern Ireland. The study found issues with indoor air quality, the use and maintenance of Mechanical Ventilation with Heat Recovery (MVHR) systems, lack of occupant knowledge and the perception of overheating in the case study dwellings. The findings provide a much needed insight into the indoor environmental quality in homes designed to the Passivhaus standard; which can be disseminated to aid the development of an effective sus-

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tainable building design that is both appropriate to localised climatic conditions and also sensitive to the health of building occupants.

Keywords Passivhaus · Indoor air quality · Overheating · Energy efficiency

11.1 Introduction

In order to meet the legally binding Climate Change Act (2008) of an 80% reduction of net carbon account by 2050 of the 1990 baseline [1], the UK Government has set a target of 'zero carbon' for all new buildings including housing by 2016 [2]. In 2009, the Government revised the definition of zero carbon by introducing the concept of 'allowable solutions' to compensate for the most challenging reductions of carbon emissions on site [3]. In the 2011 budget document released by the UK Government entitled 'The Plan for Growth', standards were relaxed to remove unregulated emissions from the definition [4]. Despite this, the challenge of an 80% carbon emissions reduction by 2050 remains eminent.

The built environment is responsible for approximately 36% of Greenhouse Gas (GHG) emissions for the whole of the UK, with domestic operational carbon emissions 54% of the built environment total [5]. In response, a number of energy efficient design strategies have been implemented in the UK housing sector, including adoption of the German Passivhaus standard. These strategies aim to reduce building carbon dioxide emissions through increased fabric energy efficiency and the adoption of low carbon technologies.

The Passivhaus concept is a voluntary construction standard established in Germany by Professor Wolfgang Feist during the early 1990s [6]. In the UK, adoption of the Passivhaus standard remains in its relatively early stages with approximately 200 completed projects [7], despite over 37,000 Passivhaus certified buildings worldwide [8]. The standard requires adherence to specific criteria; most notably annual maximum space heating requirements of 15 kWh/m^2, maximum annual primary energy of 120 kWh/m^2, utilisation of Mechanical Ventilation with Heat Recovery (MVHR) and an air tightness (n50) of less than 0.6 h^{-1} [9].

Proposals have been made for the Passivhaus standard or similar stringent nonresidential standard to be utilised as mandatory requirements for all new buildings by the European Commission [10, 11]. However, questions remain concerning the applicability of the Passivhaus standard in the UK in which there are key differences, for example, climate, space standards and procurement. The effect of these measures on indoor air quality (IAQ) and thermal comfort remain unknown, particularly in a social housing context. Accordingly, this study aims to (1) investigate the IAQ and thermal comfort of Passivhaus social housing during summer and winter seasons (both physical and perceived), (2) explore the effect of occupant activities on IAQ, and (3) examine occupant knowledge and engagement of the specialist ventilation systems installed in these homes.

11.2 Background

The effect of energy efficient design strategies on occupant health and wellbeing remains significantly under-researched, despite emerging evidence suggesting a significant lack of skills and knowledge in the area. For instance, as discussed by Sullivan et al. [12], limited published studies of IAQ in nearly zero energy homes have been identified in the UK. This is supported by Femenias [13], who explained that demonstration projects for sustainable buildings are rarely monitored adequately, leading to insufficient learning being applied to future projects. As recommended by the Zero Carbon Hub Ventilation and IAQ Task Group, 'further research should be undertaken by [UK] Government to inform future amendments to Building Regulations guidance and ensure public health and safety' [14].

This has been implemented through the Technology Strategy Board's *Building Performance Evaluation* competition, which dedicated £8 m of funding for the performance evaluation of new build/refurbishment projects over four years (2010–2014). Initial findings indicate IAQ concerns in bedrooms of contemporary dwellings [15], with particular issues in relation to the provision of adequate ventilation [16]. Similarly, apprehensions have been expressed regarding overheating in Passivhaus dwellings and significant discrepancies have been observed between measured and predicted indoor temperatures using Passive House Planning Package software [17].

Correspondingly, emerging research from Europe suggests conflicting evidence on the effect on IAQ and thermal comfort in Passivhaus dwellings. On one hand, a review of post occupancy evaluation studies in passive houses in Central Europe by Mlecnik et al. [18] found users of passive houses usually feel more comfortable in winter months compared to summer months. They suggest that further attention to overheating is required in order to improve user satisfaction. Issues with perception of IAQ and knowledge of the heating and ventilation equipment were also highlighted. This criticism of the Passivhaus Standard is supported by McLeod [19], who states that Passivhaus dwellings are inherently vulnerable to overheating and suggests, 'active cooling systems may become a de facto requirement in urban Passivhaus and low energy dwellings in the UK within the next 30–40 years.' Emerging health risks associated with passive houses were also highlighted in studies by Hasselaar and Hens [20, 21].

Conversely, a number of studies have suggested improved IAQ and thermal comfort [22–24] in Passivhaus dwellings. For instance, Mlecnik et al. [25] refer to a study where occupants of Passivhaus homes reported improved freshness of air in the bedrooms during the morning period. However, the suitability of the Passivhaus standard for the UK context remains a contentious issue, with questions regarding the necessity and/or desirability of MVHR in UK dwellings [26–28], particularly in a social housing context. This study therefore seeks to examine the IAQ and thermal comfort in UK Passivhaus social housing through a case study investigation.

11.3 Methodology

The three selected case study dwellings are within a block of five built to the Passivhaus standard, located in a residential area in Northern Ireland. Three mid-terraced Passivhaus dwellings were selected for investigation following discussions with the Housing Association[1] and building occupants. The two-storey, 3–4 bedroom timber frame dwellings also achieved Level 4 in the Code for Sustainable Homes and are compliant with the Lifetime Homes Standard. The development is south facing with main entrance and car-parking to the north (Table 11.1).

Occupant interviews and building surveys were conducted in the three Passivhaus case study dwellings to help obtain information about perception of IAQ, thermal comfort, sick building syndrome (SBS) symptoms and general building conditions. IAQ measurements were conducted in all three dwellings during the summer (May 2013) and in two of the three dwellings during the winter season (Feb–March 2013). Occupant diaries completed during the periods when air quality measurements were taken helped to provide information on occupancy levels, heating schedules and activities that may have affected the results. Construction of the dwellings was completed in April 2012.

11.3.1 Indoor Air Quality Measurements

The IAQ measurements were conducted for approximately 24 h in the ground floor open plan living room and kitchen of each dwelling during the summer and winter season (2013). The living area is south facing, opening onto an external shaded patio and rear garden. The façade consists of large, triple glazed doors and fixed glazing with brise soleil for shading. There is a double height glazed section over the dining area, with fixed shutters for shading (see Fig. 11.1). Measurement parameters include temperature, dew point, wet bulb, relative humidity, carbon dioxide (monitored with Extech EA80 Datalogger/accuracy ±3%, ±5 °C, ±3% of reading or ±50 ppm) and formaldehyde (monitored with HalTech HFX205/accuracy ±5%). Measurements were also conducted in the main bedroom during summer months (monitored with Wohlër CO_2 datalogger/ accuracy ±3% RH, ±0.6 °C, ±3% of reading or ±50 ppm). All IAQ measurements were conducted in accordance with ISO 16000. Outside conditions were monitored during the measurement period with use of a weather station (Watson W-8681-SOLAR) and Wohlër CO_2 datalogger.

Measurements of Volatile Organic Compounds (VOCs) were conducted in house No. 1 during the winter season (2014). Air samples were collected simultaneously in the kitchen, living room, main bedroom and outside. Indoor samplers were positioned at breathing height and away from possible sources of pollution.

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[1] Housing Associations are voluntary organisations that aim to help people to acquire affordable accommodation that meet their requirements.

Table 11.1 Household profiles

Household profiles	No. 1	No. 2	No. 3
No. of occupants	4	6	3
Cooking fuel	Electric	Electric	Electric
Heating fuel	Natural gas	Natural gas	Natural gas
No. of smokers	1	3	1
Cigarettes ever smoked in home	No	No	No
Average hours occupied during week	22	24	24
Average hours occupied at weekend	24	24	22

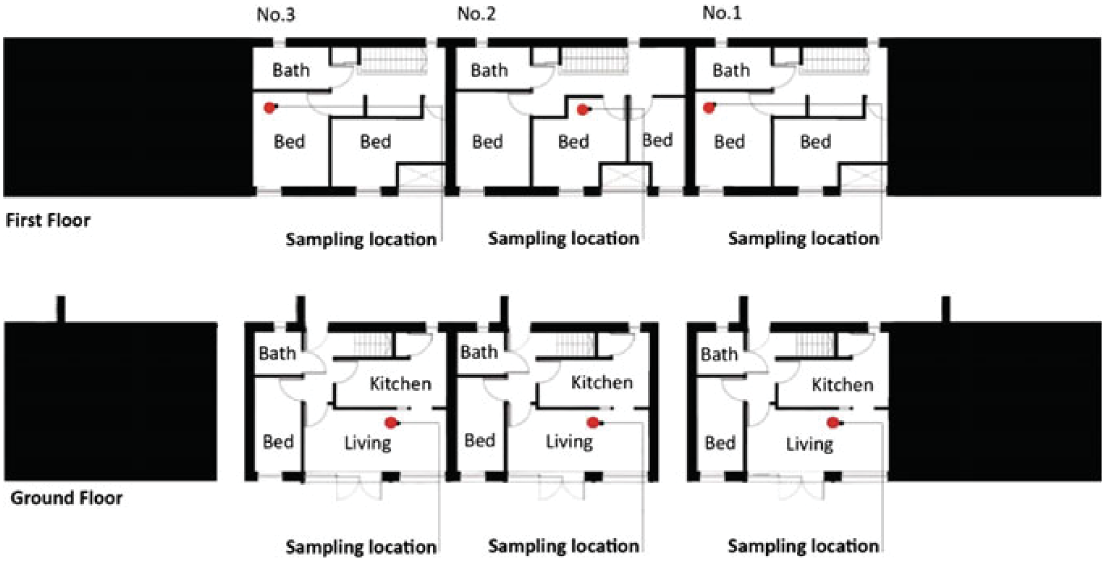

Fig. 11.1 Floor plan and sampling location

The outdoor sampler was positioned in the back garden of house No. 1, away from exhaust vents, openings and direct solar irradiation. Two field blank samples were also taken. A pumped sampling method was deployed (as described in ISO 16017-1:2000) where sorbent tubes packed with an adsorbent (HEYSEP—packed in house) were connected to a pump (pocket pump, SKC, Dorset) at a flow rate of 100 ml/min for approximately 2 h. The collected vapour on each sampling tube was then desorbed using a thermal desorber (ATB 400, PerkinElmer, Cambridge) and transferred into a gas chromatograph (Turbomass GC Mass Spec, PerkinElmer, Cambridge) equipped with a mass spectrometer and a RTX 5 capillary column (50 m, 0.25 mm). Analytical calibration was achieved through liquid spiking onto a sorbent tube. All quantification was achieved relative to toluene. Outside values for hexanal, ethanol and terpenes were not reported as concentrations were below the detectable limit.

11.3.2 Structured Occupant Interviews

Structured interviews were conducted with building occupants of all three Passivhaus dwellings, utilising specifically composed questionnaires. The questionnaires consisted of one for each household, one for each occupant (adults) and one for each child (to be completed by a parent/guardian). The interviews obtained information on the perception of IAQ and thermal comfort during summer and winter seasons, in addition to the presence of any Sick Building Syndrome symptoms (SBS) and Building Related Illnesses (BRI), utilising validated procedures [29, 30]. The household questionnaire gathered information on the building occupants, ventilation strategies, building features, frequency of particular occupant activities, heating schedules and the use of air polluting products.

11.3.3 Occupant Diary and Building Survey

An occupant diary was used to gain information on activities that occurred during the measurement period that might have affected the results. For instance, the diary required the occupants to record average occupancy in the living room/kitchen and in the home every hour. Hourly activities (such as heating, cooking, use of air polluting products, opening of doors/windows, and use of boost mode in the MVHR system) were also recorded through a tick-box method. The occupant diary was compressed to one A4 page for each measurement day, to reduce the burden on the occupants. The building survey recorded information on building features, such as the presence of operable windows, floor coverings and general observations, in addition to heating and ventilation controls. The survey was conducted on the day of the measurements.

11.4 Results

11.4.1 Heating and Ventilation

The three households were asked a number of questions about operation, maintenance and general knowledge of the Mechanical Ventilation with Heat Recovery (MVHR) system. The results suggest significant issues that require attention, particularly in a social housing context. Specifically, all three households were asked if they have ever had any issues with the MVHR system since they moved in. Two of the households stated that the MVHR system had broken down and was now not working; one stated it had broken down a month before the interviews (No. 2) and the other eight months before the interviews (No. 3). The occupants of No. 3 then went on to explain that there was a problem with the electrics and there appeared to be difficulty finding people in the local area with adequate expertise of MVHR systems.

Knowledge of the ventilation system was also an issue in the case study dwellings. For example, only one household was aware of the boost mode function and used it regularly (No. 3). Furthermore, when asked if they had ever adjusted the supply or extract vents, an occupant of house No. 3 stated; *'yes, I usually have them wider open; it doesn't affect how much air coming in, it affects the noise. (…) I close them in the bathroom sometimes because when my son gets bathed when we keep it open it extracts the air and it is cooling him as well.'* Thus the importance of balancing the MVHR system and the impact of adjusting the vents was not clearly understood by the building tenant.

All occupants had been living in the home for approximately one year when interviewed. When asked if the filters in the ventilation system had been replaced, one household stated they were not sure since maintenance of the MVHR system is the responsibility of the Housing Association. The other two households stated that although the filters needed changed, it had not yet been done. Afterwards when informed of this fact, the Housing Association explained that access to the properties for maintenance of the MVHR systems had been problematic. As a result, they have now decided to schedule the maintenance of the MVHR system in the future to coincide with the annual boiler servicing, since access for boiler servicing is a legal requirement in social housing. Households were also asked if they have ever had any issues with the MVHR system (such as noise, cost of running, thermal comfort, draughts or other). Household No. 1 stated *'yes, the system is noisy on higher settings.'* Household No. 3 also indicated that they had experienced problems with both thermal comfort and draughts in their home.

Households were asked how often the windows were opened during the summer and winter months; the results of which are illustrated in Fig. 11.2. All households reported opening the window either 'regularly' or 'constantly' in the morning, during the day and at night, during the summer months. Two households (No. 1 and No. 3)

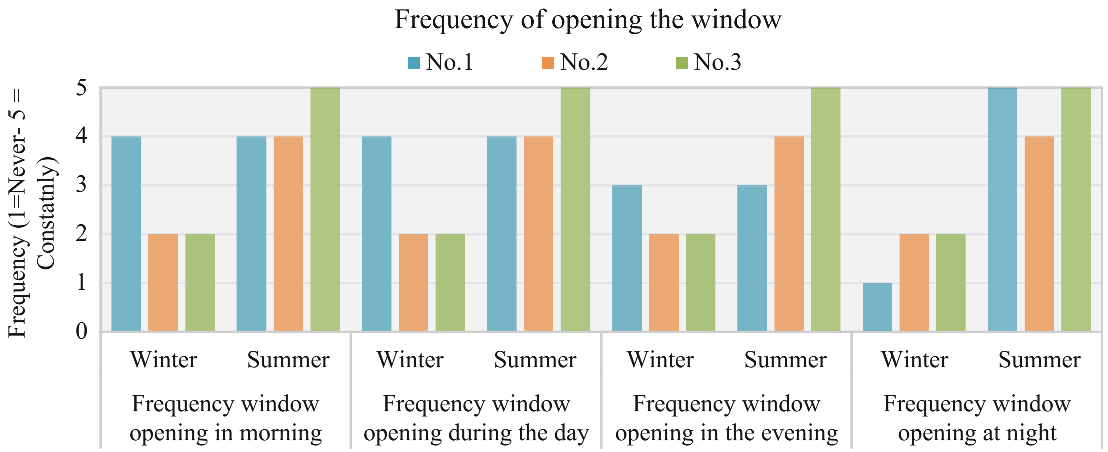

Fig. 11.2 Household reported frequency of opening windows during summer and winter season (*1* Never, *2* Rarely, *3* Occasionally, *4* Regularly, *5* Constantly)

Table 11.2 Heating schedule

Heating schedule	No. 1	No. 2	No. 3
Winter	6–7 pm	10–12 am	5–8 pm
Spring	–	5–8 pm	–
Summer	–	5–6.30 pm	–
Autumn	6–7 pm	1–4 pm	5–7 pm

explained that it was too warm indoors. During the winter months, occupants reported opening the windows less, with two households 'rarely' opening the window at any time of day (No. 2 and No. 3). These two households however also reported that the MVHR system was not working, which may lead to significant problems with ventilation during the winter months.

The homes are heated by one radiator in the lounge and two towel radiators in the bathrooms. A post heater (hot water heating coil connected to the thermal store) is also available in the MVHR system, which is controlled by a thermostat in the entrance hallway. Table 11.2 illustrates the reported heating schedule of each household for each season. Household No. 1 and No. 3 reported using the central heating system for approximately 1–3 h in the evening during autumn and winter. In house No. 2 however, the heating system was used regularly during all seasons.

11.4.2 Carbon Dioxide and Average Occupancy in Open Plan Living Area

In these studies carbon dioxide (CO_2) is being used as an indicator of ventilation rates. Levels of CO_2 correlate well with human occupancy and human-generated pollutants, but may be unconnected from pollutants not related to occupancy, such as off-gassing from building materials, carpets and furniture. Nevertheless, in the context of concern over ventilation rates, they provide a useful indicator of relative levels of ventilation. There is a general acceptance that CO_2 keeps 'bad company' and that levels above 1000 ppm are indicative of poor ventilation rates [31], which corresponds to a ventilation rate of 8 l/s per person [32]. This figure is also relevant in comparison with the findings of a review of the literature looking at the associations between ventilation rates and CO_2 levels with health outcomes which concluded, "Almost all studies found that ventilation rates below 10 Ls^{-1} per person in all building types were associated with statistically significant worsening in one or more health or perceived air quality outcomes" [33]. A recent paper by Wargocki identified associations between CO_2 levels and health and concluded "The ventilation rates above 0.4 h^{-1} or CO_2 below 900 ppm in homes seem to be the minimum level to protect against health risks based on the studies reported in the scientific literature" [34].

The CO_2 level of 1000 ppm [35] was exceeded in both the two measured households during the winter (Figs. 11.3 and 11.4) and all three households during the summer measurement period (Figs. 11.5, 11.6 and 11.7). Levels peaked as high

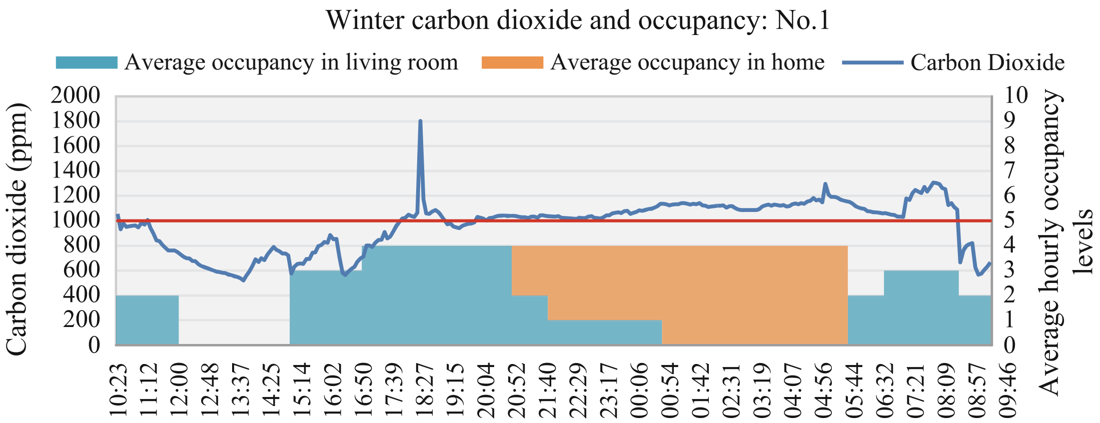

Fig. 11.3 Winter living space carbon dioxide and occupancy in House No. 1

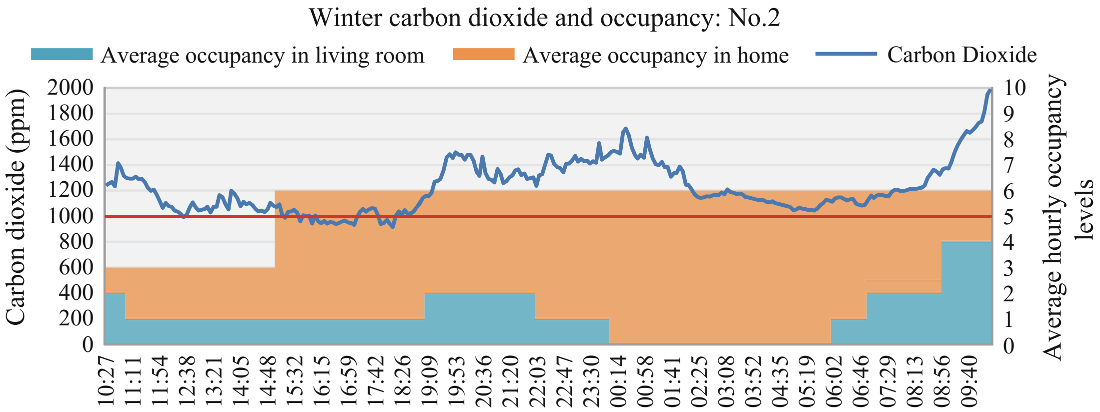

Fig. 11.4 Winter living space carbon dioxide and occupancy in House No. 2

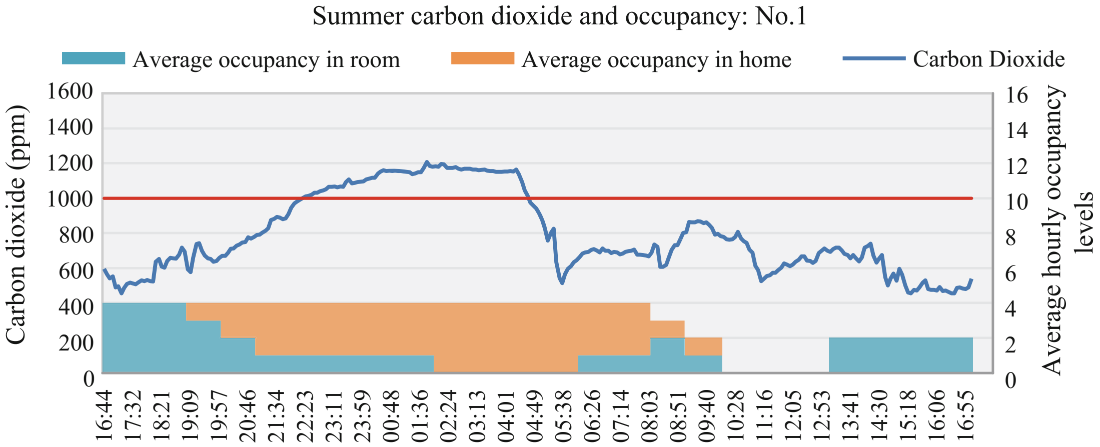

Fig. 11.5 Summer living space carbon dioxide and occupancy in House No. 1

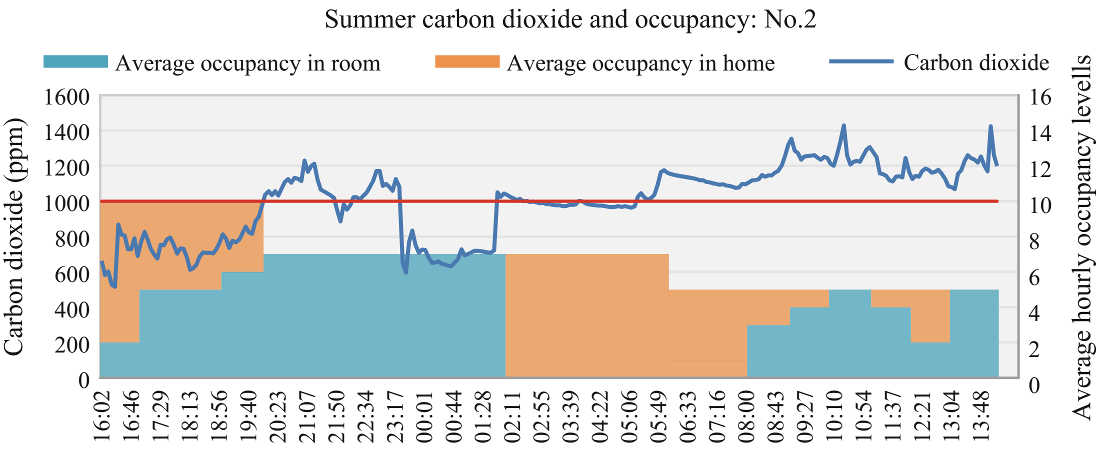

Fig. 11.6 Summer carbon dioxide levels in House No. 2

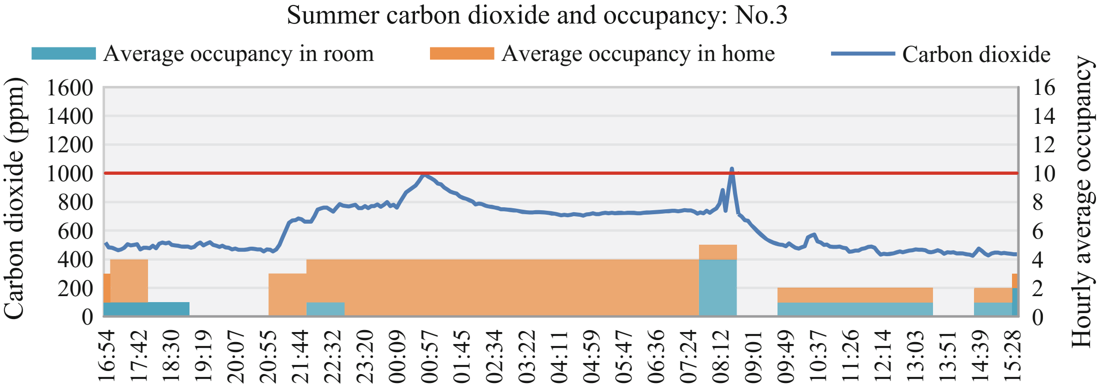

Fig. 11.7 Summer carbon dioxide levels in House No. 3

as 1992 ppm during winter measurements in House No. 2. Mean CO_2 levels also exceeded 1000 ppm during both summer and winter months in house No. 2.

In House No. 1, CO_2 levels did not correspond with reported occupancy levels in the room during the measurement period. For instance, during the early hours of the morning when reported occupancy in the measurement room (open plan living room/kitchen) was zero, CO_2 levels remained high; in most cases above 1000 ppm. This might possibly be due to air leakage from the conjoining bedrooms above into the double height space.

11.4.3 Summer Bedroom Conditions

Bedroom carbon dioxide, temperature and relative humidity were recorded during the summer months in all three households, as illustrated in Table 11.3. Carbon dioxide levels varied significantly during the measurement period, with peak levels ranging from 804 to 2598 ppm. Carbon dioxide levels in House No. 3 were significantly high

Table 11.3 Summer bedroom carbon dioxide, temperature and relative humidity

	CO_2 (ppm)			Temp (°C)			RH (%)			V.P.
	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Mean
No. 1	804	407	590.0	25.4	20.2	22.6	51.8	35.3	42.7	1.17
No. 2	1520	436	782.8	22.5	19.1	21.1	53.0	36.8	45.3	1.13
No. 3	2598	396	820.3	22.6	19.6	21.5	47.7	31.9	41.3	1.06

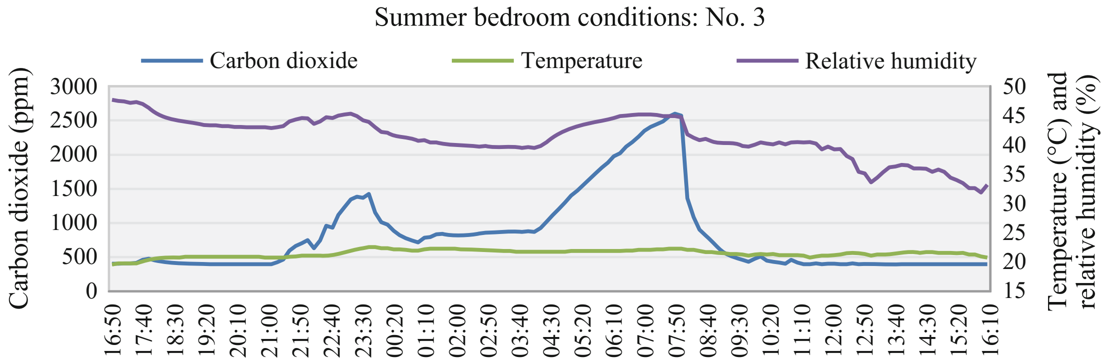

Fig. 11.8 Summer carbon dioxide, temperature and relative humidity in House No. 3

through the night, suggesting inadequate ventilation at this time. Levels dropped significantly between 8 and 9 am, most likely as a result of purge ventilation in the form of opening window(s) (Fig. 11.8). Recorded temperatures in house No. 1 peaked above the CIBSE's 'hot' temperature threshold for bedrooms of 25 °C [36], indicating problems with overheating Table 11.3.

11.4.4 Living Room Relative Humidity and Temperature

Relative humidity levels remained below the recommended maximum of 60% in all households during both summer and winter measurements (see Table 11.4). No significant difference between summer and winter seasons was found. However, as illustrated in Figs. 11.9 and 11.10, an examination of actual vapour pressure levels identified areas of concern regarding threshold levels for dust mite control. Specifically, vapour pressure levels exceeded 1.13 kPa (or 7 g of water vapour per kg of dry air), in all dwellings during both summer and winter measurements. As explained by Korsgaard and Harving [39, 40] the recommended maximum vapour pressure level of 1.13 kPa (or 7 g/kg) corresponds to a Threshold Limit Value (TLV) for house dust mite exposure of 100 mites/g of dust. This value has been derived from the literature as an exposure level 'below which no increased disease frequency can be associated with the actual exposure' [39] (p. 78). This is supported by Platt-mills et al., who stated that maintaining absolute humidity levels below

Table 11.4 Statistical analysis of relative humidity and temperature

Parameter	Statistical analysis	No. 1		No. 2		No. 3
		Summer	Winter	Summer	Winter	Summer
Relative humidity	Maximum	54.0	52.4	51.0	51.0	57.9
	Minimum	33.6	37.0	38.8	42.5	34.4
	Mean	43.4	43.1	45.7	46.3	46.9
	Standard Dev.	4.7	2.6	2.7	1.8	4.1
Temperature	Maximum	24.9	24.6	24.0	23.2	23.3
	Minimum	19.0	19.0	20.5	19.7	18.9
	Mean	23.2	22.2	22.4	21.5	21.0
	Standard Dev.	1.2	0.9	0.7	1.0	0.9
Vapour pressure	Maximum	1.70	1.62	1.52	1.45	1.66
	Minimum	0.74	0.81	0.94	0.97	0.75
	Mean	1.23	1.15	1.24	1.19	1.17

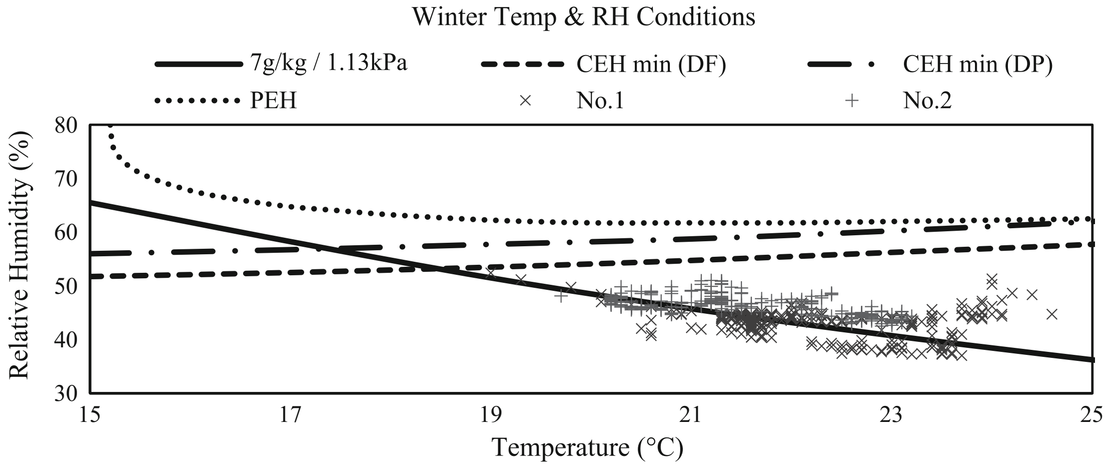

Fig. 11.9 Winter living space temperature and relative humidity. (CEH (DP) refers to Critical Equilibrium Humidity for *Dermatophagoides pteronyssinus* [37], a dust mite species common to the UK. CEH (DF) is the Critical Equilibrium Humidity for *Dermatophagoides farinae* [38], common dust mite species of USA. PEH refers to Population Equilibrium Humidity.)

7 g/kg (1.13 kPa) should reduce the risk of excess mite growth [41, 42] which may be considered significant at lower temperatures (15°–18°).

The Critical Equilibrium Humidity (CEH) for *Dermatophagoides farinae* (DF) was exceeded during the summer measurements in House No. 3; however conditions remained below the CEH for *Dermatophagoides pteronyssinus* (DP) during both summer and winter measurements. It is suggested therefore that relatively high vapour pressure levels are being masked to a degree by higher indoor temperatures in the case study dwellings. Average temperatures remained within satisfactory levels for comfort (18–24 °C) [43, 44] during the measurement periods, ranging from 21 to 23.2 °C, however peaked above 24 °C in house No. 2 during both summer and winter months.

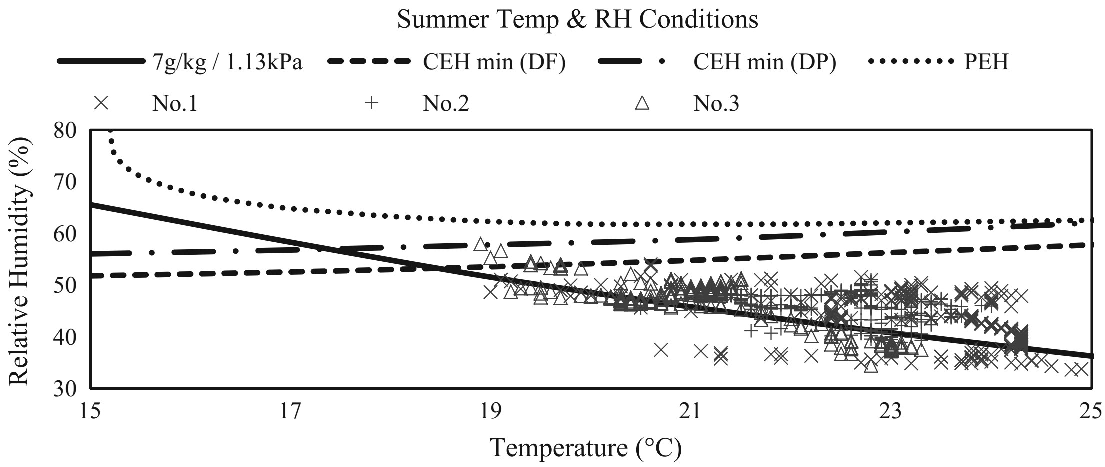

Fig. 11.10 Summer living space temperature and relative humidity

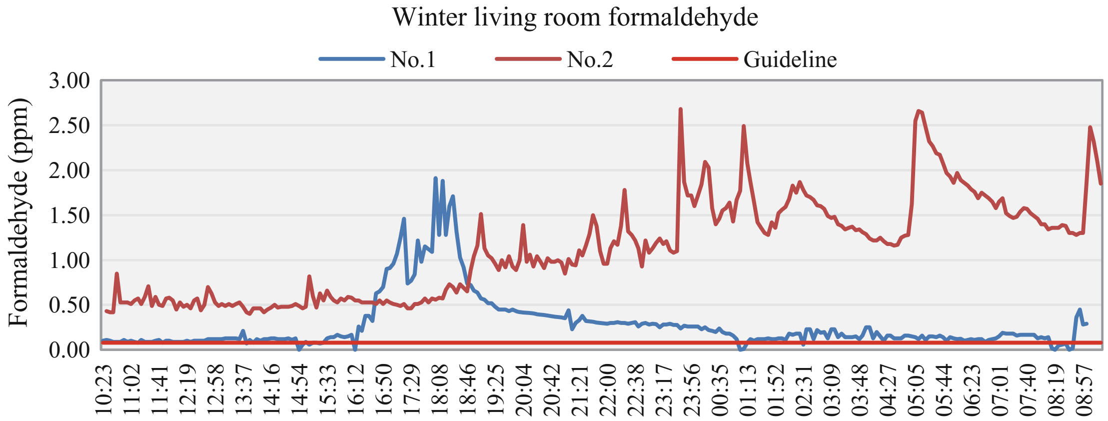

Fig. 11.11 Winter living space formaldehyde levels

11.4.5 Formaldehyde Levels in Open Plan Living Room and Kitchen

Peak levels of formaldehyde in the open plan living room and kitchen in two households (No. 1 and No. 2) significantly exceeded the WHO recommended 30 min time weighted average of 0.08 ppm [45]. In House No. 2, winter levels peaked at 2.68 ppm; over 30 times the recommended 30 min average. Mean values over the measurement period exceeded 0.08 ppm during the summer and winter of House No. 2 and during the winter in House No. 1. Winter and summer levels over the measurement period are illustrated in Figs. 11.11 and 11.12.

During the winter period of House No. 1 where the levels of formaldehyde peaked significantly (4–8 pm), the occupants reported drying clothes naturally indoors (3–11 pm) and the use of the cooker (3–5 pm). In house No. 2, the levels of formaldehyde were significantly high throughout the winter measurement period, and do not seem to correspond with activities recorded through use of the occupant

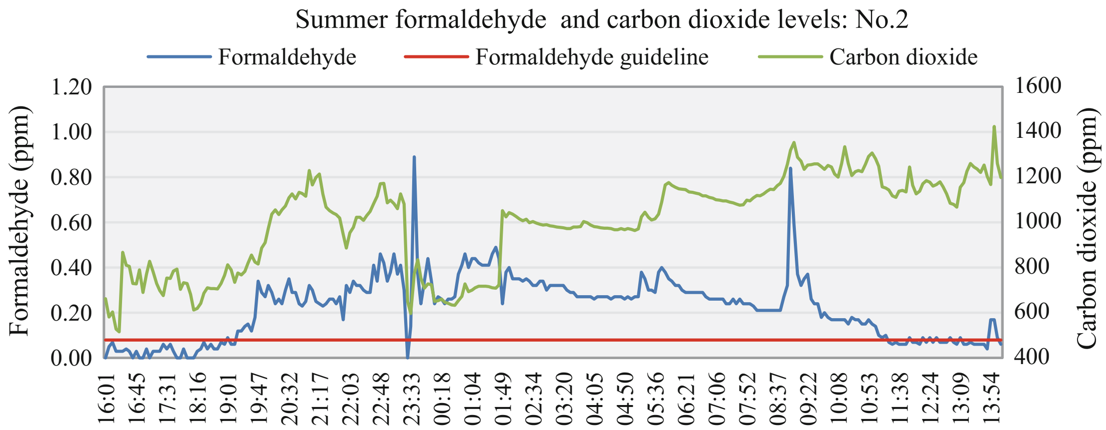

Fig. 11.12 Summer living space formaldehyde and carbon dioxide levels in House No. 2

Table 11.5 Statistical analysis of formaldehyde levels in open plan living room and kitchen

	No. 1		No. 2		No. 3
	Summer	Winter	Summer	Winter	Summer
Maximum	0.23	1.91	0.89	2.68	0.08
Minimum	0.00	0.00	0.00	0.40	0.00
Standard deviation	0.02	0.32	0.14	0.55	0.01
Mean	0.00	0.28	0.22	1.13	0.01

diary. Three occupant's in House No. 2 smoke which may have contributed to the high results, despite occupants stating that cigarettes were not smoked indoors.

Formaldehyde levels in House No. 1 during the summer measurement period peaked between 10 and 11 am. Occupants reported the use of cleaning products (8–10 am), opening external doors (9–10 am) and the use of the cooker (9–10 am) around this time, which may have contributed to the results. In House No. 3, summer formaldehyde levels recorded during the measurement period did not exceed 0.08 ppm (Table 11.5).

However, in House No. 2, formaldehyde levels were significantly high throughout the summer measurement period, with levels above 0.08 ppm between 19:16 on day one until 11:18 on day two, with a drop to 0.00 ppm from 23:23 to 23:33. During this time, the occupants recorded drying clothes naturally indoors (7 pm–6 am, 7–10 am) and the use of plug in air fresheners (4–2 pm). External doors were opened in the home from 7 to 8 pm, 9–10 pm and 6–8 am (Table 11.6). In addition, as presented in Fig. 11.12, a loose relationship existed between the carbon dioxide and formaldehyde levels over the 24 h measurement period. This supports the premise of using carbon dioxide levels as an indicator of poor ventilation; however as illustrated, is not conclusive.

Table 11.6 Frequency of activities during the measurement period (obtained by occupant diary)

Reported activities	No. 1		No. 2		No. 3
	Summer	Winter	Summer	Winter	Summer
Use of air fresheners	–	9–10 am, 6–7 am	4 pm–2 pm	10 am–1 pm, 4–8 pm	10–11 am
Drying clothes naturally indoors	–	3–11 pm	7 pm–6 am, 7–10 am	–	10 am–5 pm
Use of cleaning products	8–10 am	2–3 pm	–	8–9 am, 2–3 pm, 8–10 pm	4–5 pm
Use of incense/scented candles	–	–	–	–	–
Use of boost mode in MVHR	–	–	–	–	–
Use of the cooker	5–6 pm, 8–9 pm 9–10 am, 1–2 pm	3–5 pm, 6–7 am	4–5 pm, 7–8 am	8–9 am, 2–3 pm, 8–10 pm	4–5 pm
External doors opened	5–8 pm, 9–10 am	10–11 am, 2–3 pm, 8–9 pm	4–6 pm, 7–8 pm, 9–10 pm, 6–8 am, 10–11 am	–	4–5 pm, 10 am–5 pm

11.4.6 Volatile Organic Compounds (VOC’s) in House No. 1

In addition to the environmental monitoring, measurements of VOCs were conducted in House No. 1 in the living room, kitchen, bedroom and outside during the winter season, as illustrated in Table 11.7. In general, concentrations of VOCs did not vary significantly from room to room. However, concentrations of xylenes were significantly higher in the kitchen of House No. 1 (16.98 µg/m^3) in comparison to the living room (4.24 µg/m^3) and bedroom (3.70 µg/m^3). This may be due to the fact that the kitchen is north facing overlooking the main road, thus outdoor sources of xylenes from exhaust fumes may have influenced the results. Furthermore, indoor concentrations of all measured VOC’s were significantly higher than outdoor concentrations; with the exception of benzene.

Concentrations of all measured VOCs were below recommended maximum levels. However, benzene and styrene have both been classified by the Environmental Protection Agency (EPA) as known or possible human carcinogens; thus exposure should be limited in a domestic environment. In comparison, a study of 876 homes in England (selected using the Survey of English Housing) found higher levels of benzene (mean = 3.0 µg/m^3) indoors [46]. However, mean levels of hexanal were significantly lower (0.9 µg/m^3), in comparison to the case study

Table 11.7 VOC results in living room, kitchen, bedroom and outside in house No. 1

VOCs	Living room (μg/m^3)	Kitchen (μg/m^3)	Bedroom (μg/m$^{3)}$	Outside (μg/m^3)	BRE survey [46, 47] (mean conc. μg/m^3)
Terpene (No. 1)	101.73	125.20	77.46	n/a	n/a
Terpene (No. 2)	18.04	20.34	13.85	n/a	n/a
Terpene (No. 3)	43.27	39.77	34.19	n/a	n/a
Toluene	11.91	12.54	12.16	1.71	15.1
Ethyl benzene	2.83	2.71	2.39	0.81	1.2
Xylenes	4.24	16.98	3.70	1.55	3.8
Hexanal	31.34	25.21	29.15	n/a	0.9
Benzene	0.57	0.49	0.51	0.40	3.0
Cyclopentane	6.83	5.29	5.89	0.62	n/m
Ethanol	26.58	33.25	25.58	n/a	n/m
Pentane (No. 1)	56.78	43.48	47.22	1.10	n/a
Pentane (No. 2)	67.88	53.68	61.75	0.45	n/a
Styrene	3.73	3.37	2.92	0.10	n/m
TVOCs	330	300	280	<50	210

*n/m = not measured

results (25.2–31.3 μg/m^3). TVOC concentrations exceeded the performance criteria set out in the UK building regulations[2] (Approved Document F: Ventilation 2010) of 300 μg/m^3 in the open plan living area (330 μg/m^3); with concentrations of 300 μg/m^3 recorded in the kitchen and 280 μg/m^3 in the main bedroom. Outside TVOC concentrations were <50 μg/m^3.

11.4.7 Indoor Air Quality Perception

Occupant perception of IAQ was monitored through use of seven point uni-polar and bi-polar scales. For uni-polar scales such as ‘fresh (1)—stuffy (7)’ where one extreme is considered bad, a score greater than 3 requires further investigation and a scale greater than 5 is a cause for concern [23]. For bi-polar scales such as ‘too still (1)—too draughty (7)’ where both extremes are bad, scores outside 3–5 require further investigation and outside 2–6 is a cause for concern. The statistical analysis results were derived from results of all adult questionnaires utilised in the structured interviews for all three households.

As illustrated in Table 11.8, mean scores for the ‘fresh stuffy’ scale (3.5) and ‘satisfactory overall unsatisfactory overall’ scale (3.3) for the winter months requires further investigation. This suggests occupants of the case study dwellings

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[2] Approved Document- Part F (Ventilation) 2010 for England and Wales (Part K in Northern Ireland) recommends performance criteria of 300 μg/m^3 for TVOCs, averaged over 8 h.

Table 11.8 Perception of IAQ during winter in the Passivhaus households

IAQ perception scales	Mean	S.D	Mean + S.D	Mean − S.D	Max	Min
Dry(1)—humid(7)	3.3	0.5	3.8	2.8	4	3
Fresh(1)—stuffy(7)	3.5	1.3	4.8	2.2	5	2
Odourless(1)—odorous(7)	3.0	0.0	3.0	3.0	3	3
Too still(1)—too draughty(7)	3.0	1.4	4.4	1.6	4	1
Satisfactory overall(1)—unsatisfactory overall(7)	3.3	1.0	4.2	2.3	4	2

Table 11.9 Perception of IAQ during summer in the Passivhaus households

IAQ perception scales	Mean	S.D	Mean + S.D	Mean − S.D	Max	Min
Dry(1)—humid(7)	2.3	0.5	2.8	1.8	3	2
Fresh(1)—stuffy(7)	3.3	1.9	5.1	1.4	6	2
Odourless(1)—odorous(7)	3.0	1.4	4.4	1.6	5	2
Too still(1)—too draughty(7)	2.3	1.0	3.2	1.3	3	1
Satisfactory overall(1)—unsatisfactory overall(7)	3.8	2.2	6.0	1.5	7	2

did not perceive the air to be significantly fresh or satisfactory during winter. Similarly, during the summer, the mean score for the ‘fresh stuffy’ scale was 3.3 and the ‘satisfactory overall unsatisfactory overall’ scale was 3.8. Furthermore, mean scores for bipolar scales ‘dry humid’ and ‘too still too draughty’ were outside the range of 3–5, suggesting further investigation is required. It is important to note that the maximum score for the scale ‘satisfactory overall unsatisfactory overall’ during the summer month was 7, thus at least one occupant considered the IAQ as significantly unsatisfactory, which is certainly a cause for concern (Table 11.9).

11.4.8 Thermal Comfort Perception

Occupant perception of thermal comfort in the case study dwellings during the winter months was generally satisfactory, with all mean scores remaining within acceptable limits. However the minimum score for the scale ‘too hot too cold’ was 1, thus at least one occupant considered the home ‘too hot’ during the winter months (Table 11.10).

During the summer months, the mean score for the scale ‘too hot too cold’ was 1.8, which is a cause for concern and suggests problems with summertime overheating. Similarly, overall satisfaction of thermal comfort during the summer months requires further investigation, with an average score of 3.8. The maximum

Table 11.10 Perception of thermal comfort during winter

Thermal comfort perception scales	Mean	S.D	Mean + S.D	Mean − S.D	Max	Min
Comfortable(1)—uncomfortable(7)	2.0	0.0	2.0	2.0	2	2
Too hot(1)—too cold(7)	3.0	1.4	4.4	1.6	4	1
Stable(1)—varies throughout the day(7)	3.0	0.8	3.8	2.2	4	2
Satisfactory overall(1)—unsatisfactory overall(7)	2.8	0.5	3.3	2.3	3	2

Table 11.11 Perception of thermal comfort during summer

Thermal comfort perception scales	Mean	S.D	Mean + S.D	Mean − S.D	Max	Min
Comfortable(1)—uncomfortable(7)	3.0	2.0	5.0	1.0	6	2
Too hot(1)—too cold(7)	1.8	1.0	2.7	0.8	3	1
Stable(1)—varies throughout the day(7)	4.0	1.4	5.4	2.6	6	3
Satisfactory overall (1)—unsatisfactory overall (7)	3.8	1.5	5.3	2.3	6	3

score for the 'comfortable uncomfortable' scale was 6, which means at least one occupant considered the home as 'uncomfortable' during the summer season (Table 11.11).

11.5 Discussion

The results from the study suggest that there are significant issues with the effectiveness of the MVHR system in practice. These include: (1) design and installation issues; for example the importance of balancing the MVHR system, adjustment of the supply and extract vents and on-going system faults; (2) maintenance issues, such as lack of skilled service engineers and lack of filter replacements; and (3) occupant engagement, for example inadequate knowledge of the boost mode function, problems with noise on higher settings, draughts and problems with thermal comfort.

With regards to occupant engagement, during the handover stage the Housing Association provided a pre-allocation meeting with potential tenants, pre-handover viewings, user manuals and information posters in all dwellings. Since occupants were chosen based on a waiting list rather than environmental awareness and/or lifestyles, understanding and training was considered significantly important, particularly in a social housing context. The results however suggest that there are still improvements to be made to ensure adequate knowledge and understanding of the MVHR system from building occupants. In addition, it is suggested that a service checklist should be developed and implemented (at least once a year) to ensure adequate performance and maintenance of MVHR systems in social housing schemes.

During the summer months, occupants reported opening the windows either regularly or constantly in the morning, during the day and at night; with two households (No. 1 and No. 3) explaining it was too warm indoors. This suggests that the MVHR system alone was not capable of ensuring adequate thermal comfort. Both of these households reported using the central heating system for approximately 1 to 3 h a day during winter and autumn. Household No. 2 however stated that they utilised central heating regularly during all seasons. This suggests significant variances in heating schedules, which may have a major effect on the annual space heating demand. In winter, occupants reported opening the windows much less with two households ‘rarely’ opening windows at any time of day, which may cause problems where the MVHR systems are not performing adequately, but conversely, window opening in winter will undermine the effectiveness of the system for heat recovery.

The high levels of carbon dioxide (>1000 ppm) recorded in all monitored households during both summer and winter months suggest insufficient ventilation in the case study dwellings. This may be as a result of inadequate performance, use and/or maintenance of the MVHR system. Levels peaked as high as 2598 ppm in the bedroom of No. 3 during the summer measurement period. According to the German Working Group on Indoor Guideline Values, ‘based on health and hygiene considerations: concentrations of indoor carbon dioxide below 1000 ppm are regarded as harmless, those between 1000 and 2000 ppm as elevated and those above 2000 ppm as unacceptable’ [48]. In House No. 2, mean carbon dioxide levels exceeded 1000 ppm during both summer and winter months. More research is therefore required to investigate the performance of MVHR systems in practice and whether or not they are providing adequate ventilation in low-energy, Passivhaus dwellings; and whether heat recovery efficiencies are being undermined by adaptive behaviour to maintain comfortable conditions.

Levels of relative humidity remained reasonably low during both summer and winter months in monitored dwellings, with average values ranging from 43.1 to 46.9%, which may be partly due to the use of MVHR systems, with very little variance between summer and winter. However, an examination of vapour pressure illustrated the levels of moisture within the dwellings were high, exceeding 1.13 kPa in all dwellings and exceeding CEH (DP) in House No. 3 during the summer measurements. This suggests that the high temperatures and reasonably low relative humidity levels indoors may be disguising poor hydrothermal conditions in the case study dwellings.

With regards to thermal comfort in the dwellings, mean temperatures remained within satisfactory levels for comfort (18–24 °C) during both summer and winter measurements, however peaked above 24 °C in house No. 2. Despite this, occupants' general perception of thermal comfort was poor during the summer months, with perceived overheating a significant concern. Furthermore, at least one occupant in House No. 2 perceived the thermal comfort during winter months as 'too hot', suggesting problems with excessive internal sources of heat. This is supported by findings from a study of Passivhaus dwellings in Scotland, which reported similar issues with overheating, partially attributed to significant incidental heat gains through uninsulated hot water pipework identified through a thermography study [17]. In an effort to reduce energy demand in buildings through energy efficient strategies, architects must be careful to ensure potential savings are not offset through increased cooling requirements as a result of overheating. Awareness of this problem in new build, low energy dwellings is increasing through the publication of recent reports [19, 49–51].

Recorded formaldehyde levels over the monitoring period significantly exceeded the WHO 30 min time weighted average of 0.08 ppm, with winter levels reaching as high as 1.91 ppm (No. 1) and 2.68 ppm (No. 2). Winter levels were much higher than summer levels, possibly since occupants reported opening windows and/or external doors more frequently during the summer season, which would have helped dilute indoor concentrations (in turn illustrating the effectiveness of natural ventilation). Furthermore, homes had been occupied for longer during the summer measurements thus off-gassing from building materials would likely be reduced. The use of the occupant diaries suggested possible sources of formaldehyde from activities conducted during the measurement period. For instance, peaks in formaldehyde levels in House No. 1 (winter: 4 to 8 pm) and No. 2 (summer: 7 pm to 11 am) appeared to coincide with naturally drying of clothes indoors (No. 1: 3 to 11 pm; No. 2: 7 pm to 6 am; 7 to 10 am). This may be as a result of off-gassing of formaldehyde or VOCs from laundry products [52–54]. However House No. 3 reported drying clothes indoors during the measurement period and levels of formaldehyde did not exceed the recommended guideline of 0.08 ppm. The location of drying clothes indoors was not recorded, thus clothes may not have been dried in the measurement room. Measurements of VOCs in House No. 1 found indoor concentrations significantly higher than outside. VOC concentrations did not vary significantly between rooms, with the exception of xylenes, where higher levels were observed in the kitchen. All measured VOCs in House No. 1 were below recommended maximum levels.

Finally, the perception of IAQ recorded through the structured occupant interviews suggests occupants did not perceive the air quality to be significantly fresh or significantly satisfactory during summer or winter. Furthermore, mean scores suggest occupants perceived the air as relatively dry and still during the summer months, which may have implications on overall comfort. At least one occupant perceived the air quality as significantly unsatisfactory, which is a cause for concern. These results demonstrate convergence with the results of the IAQ measurements, and highlight the need for an urgent review of energy efficient design strategies and the effect on IAQ.

In particular, it is important to evaluate occupant knowledge and usability of mechanical systems, especially in the context of social housing. In theory, the

Passivhaus concept provides an established, systematic methodology supported by scientific literature to acquire the perfect performance, at least in terms of energy. However this must be envisaged in the presence of risk factors, such as occupant understanding, operation, and system performance, and the effect of these on overall performance. Moreover, exacerbating factors such as indoor pollutant concentrations, room volumes, and weather, play an important role in the resulting quality of the indoor environment in terms of IAQ and thermal comfort. Mitigating and/or forgiveness factors include the presence of adaptive opportunities, such as opening windows, flexibility of indoor spaces and/or control features. Similarly, adequate maintenance of the MVHR system is crucial in ensuring overall system performance.

It is recommended therefore that the Passivhaus Standard should not be adopted in isolation, as overall performance requires a fundamental understanding of the dynamic relationship between the building, the occupant and climate. Moreover, performance in practice requires a certain degree of ‘control’ over factors, which in reality is difficult to achieve, particularly in social housing. It is suggested therefore that greater attention should be placed on the provision of mitigating or forgiveness factors, and how these may be adopted to provide comfortable and healthy indoor environments, while maintaining optimal energy performance.

11.6 Conclusions

This study aimed to investigate the IAQ and thermal comfort in Passivhaus social dwellings through a UK case study. The findings suggest both measured and perceived IAQ problems, including issues with the perception of thermal comfort and overheating in the homes. A number of issues were identified relating to the use and maintenance of MVHR systems, including lack of knowledge from the building occupants. The findings cannot provide a generalisation of all UK Passivhaus social dwellings, since the number of homes investigated was significantly limited. A further limitation is the relatively small measurement period of 2 days during both summer and winter. However, it does provide interesting insights into IAQ and thermal comfort in these homes, including potential effects of occupant behaviour and activities on IAQ.

Further research is required to investigate the effects of energy efficient design strategies including the Passivhaus standard on IAQ and thermal comfort; to insure occupant health and wellbeing is not sacrificed in the drive towards the reduction of carbon dioxide emissions. Furthermore, the risk of potentially increasing demand for air-conditioning devices in low energy dwellings needs to be addressed to ensure energy savings from reduced heating demand are not off-set by increased demand for cooling. A re-evaluation of energy efficient design strategies may be required to account for future climate predictions and IAQ needs.

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