Indoor air-quality investigation in code for sustainable homes and passivhaus dwellings

A case study

Grainne McGill
School of Planning, Architecture and Civil Engineering, Queen's University Belfast, Belfast, UK
Lukumon O. Oyedele
Bristol Enterprise, Research and Innovation Centre (BERIC), University of West of England, Bristol, UK, and
Greg Keeffe
School of Planning, Architecture and Civil Engineering, Queen's University Belfast, Belfast, UK

Abstract

Purpose – Energy efficient building design strategies are growing in popularity, promoted through increased awareness of climate change, rising energy prices, global consciousness and a demand for energy security. To aid this design process, assessment tools such as Code for Sustainable Homes (CSHs) and Passivhaus were introduced in the UK. However, it is suggested that these tools prioritise energy efficiency over occupant health through a fundamental lack of attention to indoor air quality (IAQ). The purpose of this paper is to investigate IAQ in selected dwellings built using CSHs level 6, level 3 and Passivhaus homes in the UK.

Design/methodology/approach – Using a case study approach, the investigation consisted of IAQ measurements during summer and winter months, occupant diaries and occupant interviews.

Findings – The results from the IAQ measurements show the recommended maximum level of 1,000 ppm was breached in all three Code 6 and two Code 3 homes, with levels slightly below this limit in the two Passivhaus homes. Measurements found high levels of formaldehyde, carbon dioxide and low levels of relative humidity.

Practical implications – There is a need for the adequate consideration of IAQ in sustainable assessment methods, including the use of mandatory credits to ensure occupant health is not disregarded in the drive towards zero carbon.

Originality/value – These results can be used to recognise areas of improvement in the CSHs and Passivhaus standard, and the design of energy efficient homes in general. Research of this nature is essential to ensure occupant health is not sacrificed through the drive towards zero carbon.

Keywords Public health, Sustainable development, Sustainable environment, Energy efficiency, Passivhaus, Code for sustainable homes, Indoor air quality, Social housing, Zero carbon

Paper type Research paper

Introduction

Climate change is considered to be one of the most important challenges of the twenty-first century (Smith, 2005). In response, a global effort to reduce greenhouse gas emissions has begun. The UK government is addressing this challenge through the Climate Change Act (2008), which sets a legally binding target of an 80 per cent reduction of carbon dioxide emissions from 1990s figure by 2050 (HM Government, 2008). The built environment is thought to contribute to approximately 25-40 per cent

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of anthropogenic greenhouse gas emissions in developed countries (de Wilde and Coley, 2012), thus a major reform of the construction industry is needed.

Recent research, however, suggests building design strategies implemented to mitigate the effect of climate change have the potential to cause significant unintended consequences (Davies and Oreszczyn, 2012). For instance, concerns with overheating of the interior environment, indoor air quality (IAQ) problems and dependence of mechanical ventilation systems have been expressed (Corsi, 2011). To aid the transition to a more sustainable built environment, assessment methods have been devised to measure the environmental performance of building projects. The ability, however, of these schemes to adequately address occupant health and wellbeing is questionable. For instance, the predominant emphasis on energy efficiency in buildings results in a highly subjective definition of sustainability, where trade-offs between building energy conservation and IAQ are subsequently disregarded. As explained by Dols *et al.* (1996, p. 139), "rating systems that have been developed to assess the 'greenness' of a building are based largely on design features and are not particularly specific with respect to indoor air quality".

In the UK, the Code for Sustainable Homes (CSHs) was devised to enable a step change towards sustainable residential design practices (DCLG, 2006). It considers a more holistic approach to sustainable assessment as it encompasses a range of categories, including health and wellbeing. It is clear, however, that there is a fundamental lack of criteria relating to the achievement of good IAQ in the CSHs rating scheme. For example, the section on "health and wellbeing" includes day-lighting, sound insulation, private space and lifetime homes, however, makes no reference to IAQ. Similarly, the German Passivhaus standard (which is based on precise space heating and energy criteria), does not provide adequate attention to IAQ. Levin (2005, p. 1138) states that, "the integration of IAQ concerns in so-called 'sustainable' designs suffers from a lack of comprehensive assessment methods for building environmental performance and a lack of integration of the knowledge developed in the indoor air sciences during the past three decades". Thus, greater collaboration between the interior environmental quality (IEQ) research community and green building councils is needed to increase the awareness of IEQ and the effectiveness of sustainable assessment schemes in ensuring these needs are met in practice (Clausen *et al.*, 2011).

It is on these bases that the study emerges, with the following aims:

(1) to investigate and compare the IAQ of new energy efficient social homes designed to specific assessment tools (CSHs and Passivhaus);

(2) to investigate occupants' perception of IAQ and thermal comfort, occupant behaviour and occupant reported health; and

(3) to evaluate the success of these assessment tools at achieving good IAQ.

The study was conducted through a case study investigation consisting of air quality monitoring, building surveys, guided occupant interviews and occupant diaries.

IAQ and energy efficient design strategies

Prominent features of sustainable building designs make consideration of IAQ particularly important. Increased airtightness, the reduction of ventilation rates, dependence on mechanical ventilation systems and the use of new construction techniques and materials all pose a significant threat to the quality of indoor air. These potential trade-offs are discussed below.

Increased airtightness

The tightening of building envelopes reduces the amount of natural infiltration, which reduces contaminant dilution with outside air if ventilation rates are not subsequently increased. IAQ problems, sick building syndrome (SBS) symptoms (also known as tight building syndrome) and multiple chemical sensitivity have all been associated with the extensive construction of airtight buildings in response to the energy crisis (Mendell and Fine, 1994; Letz, 1990; Lyles *et al.*, 1991; Wasley, 2000).

As homes become more airtight, less dependence can be placed on air permeability to achieve adequate ventilation (Bone *et al.*, 2010). Despite the fact that infiltration is not considered a good method of ventilation (Persily and Emmerich, 2010), inattentive tightening of building envelopes has the potential to increase exposure to airborne pollutants, combustion gases (Richardson and Eick, 2006), indoor humidity and mould growth. Furthermore, the likelihood of airborne spread of infections may increase in "tighter" building designs (Schenck *et al.*, 2010). In homes of immune-suppressed individuals, young children and/or the elderly, this may be of significant concern.

Reduction of ventilation rates

Emphasis on building energy conservation has resulted in a reduction of ventilation rates in correlation with higher levels of airtightness. However, as explained by Yu and Kim (2012, p. 6), "the highly air-tight buildings with low ventilation particularly in a warm interior environment could encourage development of moisture risk, which would lead to proliferation of moulds". This is supported by Offermann (2010), who explains the combination of airtight homes and the lack of window opening results in significantly low air change rates, thus elevating indoor air contaminants.

The reduction of ventilation rates in homes has the potential to significantly affect occupant health and wellbeing. For instance, a study by Sundell *et al.* (2011), found ventilation rates above 0.5 air changes per hour (ach) in the home environment were associated with a lower risk of allergic manifestations in children. Similarly, Bornehag *et al.* (2005) conducted a study of 390 Swedish homes and found that lower ventilation rates were associated with the prevalence of rhinitis, wheezing and/or eczema. Furthermore, this study found 80 per cent of single family homes investigated did not meet the minimum recommended ventilation rate of 0.5 ach. This is supported by a study of ventilation rates in European homes which found poor ventilation in practice (below 0.5 ach) (Dimitroulopoulou, 2012). However, as pointed out by Dimitroulopoulou (2012), this widely used recommended minimum ventilation rate of 0.5 ach is not based on health criteria. For instance, significantly higher air changes (0.8 ach) may be needed to control the proliferation of house dust mites (HDM) (Ridley *et al.*, 2006; Ucci *et al.*, 2004).

Dependence on mechanical ventilation systems

The increasing use of mechanical ventilation systems in housing signifies a step-change in the UK construction sector. Attributable to improvements in technology, mechanical ventilation with heat recovery (MVHR) systems are now practically standard in new, more energy efficient UK homes (NHBC, 2009). These systems have been proven to achieve a reduction of energy consumption (Mardiana-Idayu and Riffat, 2012), improved IAQ (Mlecnik *et al.*, 2012), reduction of HDM (Eick and Richardson, 2011) and improved thermal comfort (Schnieders and Hermelink, 2006). However, recent research has also highlighted numerous problems with MVHR, such as inadequate specification, poor installation and performance, incorrect commissioning, lack of maintenance, thermal comfort complaints, noise, occupant interference and a lack of knowledge and awareness of the systems (Table I).

These deficiencies of MVHR systems are now widespread in the construction industry, particularly in the UK where mechanical ventilation in the residential sector is

Common MVHR Shortcomings	Reference(s)
Specification	
Wrong type of fan installed	DCLG (2008b), Dorer and Breer (1998)
Poor manufacturing of components	Dorer and Breer (1998)
Lack of summer by-pass function	Balvers *et al.* (2012)
Poor control interface/ inadequate occupant control	Schnieders and Hermelink (2006)
Inadequate filter grade specification (urban areas)	
Installation	
Inadequate adjustment of control settings	Balvers *et al.* (2012)
Failure to insulate ductwork	DCLG (2008b)
Failure to securely affix fan	DCLG (2008b)
Field assembled without design specifications/ redesigned on site	Turner *et al.* (2013)
Failure to connect ductwork to outside terminal	DCLG (2008b)
Supply and extract ductwork installed the wrong way around	Lowe and Johnston (1997)
Supply/extract vents too close together in individual rooms (short circuiting)	Balvers *et al.* (2012)
Outside supply/extract vents too close together- recirculation of exhausted air	Balvers *et al.* (2011)
Pollutant sources within 2 m of supply grill	Hill (1999)
Poor sound installation/ silencers not installed properly	Balvers *et al.* (2012)
Over-use of flexible ducting (bends in ductwork)	Balvers *et al.* (2012), Sullivan *et al.* (2012)
Contamination of ductwork during construction	Balvers *et al.* (2012)
Leaky joints	Balvers *et al.* (2012)
Air supply and/or extract vents not locked in place/ marked; wrong vents used	Balvers *et al.* (2012)
Insufficient gradient on condensate drains	Lowe and Johnston (1997)
Lack of traps (condensate tubes)	Hill (1999)
Commissioning	
Insufficient and/or inaccurate commissioning	Dorer and Breer (1998)
Maintenance	
Inadequate access for cleaning	Dorer and Breer (1998)
Insufficient changing of filters	Dorer and Breer (1998), Hill (1999)
Lack of dedicated trade body/accredited training for servicing/installation	Bone *et al.* (2010), Schnieders and Hermelink (2006)
Occupant knowledge/use	
Inadequate occupant knowledge of ventilation system	Mlecnik *et al.* (2012), Bone *et al.* (2010)
Occupant(s) turning system off altogether or at certain times of the year	Aizlewood and Dimitroulopoulou (2006), Offermann (2009), Gill *et al.* (2010)
Tightening/blocking of supply/extract vents, restricting air distribution	Leech *et al.* (2004)
Inadequate use of "boost" mode	Schnieders and Hermelink (2006)
MVHR system operated in lowest setting	Schnieders and Hermelink (2006)
Performance (thermal comfort, noise, air quality)	
Problems with noise, particularly in bedrooms	van der Pluijm (2010)
Thermal comfort, perceived draughts, overheating	Balvers *et al.* (2012), Offermann (2009)

Table I. Common shortcomings of mechanical ventilation with heat recovery systems still relatively immature. As suggested by Turner *et al.* (2013, p. 194), "such deficiencies occur because systems are field assembled (usually without design specifications), there is no consistent process to identify and correct problems, and the value of such activities in terms of reducing energy use and improving IAQ is unknown". Maintenance of mechanical ventilation systems in residential environments is also of significant concern. As suggested by Crump *et al.* (2009), the market for filter replacements in the UK remains largely unsaturated with limited options for consumers, suggesting maintenance of ventilation systems is significantly lacking.

New construction techniques and materials

The utilisation of new construction methods and building materials in the residential sector poses significant risk to occupant health through potential unintended consequences on the quality of the indoor air. As explained by Corsi (2011, p. 440), "new green and sustainable materials, from flooring to coatings and insulation, are being introduced at a rate that exceeds our current ability to properly evaluate them, their long term performance in buildings and their effects on building occupants". Efforts to classify, regulate and eliminate the use of toxic materials, however, are hindered through variances in individual susceptibility, complex interactions between contaminants and the unknown effect of variations in interior environmental conditions (Persily and Emmerich, 2010; Dols *et al.*, 1996).

In addition, the transition from solid, site built construction to more lightweight, pre-fabricated systems not only reduces the sink area for pollutant absorption, but also considerably increases interior contaminant concentrations, through the creation of impervious surfaces (Spengler and Chen, 2000). Energy efficient design strategies which increase interior temperatures further exacerbate the degradation of IAQ through increasing vapour pressures which increase the emission of VOCs (Levin, 1995). In addition, the increased use of recycled materials (Crump, 2011), wood-based composites and/or synthetic materials (Lee *et al.*, 2012) in modern construction processes have increased off-gassing of toxic chemicals into the interior environment.

Based on the existing literature, lessons are gradually being learned about the potential problems in mechanically ventilated, energy efficient homes and how to overcome these. As suggested by Taylor and Morgan (2011), latest evidence raises concerns for the entire UK home building industry, since many unmonitored energy efficient homes may have IAQ and/or ventilation problems that subsequently go undiagnosed. Thus there exists a significant need for IAQ research and post occupancy studies in UK energy efficient homes, including the monitoring and evaluation of MVHR systems in a residential setting (Sullivan *et al.*, 2012, 2013; Crump *et al.*, 2009). The fundamental influence of human behaviour has been largely neglected in IAQ research to date, yet inhabitants play an active role in determining the quality of indoor air. The case study method provided the opportunity to investigate IAQ in energy efficient homes, in a real life, multivariate context.

Methodology

Household characteristics

This study investigated the IAQ in three zero carbon homes designed to meet CSHs Level 6, two Passivhaus homes and two CSHs Level 3 homes. The homes are all new-build; construction work was completed between October 2012 and January 2013. Code level 6 requires net-zero carbon dioxide emissions from all home energy use, including heating, lighting, hot water and appliances (DCLG, 2006). The Passivhaus standard requires adherence to specific criteria, most notably an annual primary energy demand of $\leqslant$120 kWh/m^2, airtightness of $\leqslant$0.6 ach-1, an annual heating requirement of $\leqslant$15 kWh/m^2 and a peak space heating load of 10 W/m^2 (Table II).

The case study dwellings are all social rented properties located in England within the same development, with similar orientation. All dwellings are three storey, cavity wall (Passivhaus and Code 6) or timber frame construction (Code 3) with brick outer leaf; either semi-detached or mid terraced with a total floor area between 100-120 m^2. The Passivhaus and Code 6 properties incorporate a range of energy efficient design strategies, including the use of triple glazing (low E), increased airtightness, MVHR, A+ rated appliances and low flow rate sanitary ware. The Code 3 dwellings have double glazed windows (low E) and utilise mechanical extract ventilation with trickle vents.

The field work consisted of physical IAQ measurements with simultaneous measurements of outside conditions, occupant interviews, analysis of construction drawings, building survey and occupant diaries during the measurement period. The occupant interviews were conducted to gain information on perception of IAQ and thermal comfort, occupant activities, presence of building related illnesses (BRI) or SBS symptoms and occupant behaviour. The building survey gained information on building conditions and was conducted on the day of the measurements. The occupant diary gained information on occupancy rates and occupant activities during the measurement period.

Physical IAQ measurements

The physical IAQ measurements included real-time monitoring over a 24-hour period (typical weekday) in each home on subsequent days in the main living room, bedroom and outside. Measurements were conducted during the summer months, with winter measurements also conducted in available homes (as only a number of homes were occupied at this time). Temperature, relative humidity and carbon dioxide were monitored in the living room with an Extech IAQ datalogger (Easyview EA80-RH resolution 0.1 per cent, accuracy ±3-5 per cent, temperature resolution 0.1°C, accuracy ±0.5°C, carbon dioxide resolution 1 ppm, accuracy ±3 per cent or ±50 ppm) and in the bedroom and outside with Wohler CO_2 datalogger (CDL 210- RH resolution 0.1 per cent, accuracy ±3-5 per cent, temperature resolution 0.1°C, accuracy ±0.6°C, carbon dioxide resolution 1 ppm, accuracy ±5 per cent or ±50 ppm). Formaldehyde measurements were conducted with a HalTech (HAL-HFX205 – resolution 0.01 ppm, accuracy ±2 per cent) handheld formaldehyde metre which utilises electro-chemical sensing technology.

Table II. Dwelling construction and household characteristics

House no.	House type	q50	FEE	DER	No. of occupants
C6 No. 1	Code 6	2.71 m^3/m^2/hr	35.4	−15.78 kg/m^2	1 adult, 3 children
C6 No. 2	Code 6	2.71 m^3/m^2/hr	35.4	−15.78 kg/m^2	1 adult, 3 children
C6 No. 3	Code 6	2.71 m^3/m^2/hr	35.4	−15.78 kg/m^2	2 adults, 3 children
Pa No. 1	Passivhaus	0.44 m^3/m^2/hr	33.2	10.88 kg/m^2	2 adults, 3 children
Pa No. 2	Passivhaus	0.42 m^3/m^2/hr	36.9	11.41 kg/m^2	2 adults, 3 children
C3 No. 1	Code 3	4.85 m^3/m^2/hr	39.1	15.45 kg/m^2	1 adult, 3 children
C3 No. 2	Code 3	4.98 m^3/m^2/hr	43.3	16.42 kg/m^2	1 adult, 4 children

Notes: FEE, fabric energy efficiency; DER, dwelling emission rate; q50, air permeability @ 50 Pa

Equipment was set up at least 1m from walls and 1.2 m above finished floor level (in correspondence with ISO:16000.1). Care, however, was taken to place equipment in a convenient location given the nature of the measurements; for instance it was important to ensure that the normal use of the room was not affected. Outside measurements were taken with a weather station (Watson W-8681 Solar weather station), and data were also obtained from a nearby monitoring centre.

Occupant interviews, observations and diary

Structured occupant interviews were conducted through the use of specific questionnaires: one for each occupant, one for each household and one for each child (answered by parent/guardian on behalf of the child) and a building survey form. This format provided the opportunity for further discussion and enabled the utilisation of open ended questions and prompts for explanations or comments to support the quantitative data. Occupants were also asked to demonstrate knowledge of the MVHR system through practical exercises observed by the researcher (e.g., locating controls, changing settings, etc.). Validated procedures were followed (Berry *et al.*, 1996; Raw *et al.*, 1995, 1996; Burge *et al.*, 1990, 1993) for acquisition of data on perception of IAQ and thermal comfort, and the presence of BRI and SBS symptoms. A dictaphone was used to record the interview when possible.

The occupant diary consisted of a brief record sheet (single A4 page for each day of measurements), which was devised to reduce the burden on occupants and increase the response rate. The diary recorded information for each hour of the measurement period, including average hourly occupancy rates, heating patterns, window/door opening behaviour, cooking, cleaning, smoking (indoors), use of air-polluting products (such as cleaning products, candles, incense) and use of boost mode in MVHR (if applicable). There was also a section at the bottom of the occupant diary which provided the opportunity to record any other activities which may have affected the measurement results.

Results

Physical measurements

Carbon dioxide – living room. Summer carbon dioxide levels in the living room over the 24-hour monitoring period peaked above the recommended maximum level of 1,000 ppm (EPA and NIOSH, 1991) in all Code level 6 and Code level 3 homes. In comparison, the two Passivhaus homes peaked at 958 ppm and 976 ppm respectfully (as illustrated in Table IV). Two homes (C6 No. 2 and C3 No. 2) peaked above 2,000 ppm, suggesting unacceptable levels of carbon dioxide with regard to health and hygiene (German Working Group, 2008) (Table III).

As illustrated in Figure 1, carbon dioxide levels peaked above 2,000 ppm for only a short period of time, which is most likely a result of an occupants breathing close to the sensor. Carbon dioxide levels correlated with recorded average hourly occupancy, as measured through the occupancy diary.

During the winter months, one Code 3 home (C3 No. 1) and two Code 6 homes (C6 No. 1 and C6 No. 2) were available to monitor. During the 24-hour monitoring period, the peak levels of carbon dioxide were above the recommended guideline value of 1,000 ppm in all case study dwellings (C6 No. 1: 1,189 ppm; C6 No. 2: 2,416 ppm; C3: No. 1: 1,431 ppm), with mean living room occupancy ranging from 1.18-1.73 people. Average living room carbon dioxide levels, however, were all below 1,000 ppm.

Carbon dioxide: bedroom night time levels. Summer carbon dioxide levels were recorded in the main bedroom over the 24-hour monitoring period. All occupants stated that the bedroom windows were closed during this time. The results in Table IV present the carbon dioxide levels from the reported time the occupants went to bed, until the reported time they got up. In the two kids bedrooms measured (C6 No. 2 and Pa No. 2); the levels of carbon dioxide were significantly low. However, in four out of the five main bedrooms measured, carbon dioxide levels peaked above 1,000 ppm, with only the Passivhaus dwelling (Pa No. 1) remaining below this guideline value. Furthermore, in the main bedroom of one Code 6 (C6 No. 1) and one Code 3 home (C3 No. 1), the average carbon dioxide value was also above 1,000 ppm.

Relative humidity: living room. As presented in Table V, summer relative humidity levels in only one home peaked slightly above 60 per cent (C3 No. 1), with all average values below 60 per cent. However, in one of the Passivhaus dwellings (Pa No. 1), humidity levels dropped below 30 per cent (26.4 per cent), which may result in comfort complaints, such as the perception of "dry air", eye irritation and/or upper airway irritation (Wolkoff *et al.*, 2005; Wolkoff and Kjærgaard, 2007). During the winter, relative humidity levels in the living room were below 60 per cent in all homes. However, in two homes, minimum values were recorded below 30 per cent (C6 No. 1: 26.7 per cent; C3 No. 1: 24.8 per cent). Average living room humidity levels during the winter monitoring period were as follows: C6 No. 1: 44.8 per cent; C6 No. 2: 38.9 per cent; C3 No. 1: 32.1 per cent.

Table III.
Summer living room carbon dioxide levels

House no.	Max. (ppm)	Min. (ppm)	SD (ppm)	Mean (ppm)	Mean occupancy in living room	Mean occupancy in home
C6 No. 1	1,207	421	214.9	756.1	0.67	2.50
C6 No. 2	2,323	453	216.8	767.5	1.04	3.32
C6 No. 3	1,058	431	145.6	673.5	0.95	3.63
Pa No. 1	958	448	131.5	705.7	1.60	3.04
Pa No. 2	976	436	134	565.1	1.17	3.67
C3 No. 1	1,363	440	225	729.5	0.56	2.84
C3 No. 2	2,033	387	384.3	823	1.04	5.08

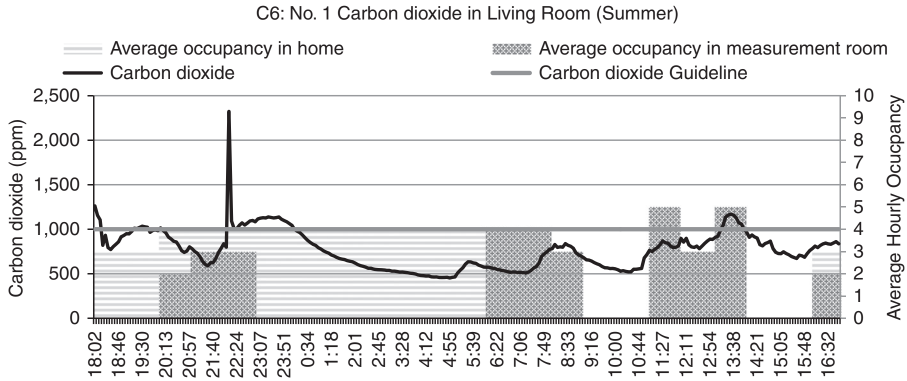


Figure 1.
Living room carbon dioxide levels in code 6 home (C6: No. 1)

Relative humidity: bedroom. Relative humidity levels above 60 percent provide sufficient conditions for mould growth; however, above 50 percent provides sufficient conditions for the proliferation of HDM (Arlian *et al.*, 1999; Arundel *et al.*, 1986). Summer relative humidity levels peaked above 50 percent in five out of seven bedrooms monitored, with average values above 50 percent in three. Two homes recorded maximum relative humidity values ⩾60 per cent (C6 No. 1; C3 No. 2). There was no significant difference between the three house types monitored, or the use of MVHR (Table VI).

Temperature: living room, bedroom and outside. Average temperatures during winter in C6 No. 1 and C3 No. 1 were below 18°C (C6 No. 1: 17.7°C; C3 No. 1: 17.5°C); however, outside average temperatures were close to freezing during these measurement periods. Peak temperatures ranged from 21.2-24.7°C in the measured dwellings. Outside conditions varied during the summer measurement period. In dwelling C6 No. 3, summer living room temperatures reached 28.2°C with an average temperature of 26.2°C, suggesting significant problems with overheating. During the

House no.	Bedroom	Bedroom door	Max. (ppm)	Min. (ppm)	SD (ppm)	Average (ppm)
C6 No. 1	Main	Open	1,139	938	50.8	1,031.1
C6 No. 2	Kids	Open	870	500	130.5	662.8
C6 No. 3	Main	Closed	1,017	681	65.3	879.9
Pa No. 1	Main	Closed	967	676	58.8	858.2
Pa No. 2	Kids	Open	651	544	33.0	582.7
C3 No. 1	Main	Closed	1,468	739	194.3	1,053
C3 No. 2	Main	Closed	1,489	746	201.6	955

Table IV. Bedroom night time carbon dioxide levels in summer

	Living room relative humidity			Outside relative humidity			
House no.	Max. (%)	Min. (%)	Mean (%)	Max. (%)	Min. (%)	Mean (%)	General weather conditions
C6 No. 1	49.5	42.9	47.1	88.4	24.4	63.9	Sunny intervals, showers
C6 No. 2	43.8	33.4	40.4	82.3	37.5	61	Sunny intervals, showers
C6 No. 3	51.4	43.7	48.9	85	32.4	69	Clear, partly cloudy
Pa No. 1	51.9	43.8	48.6	90.9	50.3	76	Partly cloudy
Pa No. 2	36.9	26.4	33.8	98	30.8	69.8	Sunny intervals, showers
C3 No. 1	45.5	35.4	41.4	96.1	54.8	86.1	Rain
C3 No. 2	60.2	51.2	55.8	92.7	50.9	85.2	Scattered showers

Table V. Living room and outside relative humidity levels in summer

House no.	Bedroom	Max. (%)	Min. (%)	SD (%)	Average (%)
C6 No. 1	Main	60	49.7	3.7	54.8
C6 No. 2	Kids	46.4	37.8	1.7	42.1
C6 No. 3	Main	55.1	44.5	1.7	48.9
Pa No. 1	Main	56.6	30.2	3.0	36.1
Pa No. 2	Kids	55.7	46.6	2.3	51.8
C3 No. 1	Main	44.3	32	2.3	39.4
C3 No. 2	Main	61.8	49.5	1.3	53.5

Table VI. Bedroom relative humidity levels in summer monitoring period of C6 No. 3, outside temperatures peaked at 28.4°C, however, average temperatures were significantly lower at 18.3°C. There was no significant difference between the three house types (Table VII).

Formaldehyde: living room. Summer formaldehyde levels in all dwellings peaked above the World Health Organisation's (2000) recommended maximum 30 minute time weighted average of 0.08 ppm (0.01 mg/m^3). Furthermore, two Code 6 homes recorded 24-hour average levels above this guideline value. Both Passivhaus homes and Code 3 homes recorded average values below 0.08 ppm. Peak formaldehyde levels were significantly high in the majority of the case study homes, with levels reaching over tenfold the guideline value in three homes (C3 No. 1, Pa No. 2, C6 No. 2), which suggests intermittent sources. Furthermore, as these dwellings were new build and had only been occupied for a number of months, off-gassing from building materials is likely and therefore may have contributed to the high average levels (Table VIII).

Results from the occupant diaries (presented in Table IX) show that occupant(s) of one Code 6 home (C6 No. 2) and the two Code 3 homes smoked indoors during the

Table VII. Summer temperatures in living room, outside and bedroom

House no.	Living room temperature (°C) Max.	Min.	Mean	Outside temperature (°C) Max.	Min.	Mean	Bedroom temperature (°C) Max.	Min.	Mean
C6 No. 1	22	17.6	20.2	19.7	6.6	11.2	19.3	17.2	18.6
C6 No. 2	23.8	18.3	20.7	19.4	4.1	8.4	22.9	19.4	20.7
C6 No. 3	28.2	23.5	26.2	28.4	14.1	18.3	25.2	24.2	24.7
Pa No. 1	23.8	20.4	22.4	22.4	8.2	11.3	22.1	18.9	20.9
Pa No. 2	24.7	21.1	22.6	16.8	3.5	8.6	22.9	17.6	21.4
C3 No. 1	23.1	19.6	20.9	14.6	3.4	6.2	25.7	20.6	22.1
C3 No. 2	20	17	18.2	16.3	7.1	8.8	20.7	17.9	19.5

Table VIII. Living room formaldehyde levels in summer

House no.	Max. (ppm)	Min. (ppm)	SD (ppm)	Average (ppm)
C6 No. 1	0.23	0.00	0.04	0.15
C6 No. 2	1.50	0.00	0.12	0.11
C6 No. 3	0.12	0.00	0.02	0.01
Pa No. 1	0.10	0.00	0.02	0.03
Pa No. 2	0.93	0.00	0.09	0.01
C3 No. 1	2.53	0.00	0.17	0.04
C3 No. 2	0.12	0.00	0.04	0.03

Table IX. Occupant activities during measurement period

House no.	Smoking indoors	Use of air fresheners	Use of cleaning products	Use of incense/ scented candles
C6 No. 1	No	Yes plug in	No	No
C6 No. 2	Yes	Yes (1-2 p.m.; 4-5 p.m.)	Yes (10-12 p.m.; 4-5 p.m.)	No
C6 No. 3	No	Yes (5-6 p.m.; 1-2 p.m.)	Yes (11-12 p.m.; 1-2 p.m.)	No
Pa No. 1	No	Yes (12-1 p.m.) in toilets	Yes (11 a.m.-12 p.m.)	No
Pa No. 2	No	Yes (5-7 p.m.; 11-1 p.m.; 4-5 p.m.)	Yes (5-6 p.m.; 10-1p.m.)	No
C3 No. 1	Yes	No	Yes (4-5 p.m.)	No
C3 No. 2	Yes	Yes plug in	Yes (9-11 a.m.)	Yes (10-11 a.m.)

measurement period. This may explain the significantly high peak levels of formaldehyde in C6 No. 2 (1.50 ppm) and C3 No. 1 (2.53 ppm). In C6 No. 1, however, maximum levels of formaldehyde remained reasonably low (0.12 ppm) in comparison. This may be due to a number of factors, such as distance from the monitoring equipment or duration of smoking, which was not recorded in the occupant diary. Also important to note is that during the monitoring period occupants of all homes used some form of air freshener indoors. This may have significantly contributed to the levels of formaldehyde recorded, particularly if the air freshener was used close to the monitoring equipment (Figure 2).

All Passivhaus dwellings, Code 3 dwellings and one Code 6 dwelling (C6 No. 2) had one occupant who smoked. Of these, the Code 6 household and the two Code 3 households monitored stated that cigarettes are smoked in the home. Furthermore, six out of seven households used air-fresheners, scented candles or incense on a daily basis indoors, with the other household stating the used them 1-2 times a week (C6 No. 3). This raises the question of whether or not these homes require a certain degree of lifestyle adjustment to ensure occupant health and well-being is not at risk in more energy efficient dwellings.

Occupant interviews

Ventilation strategies – natural. Occupants of the case study dwellings were asked how often the windows were opened during the summer months. As illustrated in Figure 3, occupants of the Passivhaus homes opened the windows most often, suggesting the presence of MVHR in the homes did not reduce the need to open the windows. In the two Code 3 dwellings, both households were aware of the presence of trickle vents, however, in C3 No. 1 occupants stated they are never used for background ventilation. In C3 No. 2, occupants stated trickle vents were constantly used for background ventilation, however, the building survey on the day of the measurements identified that all the trickle vents were closed, similar to C3 No. 1. Occupants of the Code 6 and Passivhaus dwellings were asked their preferred strategy for ventilation: either natural ventilation (opening windows or doors) or technological (use of mechanical ventilation system). In the Code 6 homes, natural ventilation was the preferred strategy apart from one occupant in C6 No. 1 who stated they preferred natural ventilation during the summer months and mechanical ventilation in winter. They explained: “if it is summer, I will open the windows, but in the winter months, if you open the windows you will lose the heat, so it depends”. In the Passivhaus dwellings, all occupants stated they preferred natural ventilation.

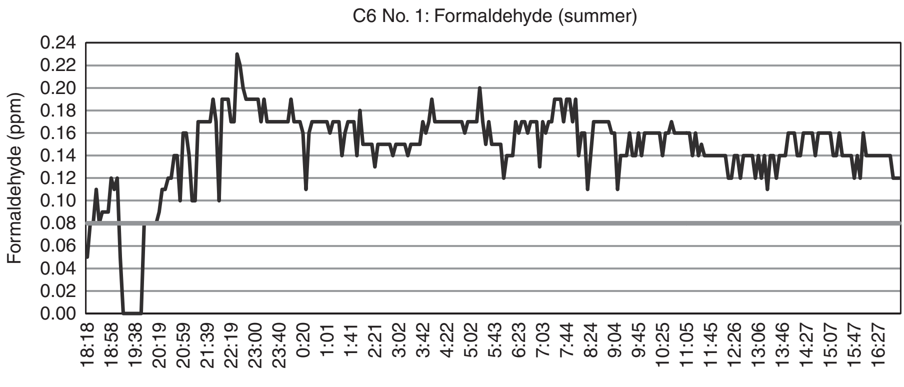
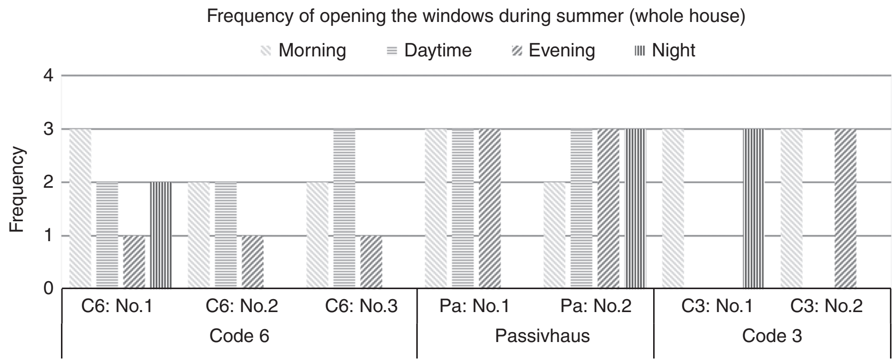


Figure 2.
24-hour formaldehyde levels in code 6 home (C6: No. 1) in summer



Notes: Frequency scores relate to nominal scale where 0 = never, 1 = rarely, 2 = occasionally, 3 = regularly, 4 = constantly

Figure 3.
Occupant reported frequency of opening the windows in summer

Interference with the MVHR system. Findings suggest a significant problem of occupant interference with the mechanical ventilation system. Out of the three Code 6 households interviewed, two (C6 No. 2 and C6 No. 3) had turned the MVHR system off completely. During the interview process, an occupant from C6 No. 2 explained that there was an early fault with the system (a flashing red light) so they turned it off. However, they further stated, "the kids have turned it off and it just has not been back on, […] we just don't use it". In dwelling C6 No. 3, at the initial interview occupants stated that they did not have any problems with the system; however, during the building survey they mentioned they had turned the ventilation system off as it was making a loud noise.

In the other Code 6 home (C6 No. 1), although the system had not been turned off, the building survey revealed that the supply/extract vents had been tightened in the living room, main bathroom, and two out of the three bedrooms, so that they were effectively closed. The occupant explained they had tightened the vents as they were having issues with the noise of the machine and thermal comfort as "the vents were blowing out cold air". In comparison, the MVHR in the two Passivhaus dwellings had not been interfered with, however, it should be noted that in these homes the MVHR units were located in a locked cupboard which occupants did not have access to.

Awareness and use of the boost mode function. All occupants of the Code 6 and Passivhaus homes were asked if there was a boost mode function on the MVHR system, and if so, how often it was used. In the Code 6 homes, two out of three households (C6 No. 2 and C6 No. 3) stated that they were "not sure" if there was a boost mode function, despite numerous boost mode switches clearly visible in the landings of all three homes. In C6 No. 1, occupants stated that there was a boost mode function and they used it frequently, however, mentioned issues with the noise of the fan boost, particularly as the ventilation unit was located beside the main bedroom. In the two Passivhaus dwellings, both households were aware of the boost mode function, however, they stated it was used rarely (Pa No. 1) or occasionally when cooking (Pa No. 2).

Over-heating. All case study dwellings were asked if they had ever experienced any problems with over-heating in the home. Out of the three Code 6 dwellings, one household answered yes explaining "if the heating is on too much downstairs all the heat goes upstairs". Furthermore one out of the two Passivhaus dwellings investigated stated yes explaining, "it gets really hot during the night". In comparison, all Code 3 households stated no.

Knowledge of the ventilation system. Households with MVHR were asked a variety of questions in order to identify their knowledge of the system operation. For example, occupants were asked if they knew what setting the ventilation system was at and to demonstrate how to change the settings; all of which replied no or not sure. Control panels were not made available to the occupants in the Code 6 or Passivhaus dwellings. The occupants of the Passivhaus homes explained the units were located in a locked cupboard; therefore they did not have access to the controls. All households interviewed stated that they did not know how to change the filters in the MVHR systems. Furthermore, general questions on whether it was possible to adjust the temperature of the incoming air and if there was a by-pass mode for summer months were answered with "not sure" by all households.

IAQ perception. Occupants were asked to rate the IAQ of the homes during both summer and winter months, based on standard rating scales. As illustrated in Table X, the average scores in C6 No. 2 for the "dry-humid" scale during winter was 6, suggesting problems with indoor humidity. However, overall satisfaction scores during both summer and winter in Code 6 homes do not suggest any significant problems with the perception of IAQ.

In the Passivhaus homes during the winter months, overall satisfaction of the IAQ was good, with scores of 1 and 1.5. However, during the summer months, results suggest issues with humidity (dry-humid scale score = 5-6) in both households. Furthermore, in Pa No. 2, the average score for the "fresh-stuffy rating scale was 6, suggesting ventilation problems. The overall satisfaction score in this home was 4, suggesting IAQ issues.

Finally, in one of the Code 3 homes (C3 No. 1), perception of draughts was identified (too still-too draughty rating scale score of 5) during both summer and winter months; which is likely to be the cause of the low satisfaction score (satisfactory overall-unsatisfactory overall rating scale score of 5). No significant IAQ issues were identified in the other Code 3 home (C3 No. 2) (Table XI).

	Code 6			Passivhaus		Code 3	
Indoor air quality factors	C6: No. 1	C6: No. 2	C6: No. 3	Pa: No. 1	Pa: No. 2	C3: No. 1	C3: No. 2
Winter							
Dry(1)-humid(7)	4	6	3	4	4	4	4
Fresh(1)-stuffy(7)	1	4	1	2	4	3	3
Odourless(1)-odorous(7)	1	4	2	2.5	1	3	2
Too still(1)-too draughty(7)	4	4	2	2.5	2	5	4
Satisfactory overall(1)-unsatisfactory overall(7)	1	2	1	1.5	1	4	1
Summer							
Dry(1)-humid(7)	4	4	1	6	5	4	4
Fresh(1)-stuffy(7)	1	1	2	2	6	3	3
Odorless(1)-odorous(7)	1	1	2	2	2	3	2
Too still(1)-too draughty(7)	4	4	2	2	2	5	4
Satisfactory overall(1)-unsatisfactory overall(7)	1	1	1	2	4	5	1

Note: Occupants were asked to rate indoor air quality factors on a scale of 1-7 (for instance dry = 1, humid = 7)

Table X. Average score for occupant perception of IAQ in each household

Thermal comfort factors	C6 No. 1	Code 6 C6 No. 2	C6 No. 3	Pa No. 1	Passivhaus Pa No. 2	C3 No. 1	Code 3 C3 No. 2
Winter							
Comfortable(1)-uncomfortable(7)	1	1	1	2	2	4	2
Too hot(1)-too cold(7)	4	3	4	3.5	4	7	4
Stable(1)-varies throughout the day(7)	1	1	4	3	1	6	3
Satisfactory overall(1)-unsatisfactory overall(7)	1	1	1	3	1	6	1
Summer							
Comfortable(1)-uncomfortable(7)	1	1	1	5.5	3.5	4	2
Too hot(1)-too cold(7)	4	4	4	1.5	3	5	4
Stable(1)-varies throughout the day(7)	1	4	4	3.5	3	5	3
Satisfactory overall(1)-unsatisfactory overall(7)	1	1	1	3.5	3	5	1

Note: Occupants were asked to rate thermal comfort factors on a scale of 1-7 (for instance too hot = 1, too cold = 7)

Table XI. Household thermal comfort perception

Thermal comfort perception. In the Code 6 dwellings, overall thermal comfort satisfaction was very good during both summer and winter months, with average scores of 1 for all three households. However, in the Passivhaus dwellings, results suggest issues with thermal comfort during the summer months, with overall satisfaction scores of 3-3.5. Similarly, average scores for the rating scale comfortable (1) to uncomfortable (7) during summer months were 5.5 and 3.5. Average scores of 1.5 and 3 were reported for the too hot (1) to too cold (7) rating scale, suggesting problems with overheating. In the Code 3 dwellings, results varied significantly. One household reported low levels of satisfaction during both summer and winter months, with average scores of 7 for the too hot (1) to too cold (7) scale during winter; suggesting significant issues with thermal comfort. In the other household, no issues were identified.

SBS symptoms. As illustrated in Table XII, SBS symptoms were reported in the case study buildings; however, this is not of significant concern considering the low prevalence. The symptoms were identified if occupants stated they experienced more than one episode of the symptom and it was better at times away from the home. In some cases, occupants stated that they were not sure if the symptom was better since they spent the majority of time at home; in this case, the symptom was still included. As defined by Raw *et al.* (1995), BSI_5 includes the following symptoms: dryness of the eyes, blocked or stuffy nose, dry throat, lethargy and/or tiredness and headache. BSI_8 includes these five symptoms and the following: dry, itchy or irritated skin, runny nose, and itchy or watery eyes.

Discussion

The results from the IAQ measurements show the recommended maximum level of 1,000 ppm was breached in all three Code 6 and two Code 3 homes, with levels slightly below this limit in the two Passivhaus homes. During the building survey, it was identified that trickle vents in both Code 3 homes were closed, which may significantly diminish the ability of these homes to provide adequate ventilation. Furthermore,

House type	House no.	BSI_8	BSI_5	Occupant	PSI_8	PSI_5
Code 6	C6: No. 1	0.25	0	Adult (F)	1	0
				Child (F)	0	0
				Child (F)	0	0
				Child (F)	0	0
	C6: No. 2	0.5	0.25	Adult (F)	0	0
				Child (F)	0	0
				Child (F)	0	0
				Child (M)	2	1
	C6: No. 3	0	0	Adult (F)	0	0
				Adult (M)	0	0
				Child (F)	0	0
				Child (F)	0	0
				Child (M)	0	0
Passivhaus	Pa: No. 1	0	0	Adult (F)	0	0
				Adult (M)	0	0
				Child (M)	0	0
				Child (F)	0	0
				Child (F)	0	0
	Pa: No. 2	0.2	0.2	Adult (F)	0	0
				Adult (M)	1	1
				Child (F)	0	0
				Child (F)	0	0
				Child (M)	0	0
Code 3	C3: No. 1	0.25	0	Adult (F)	1	0
				Child (F)	0	0
				Child (F)	0	0
				Child (M)	0	0
	C3: No. 2	0	0	Adult (F)	0	0
				Child (F)	0	0
				Child (F)	0	0
				Child (M)	0	0
				Child (M)	0	0

Table XII. Building symptom index (BSI) and personal symptom index (PSI) for each house type

during the occupant interviews and observations, the MVHR system in two of the Code 6 homes (C6 No. 2; C6 No. 3) was turned off completely. The supply and extract vents in the other Code 6 home (C6 No. 1) had been effectively closed. These results suggest occupant awareness of the importance of home ventilation is required, in addition to improvements in the commissioning process to ensure vents are adequately locked in place to limit occupant interference. Further research is required to investigate thermal comfort complaints associated with the MVHR systems, including actual in-built efficiency of the heat recovery aspect. Occupant control is a significant issue in the application of MVHR in social housing. On one hand, if occupants are given too much control (e.g. in the Code 6 dwellings), MVHR systems may be interfered with or turned off altogether. However, if no control is given (e.g. the Passivhaus dwellings), this raises significant concerns regarding maintenance issues and the ability to appropriately adjust the system for seasonal variations (e.g. summer by-pass mode), occupancy levels and/or occupant activities. Furthermore, problems with the MVHR may go unnoticed in the future.

Strategies for the implementation of MVHR systems in social housing, however, should consider variation of user groups, such as older people, families and/or socio-economically-disadvantaged. For example, full control may not be appropriate or desired for older people. In this case, sensors may be more suitable to adequately regulate the system according to requirements, with regular maintenance conducted by the housing association or associated body. A major concern for socio-economically disadvantaged occupants is the cost association with running the systems, which can lead to occupants turning off the system altogether. It is important therefore to ensure systems cannot be easily disconnected and the heat recovery strategy is fully explained. For example, the results from the case study investigation looking at family user groups suggest inadequate use of purge ventilation, which may significantly increase the concentration of contaminants and/or moisture indoors. It may be more beneficial to provide automatic boost mode functions linked with particular activities, for example turning on the cooker in the kitchen and/or the shower in the bathroom. These strategies may help to improve the removal of pollutants and excess moisture in energy efficient social housing.

Overheating was reported in one Code 6 home and one Passivhaus home, which was supported by the results of the summer physical measurements. Apprehensions have been expressed regarding the ability of mechanical ventilation systems in achieving adequate purge ventilation for effective cooling, suggesting the need for incorporation of additional passive design strategies in energy efficient homes (Bone *et al.*, 2010). This should be incorporated effectively in the sustainable assessment methods in order to ensure IAQ and thermal comforts are not sacrificed in the drive towards energy efficiency.

Occupant knowledge of the ventilation system observed through the physical exercise was significantly poor. For example, all households stated that they did not know how to change the settings or the filters in the MVHR systems. As these homes are rented properties, this is not of particular concern as the housing association is likely to deal with maintenance, however, it does mean occupants are relying on the housing association to maintain the system effectively. This could cause significant problems in the future, especially were systems are inaccessible thus occupants may not be aware of maintenance and/or servicing requirements. Occupants were asked the frequency of various activities carried out in the home, including the use of air polluting products. The results suggest important sources of contaminants in the home environment (such as use of air fresheners or smoking), which are rarely considered during the design process. This raises concern of the suitability of airtight, mechanically ventilated dwellings for particular occupants and/or activities, and whether or not these homes require a certain lifestyle adjustment. Thus further consideration of occupant related sources of pollutants indoors is required in the design of energy efficient homes, including the need to educate and inform residents on the importance of minimising indoor air pollutants.

Moisture control is a significant issue in new build, airtight homes. This is further exacerbated through the activity of passively drying clothes indoors, which was reported in the majority of the case study homes. Furthermore, the inadequate use of purge ventilation, particularly after showering/bathing may present significant issues with indoor humidity, including the risk of mould growth. In addition, high humidity levels observed in the bedrooms of the case study dwellings may increase the proliferation of HDM, which have been linked to the development of asthma (Korsgaard, 1998b). As stated by Korsgaard (1998a, p. 36), "present-day building of energy-efficient houses with increased sealing of the building envelope, paralleled by a similar renovation of older houses, has increased indoor air humidity and is probably the cause of the almost fourfold increase in the occurrence of house-dust mites". Thus sustainable assessment methods should make adequate steps to address this issue, including the consideration of mandatory credits for strategies such as automatic purge ventilation, dedicated drying spaces or humidity sensors linked to the mechanical ventilation system.

Conclusion

The aim of this study was to examine the IAQ of energy efficient dwellings built to the CHSs and Passivhaus standard. The study found high levels of carbon dioxide in living rooms and main bedrooms of the case study dwellings, significantly high levels of formaldehyde, low relative humidity levels in living rooms and high relative humidity levels in bedrooms. Furthermore, issues with interference with the MVHR system, inadequate use of purge ventilation, lack of knowledge and awareness of the MVHR system, overheating, preference for natural ventilation strategies, high prevalence of air polluting activities and inadequate perception of IAQ were identified.

The findings are based on relatively limited data from a case study investigation of IAQ in seven homes designed to meet Passivhaus standard and CHSs (Level 3 and Level 6). For this reason, it is questionable whether the findings from this study can be generalised to the broader UK housing sector based on this study alone, thus further research is required. This case study, however, provided a unique opportunity to analyse and compare the IAQ of homes designed to a variety of energy efficient design strategies within one single building project.

Although based on a limited sample, this investigation has highlighted a number of issues in homes designed to meet the CHSs and Passivhaus standard, which should be addressed as a priority in future UK energy efficient housing schemes. A case has been made for the adequate consideration of IAQ in sustainable assessment methods, including the use of mandatory credits to ensure occupant health is not disregarded in the drive towards zero carbon. Future research needs include a large scale investigation on the performance of MVHR systems in UK energy efficient homes, including the perception and use of these systems in practice.

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Corresponding author
Professor Lukumon O. Oyedele can be contacted at: ayolook2001@yahoo.co.uk