International Journal of Sustainable Built Environment (2015) 4, 58–77

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International Journal of Sustainable Built Environment

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Original Article/Research

Case study investigation of indoor air quality in mechanically ventilated and naturally ventilated UK social housing

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Received 5 August 2014; accepted 4 March 2015

Abstract

There is a significant lack of indoor air quality research in low energy homes. This study compared the indoor air quality of eight newly built case study homes constructed to similar levels of air-tightness and insulation; with two different ventilation strategies (four homes with Mechanical Ventilation with Heat Recovery (MVHR) systems/Code level 4 and four homes naturally ventilated/Code level 3). Indoor air quality measurements were conducted over a 24 h period in the living room and main bedroom of each home during the summer and winter seasons. Simultaneous outside measurements and an occupant diary were also employed during the measurement period. Occupant interviews were conducted to gain information on perceived indoor air quality, occupant behaviour and building related illnesses. Knowledge of the MVHR system including ventilation related behaviour was also studied. Results suggest indoor air quality problems in both the mechanically ventilated and naturally ventilated homes, with significant issues identified regarding occupant use in the social homes.

Keywords: Indoor air; Mechanical Ventilation with Heat Recovery (MVHR); Social housing; Code for sustainable homes; Energy efficient design

1. Introduction

There exists a significant need for indoor air quality research in contemporary energy efficient dwellings. As suggested by a number of recent reports, the impact of energy efficient design strategies on the quality of the indoor environment remains largely under-researched, with a worrying absence of skills and knowledge in this area (Crump et al., 2009; Innovation and Growth Team, 2010; Sullivan et al., 2012, 2013). This is despite research suggesting that the tightening of building envelopes, reduction of ventilation rates, use of new building materials and techniques with unknown consequences and reliance on technology to provide sufficient ventilation may significantly diminish the quality of indoor air.

In particular, studies are needed to compare indoor air quality in low energy dwellings with indoor air quality in otherwise similar non-low energy dwellings. As suggested

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Peer review under responsibility of The Gulf Organisation for Research and Development.

http://dx.doi.org/10.1016/j.ijsbe.2015.03.002
2212-6090/

by Mendell (2013), future research questions should focus on specific energy-related factors and compare buildings as alike as possible excluding the particular energy related factor under consideration. Numerous studies investigating the effects of energy efficient retrofits have been conducted, however similar studies investigating new buildings are significantly lacking. For example, a study by Less and Walker (2013) investigated indoor air quality in 17 mechanically ventilated and naturally ventilated deep energy retrofits. They found statistically indistinguishable air change rates between the two house types. Furthermore, a number of faults with mechanical ventilation systems were identified, including air recirculation, clogged outside air inlets, failed attachment of ducts to units, irregular speed fluctuating from low to high and poor control.

Studies investigating indoor air quality in energy efficient dwellings have also focused on apartments or detached homes as opposed to terraced/semi-detached homes (such as (Aizlewood and Dimitroulopoulou, 2006; Mickaël et al., 2014). For instance, a study by Noris et al. (2013) investigated the effect of energy retrofits on indoor environmental quality in sixteen apartments (eight with continuous mechanical ventilation and eight without). The findings suggest improvements in levels of carbon dioxide, VOC's, acetaldehyde, PM2.5, comfort conditions and bathroom relative humidity; however mixed results were reported for concentrations of formaldehyde and nitrogen dioxide. In general, apartments with continuous mechanical ventilation showed a greater improvement of indoor environmental quality (other than PM2.5) compared to those without.

Furthermore, social housing is generally under-researched despite the fact that low-income households are at increased risk of exposure to indoor air pollution (Chuang et al., 1999; Krieger et al., 2002, 2000). For example, a study by Fung et al. (2006) looked at the conflict between air quality and energy efficiency in social housing, with particular reference to occupant behaviour. The results suggest a risk of negative impact on health from indoor air pollution in the social housing sector. Similarly, a case study investigation of low energy social housing by Ward (2008) suggests recent changes to the UK building regulations on the provision of natural ventilation in dwellings do not ensure adequate supply of fresh air. The poor perception of ventilation by the social tenants was also highlighted.

Despite this, there remains a significant emphasis on energy efficiency and fuel poverty in the social housing sector, with limited attention to indoor air quality. For instance, there remains greater obligation on local authorities to adopt energy efficient design strategies for newly built housing projects and for the retrofitting of existing housing stock. Also, unlike owner-occupied newly built dwellings, the Homes and Community agency in the UK require newly built affordable/social housing to meet the Code for Sustainable Homes Level 3 or above (Department for Communities and Local Government, 2012). The effect however of the Code for Sustainable Homes on indoor air quality is significantly under-researched.

This study therefore aims to (1) investigate the indoor air quality of newly buillt social housing in a UK context and (2) compare the results of homes designed to meet the Code for Sustainable Homes (CSHs) level 3 (naturally ventilated) and level 4 (MVHR). This was conducted through physical indoor air quality measurements alongside occupant diaries, in eight newly built dwellings (4× Code level 3 and 4× Code level 4). Interviews were also conducted to gain information on occupants' perception of indoor air quality and thermal comfort, Sick Building Syndrome symptoms and occupant behaviour. Building surveys were conducted on the day of the measurements to record information on general building conditions. This paper discusses the methodological approach followed by presentation of results and discussion. Finally, conclusions and further research opportunities are described.

2. Methodology

A case study approach was adopted in order to gain a comprehensive understanding of indoor air quality in newly built social housing. This included an investigation on the effect of occupant behaviour on indoor air quality, the performance of MVHR systems and occupant knowledge of these systems, building related health and perception of indoor air quality in Code 3 and 4 homes.

The case study homes were selected based on a number of criteria: single family social housing, availability, terraced or semi-detached, newy built ($\geqslant$2010), similar location and similar levels of airtightness ($<5\ m^3/h\ m^2$). Each household was approached initially through the housing association, followed by a phone call to explain the study and a subsequent meeting. Simultaneous air quality measurements were then conducted in the main bedroom, living room and outside during the summer (July–August 2013) and winter (November 2013–January 2014) months. An occupant diary was employed during the measurements to gain information on occupancy levels and activities which may have influenced the results. For example, occupants were asked to record various activities such as opening windows, use of air polluting products, smoking, cooking, use of boost mode function (if applicable), opening of internal doors and measurement room/household occupancy each hour. The diary was condensed to one A4 page for each measurement day.

Physical indoor air quality measurements were conducted in the main living room and bedroom at a height of approximately 1.1 m above the finished floor level, in accordance with ISO: 16000-1. Parameters included temperature, relative humidity and carbon dioxide which were monitored in the living room with an Extech IAQ datalogger (Easyview EA80-RH resolution 0.1%, accuracy ±3–5%, temperature resolution 0.1 °C, accuracy ±0.5 °C, carbon dioxide resolution 1 ppm, accuracy ±3% or ±50 ppm) and the main bedroom and outside with Wohler CO_2 datalogger (CDL 210-RH resolution 0.1%, accuracy ±3–5%, temperature resolution 0.1 °C, accuracy ±0.6 °C, carbon dioxide resolution 1 ppm, accuracy ±5% or ±50 ppm). Formaldehyde was monitored using a HalTech (HAL-HFX205-resolution 0.01 ppm, accuracy ±2%) handheld formaldehyde meter. Outside conditions were monitored with use of a weather station (Watson W-8681 Solar weather station-resolution: temperature 0.1 °C, relative humidity 1%, rain volume 0.1 mm, Air pressure 0.1 hPa) and data obtained from a local air quality monitoring site.

To gain information on occupant use, knowledge of the MVHR system (where applicable), perception of indoor air quality and thermal comfort, and building related health; structured occupant interviews were conducted with each household. A number of questionnaires were devised utilising validated procedures (Berry et al., 1996; Burge et al., 1990, 1993; Raw et al., 1996, 1995); one for each household, one for each occupant and one for each child. A building survey was also conducted after each interview, to gain information on general building conditions.

2.1. Building and household characteristics

Code 3 (C3) and Code 4 (C4) homes are both located in Northern Ireland, within 0.3 miles of each other. The homes are all 2/3 bedroom terraced houses, heated primarily with gas. Code 4 homes (Fig. 1b) are three storied and utilise Mechanical Ventilation with Heat Recovery (MVHR) systems for ventilation, where-as Code 3 homes (Fig. 1a) are two storied and naturally ventilated with trickle vents. The dwellings are part of two new-build social housing developments; Code 3 homes were completed in December 2010 and Code 4 in February 2013.

As illustrated in Table 1, household occupancy ranged from 3 to 6 people in Code 4 dwellings and 2–3 people in Code 3 dwellings. Smokers were present in three Code 4 and two Code 3 dwellings, however all households stated cigarettes were not smoked in the home, with the exception of Code 3:No.4. Occupancy of the case study dwellings was generally high; with two Code 3 and three Code 4 households stating that the homes are occupied on average twenty-four hours a day during weekdays. The dwellings were occupied by families with ages ranging from 1 to 67 years (Figs. 2 and 3).

2.2. Dwelling construction

Three of the case study dwellings are end terraces (C4:No.1, C3:No.1, C3:No.4); the remaining are mid-terraces. The dwellings are located in a residential area of moderate to high traffic flow. Dwelling construction and energy efficiency information is presented in Tables 2 and 3.

3. Results

3.1. Carbon dioxide during summer months

Carbon dioxide levels were significantly high in the living room of C4:No.3, peaking at 2558 ppm (as illustrated in Table 4). High levels (above 1000 ppm) were also recorded in C4:No.2, C4:No.4, C3:No.3, and C3:No.4. Fig. 4 presents the carbon dioxide levels over a 24 h period in the living room of C4:No.3. Mean living room carbon dioxide levels remained below the recommended guideline of 1000 ppm in all dwellings (Tables 5–8).

Figure 1. (a) Code 3 dwelling, (b) Code 4 dwelling.

Table 1
Building and household characteristics of Code 3 (C3) and Code 4 (C4) dwellings.

House No.[1]	Cooking fuel	Household occupancy	Household description (age)	No. of smokers	Average weekday occupancy	Average weekend occupancy
C4:No.1	Gas	3–4	Couple (48 & 37), with teenage daughter (18)	2	24/24 h	20/24 h
C4:No.2	Electric	3	Single mother (28), with daughter and son (4 & 7)	0	19/24 h	22/24 h
C4:No.3	Electric	6	Single mother (29) with twin girls (2) and daughter (6). Parents stay frequently.	2	24/24 h	24/24 h
C4:No.4	Electric	5	Couple (27 and 28) with three girls (1, 2 and 6)	1	24/24 h	18/24 h
C3:No.1	Electric	3	Couple (67 and 65) with adult son (34)	0	24/24 h	24/24 h
C3:No.2	Gas	2	Single mother with son (3)	0	24/24 h	15/24 h
C3:No.3	Electric	3	Single mother (27) with daughter (11) and son (3)	1	14/24 h	24/24 h
C3:No.4	Gas	2	Single mother with son (3)	1	16/24 h	16/24 h

[1] Dwellings are referred to as C4 (Code 4) or C3 (Code 3) followed by an anonymous number to protect the identity of the building occupants.

In the main bedroom however, mean carbon dioxide levels were recorded above 1000 ppm in two Code 3 homes (No.1 and No.3) and one Code 4 home (No.3); with maximum levels reaching 4,173 ppm (C3:No.1) and 3751 ppm (C3:No.3). In C3:No.1 and C3:No.3 the bedroom door was closed during the night, which may have contributed to the high readings. All Code 4 homes, C3:No.3 and C3:No.4 had the window open during the night. Fig. 5 presents the carbon dioxide levels over a 24 h period in the bedroom of C3:No.1.

Results from the occupant interviews suggest inadequate knowledge of the ventilation system, with all Code 4 homes stating 'not sure' when asked about various features of the MVHR system, including the current settings, changing of filters, boost mode function and location of controls. Furthermore, problems with noise of the MVHR system were reported in C4:No.1 and C4:No.4. In Code 3 homes, three out of four dwellings were aware of the presence of trickle vents, and stated that they were 'constantly' used for background ventilation. One dwelling (C3:No.1) however stated 'not sure' when asked about the presence of trickle vents.

3.2. Winter carbon dioxide

During the winter months, all Code 3 and Code 4 dwellings recorded carbon dioxide levels in the living room above the recommended level (>1000 ppm). Furthermore, average levels were above 1000 ppm in one Code 4 (C4:No.3) and two Code 3 (C3:No.1, C3: No.3) homes. Significantly high peak carbon dioxide levels (>2000 ppm) were recorded in C3: No.1. As illustrated in Table 9, the two Code 3 homes with the lowest average carbon dioxide levels reported significantly low average occupancy levels in the measurement room.

Significantly high carbon dioxide levels (>2000 ppm) were recorded in the bedroom of three Code 3 homes, with all Code 3 and Code 4 dwellings recording levels above the recommended guideline (>1000 ppm). Average carbon dioxide levels were significantly high (2744 ppm) in C3: No.1, suggesting major problems with ventilation in the main bedroom. All average carbon dioxide levels in Code 4 dwellings were below 1000 ppm (Tables 10 and 11).

4. Temperature

4.1. Summer temperature

As illustrated in Table 12, living room temperatures peaked at 28 °C in C4:No.4, and 27 °C in C4:No.2, which suggests problems with overheating. Bedroom temperatures were lower, peaking at 25.9 °C in C4:No.2. Similar temperatures were recorded in Code 3 homes, with living room temperatures in C3:No.4 reaching 27.5 °C (Table 13). Average living room and bedroom temperatures ranged from 22.5–25 °C in Code 3 dwellings and 21.5–25.2 °C in Code 4 dwellings. During the interview process, all Code 4 households stated problems with overheating in the home, with C4:No.1 and C4:No.3 explaining it gets too warm at night. Similarly, two Code 3 households (C3:No.2 and C3:No.4) stated problems with overheating.

4.2. Winter temperature

During the winter months, living room temperatures reached 26.2–27 °C in Code 4 dwellings, despite outside temperatures peaking at only 8–11.9 °C. This suggests over-heating caused by internal sources and/or over-use of heating devices. Peak living room temperatures were higher than the recommended levels for comfort (18–24 °C) in all Code 4 dwellings and three Code 3 dwellings. Average bedroom temperatures remained within comfortable limits in all dwellings (Tables 14–16).

5. Relative humidity

5.1. Summer relative humidity

Summer levels of relative humidity remained below 60% in the living room and bedroom of all Code 4 homes, with mean levels ranging from 45 to 54%. In comparison, relative humidity levels peaked above 60% in the living room and bedroom of C3:No.2 and C3:No.3 (Table 17). In

Figure 2. Plans and sections of Code 3 dwellings (Two and three bedroom).

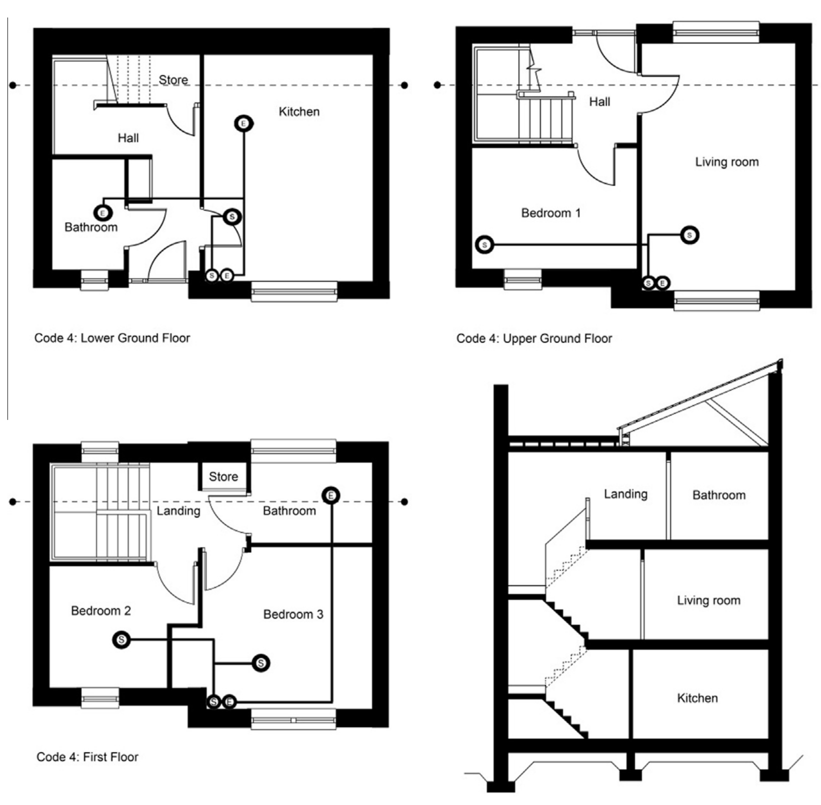


Figure 3. Plans, sections and MVHR layout of Code 4 dwellings.

Table 2
Construction of Code 3 and Code 4 dwellings.

Features	Code 3 dwellings	Code 4 dwellings
Construction	Timber frame-brick outer leaf	Cavity wall-brick outer leaf
Glazing	Double glazing	Triple glazing
Floor area	2 bed 75.6 m^2/3 bed 94.9 m^2	100.9 m^2
No. of storeys	Two	Three
Orientation	East/West	North/South

Table 3
Energy efficiency of Code 3 and Code 4 dwellings.

House no.	q50	CO2 emissions	Dwelling emission rate	Primary energy demand	SAP rating
C4:No.1	2.12 m^3/h m^2	0.83 t/year	9.83 kg/m^2/yr	57 kWh/m^2/yr	93 A
C4:No.2	2.04 m^3/h m^2	0.76 t/year	9.04 kg/m^2/yr	52 kWh/m^2/yr	93 A
C4:No.3	2.04 m^3/h m^2	0.73 t/year	8.83 kg/m^2/yr	51 kWh/m^2/yr	93 A
C4:No.4	2.04 m^3/h m^2	0.95 t/year	10.98 kg/m^2/yr	63 kWh/m^2/yr	92 A
C3:No.1	4.8 m^3/h m^2	1.28 t/year	18.13 kg/m^2/yr	108 kWh/m^2/yr	87 B
C3:No.2	4.6 m^3/h m^2	1.15 t/year	16.17 kg/m^2/yr	98 kWh/m^2/yr	88 B
C3:No.3	4.2 m^3/h m^2	1.40 t/year	15.68 kg/m^2/yr	94 kWh/m^2/yr	87 B
C3:No.4	4.8 m^3/h m^2	1.27 t/year	17.98 kg/m^2/yr	107 kWh/m^2/yr	87 B

Table 4
Summer carbon dioxide levels in the living room (ppm).

Descriptive statistics	Code 4 (C4)				Code 3 (C3)			
	No.1	No.2	No.3	No.4	No.1	No.2	No.3	No.4
Maximum	764	1181	2558	1474	844	752	1696	1679
Minimum	453	731	448	431	602	452	458	427
Standard deviation	74.2	91.2	437.7	224.9	55.3	84.4	255.2	212.3
Average	548.3	825.9	989.4	621.5	723.0	599.0	760.9	648.1

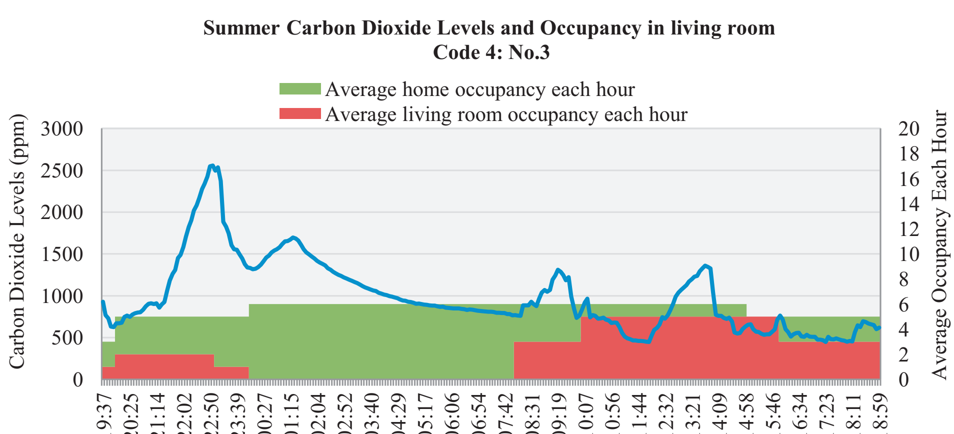


Figure 4. Carbon dioxide levels and occupancy in the living room of Code 4: No.3.

Table 5
Average occupancy levels during summer in a 24 h monitoring period.

Average occupancy levels	Code 4 (C4)				Code 3 (C3)			
	No.1	No.2	No.3	No.4	No.1	No.2	No.3	No.4
In home	2.04	2.40	5.57	3.17	2.82	1.92	2.43	1.70
In living room	0.64	1.20	2.35	1.67	1.60	1.13	0.91	0.78

C3:No.3, living room levels reached 70.4%, which suggests the potential for mould growth. This corresponds with the results from the interview process, as C3:No.2 reported the presence of mould in the last 12 months, on the bedroom ceilings. Mean levels of all Code 3 homes however remained below 60% (Tables 18 and 19).

Table 6
Summer carbon dioxide levels in the main bedroom (ppm).

Descriptive statistics	Code 4 (C4)				Code 3 (C3)			
	No.1	No.2	No.3	No.4	No.1	No.2	No.3	No.4
Maximum	968	664	1153	965	4173	1771	3761	1244
Minimum	437	424	418	412	463	417	435	405
Standard deviation	191.3	67.0	254.3	189.3	1247.3	440.3	1102.2	262.5
Average	601.5	522	674.0	645.5	1639.0	905.5	1453.9	688.9

Table 7
Measurement conditions in the main bedroom.

Measurement conditions	Code 4 (C4)				Code 3 (C3)			
	No.1	No.2	No.3	No.4	No.1	No.2	No.3	No.4
Door	Closed	Open	Closed	Closed	Closed	Open	Closed	Open
Window	Open	Open	Open	Open	Closed	Closed	Open	Open
Night time occupancy	2 Adults	1 Adult 1 Kid	2 Adults	2 Adults	2 Adults	1 Adult	1 Adult 2 Kids	1 Adult 1 kid

Table 8
Winter carbon dioxide levels in the living room (ppm).

Descriptive statistics	Code 4				Code 3			
	No.1	No.2	No.3	No.4	No.1	No.2	No.3	No.4
Maximum	1445	1070	1539	1325	3427	1203	1741	1995
Minimum	481	567	706	544	734	612	660	503
Standard deviation	234.6	146.2	199.6	159.7	743.2	119.5	302.0	308.6
Average	662.1	775.4	1047.3	868.8	1675.9	800.3	1143.0	842.6

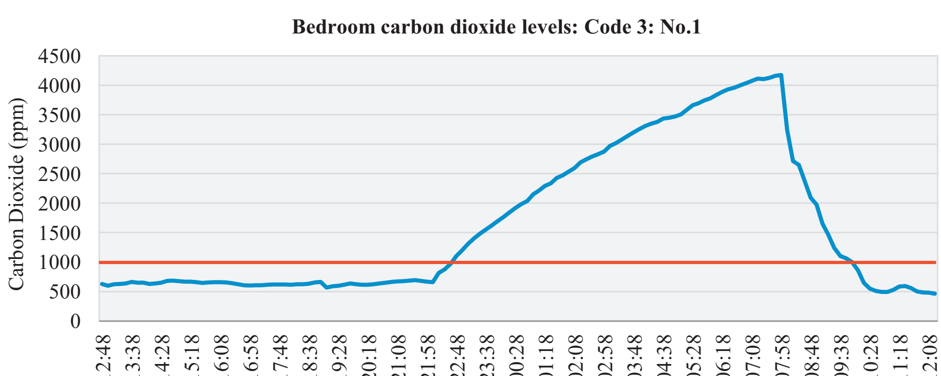


Figure 5. Carbon dioxide levels and temperature in the bedroom of Code 3: No.1.

5.2. Winter relative humidity

Peak living room relative humidity levels were lower in Code 4 dwellings (ranging from 33.6 to 53.2%) compared to Code 3 dwellings (ranging from 52 to 62.7%). Relative humidity levels below 30% were recorded in one Code 4 dwelling (C4:No.1), which had the potential to cause sensory irritation. All Code 4 dwellings remained below the recommended maximum level of 60%. The bedroom of C3:No.1 and the living room and bedroom of C3:No.3 however recorded peak levels above 60%, suggesting potential for mould growth.

6. Formaldehyde

6.1. Summer formaldehyde

As illustrated in Table 20, summer formaldehyde levels peaked above the recommended level of 0.08 ppm in two Code 4 (C4:No.2 and C4:No.4) and two Code 3 (C3:No.1 and C3:No.3) homes. Mean levels in all dwellings remained below 0.08 ppm. All Code 4 households and three Code 3 households (C3:No.1, C3:No.2 and C3:No.3) reported using air-fresheners, scented candles or incense on a daily basis. During the monitoring period, the use of incense,

Table 9
Average occupancy levels during the winter monitoring period.

Average occupancy levels	Code 4				Code 3			
	No.1	No.2	No.3	No.4	No.1	No.2	No.3	No.4
In home	2.46	3.22	4.65	4.09	2.46	0.80	2.24	1.63
In living room	1.00	2.04	2.52	2.13	1.33	0.36	1.24	0.63

air fresheners or scented candles was reported in the case study dwellings (as illustrated in Table 21).

Figs. 6 and 7 present the formaldehyde levels in C3:No.1 and C4:No.2. It is clear from these graphs that the source of formaldehyde within the home is intermittent, thus it is suggested emissions from building materials were not the predominant source. However the data recorded from the occupant diaries of C3:No.1 and C4:No.2 during the measuring period do not suggest a likely source of formaldehyde resulting from occupant use. It is interesting to note that after the peak emission of formaldehyde, it took approximately one hour for levels to return below maximum recommended levels (0.08 ppm) (Figs. 8 and 9).

6.2. Winter formaldehyde

During the winter months, the maximum recommended value of formaldehyde was exceeded in all Code 3 dwellings and three out of four Code 4 dwellings. Average values for the monitoring period however were all below 0.08 ppm. Similar to summer results, the information gained from the occupant diary (use of cleaning products, air fresheners, scented candles, incense, smoking, natural drying of clothes indoors, heating schedule) does not suggest a probable source of formaldehyde.

For instance, in C4:No.3, occupants stated a plug in incense/scented candle was utilised from approximately 6 pm to 1 am on day one, and from 9 am to 4 pm on day two. Cleaning products were utilised from approximately 2 pm to 4 pm on day two, and the heating was turned on from 10 to 12 pm on day one and 3 to 4 pm on day two. Time and duration of these activities do not correspond with the peaks of formaldehyde.

In C3:No.1, occupants stated no-one was home on day two from approximately 1 to 4 pm, during which time the significant peak of formaldehyde occurred. This is considerably unusual, and suggests either the source of formaldehyde was not occupant related, or the use of the occupant diary did not allow for accurate recording of activities during the monitoring period. Results from the living room carbon dioxide measurements however demonstrate a steady decline in levels from 13:35 to 16:05, suggesting that the occupants had indeed left the home.

7. Indoor air quality perception

7.1. Indoor air quality perception during the summer months

Occupants were asked to rate various aspects of the indoor air quality, using seven point rating scales, for instance 'Dry' = 1 to 'Humid' = 7. The scales were either uni-polar (one extreme bad- the other good) or bi-polar (neither extreme ideal), depending on the variable. Raw et al. (1995) suggests for uni-polar scales, a score >3 requires further investigation and >5 is a cause for concern; and for bi-polar scales, a score outside the range 3–5 requires investigation and outside 2–6 is cause for concern (Tables 22 and 23).

In Code 3 dwellings (Table 24), the average rating for the scale 'Fresh (1)–Stuffy (7)' was 4.8, suggesting further investigation is required. Average overall satisfaction of the air quality in Code 3 dwellings was generally good (mean = 2.1), however maximum values were recorded as high as 6 for the scale 'Satisfactory overall (1)–unsatisfactory overall (7)', representing a cause for concern in some dwellings (Tables 25–27).

In Code 4 dwellings, the average score for the 'Dry (1)–Humid (7)' scale was 4.9, suggesting occupants found the air quality quite humid. For the scale 'Fresh (1)–Stuffy (7)', the average occupant score was 5.1, which is a cause for concern. However, overall satisfaction with the air quality in Code 4 homes was better than that recorded in Code 3 dwellings.

7.2. Indoor air quality perception during the winter months

Similarly, during the winter months, occupants of both Code 3 and Code 4 dwellings did not perceive the air to be significantly fresh. Mean scores for the 'Fresh (1)–Stuffy (7)' scale were 5.2 (suggesting cause for concern) in Code 3 dwellings and 3.3 (suggesting further investigation required) in Code 4 dwellings. Over-all satisfaction however in Code 3 and Code 4 dwellings however was relatively good.

8. Personal and Building Symptom Index

The average Building Symptom Index (BSI_5 and BSI_8) for both Code 3 and Code 4 dwellings is reported in Table 28. It is clear, with the exception of C4:No.3, Code 4 dwellings reported significantly less Sick Building Symptoms than Code 3 dwellings. BSI_5 represents five symptoms: blocked/stuffy nose, headache, dry throat, lethargy/tiredness, and dryness of the eyes; BSI_8 also includes the following three symptoms: dry, itching or irritated skin, itchy/watery eyes and runny nose.

Symptoms were recorded if occupants stated that they experienced more than one episode and the symptom was better on days away from the home. In some cases, occupants stated they were not sure if the symptom was better

Table 10
Winter carbon dioxide levels in the main bedroom (ppm).

Descriptive statistics	Code 4				Code 3			
	No.1	No.2	No.3	No.4	No.1	No.2	No.3	No.4
Maximum	1407	1076	1578	1479	4456	1521	3268	2584
Minimum	548	641	559	551	1608	531	768	573
Standard deviation	188.3	100.1	287.7	233.3	846.7	331.7	776.3	643.1
Average	762.7	861.4	969.3	908.1	2744.4	981.7	1901.1	1214.0

Table 11
Winter measurement conditions in the main bedroom.

Measurement conditions	Code 4				Code 3			
	No.1	No.2	No.3	No.4	No.1	No.2	No.3	No.4
Door	Closed	Open	Closed	Closed	Closed	Closed	Closed	Closed
Window	Closed	Closed	Open	Open	Closed	Closed	Closed	Open
Occupancy	2 adults	1 adult, 1 child	2 adults	2 adults	2 adults	1 adult	1 adult, 1 child	1 adult, 1 child

Table 12
Code 4 summer temperatures (°C).

	No.1			No.2			No.3			No.4		
	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out
Max	25.3	23.6	25.8	27.8	25.9	27.6	25.8	22.6	24.2	28.1	22.6	27.7
Min	22.0	20.3	14.2	22.2	22.9	14.1	22.7	20.6	13.5	22.4	21.7	13.8
S.D	0.7	0.7	3.2	0.9	0.6	3.2	0.7	0.4	3.3	0.8	0.2	3.7
Mean	23.0	21.5	17.9	25.2	24.5	17.7	24.5	21.9	17.3	23.5	22.2	18.2

[a] Liv = Living room.
[b] Bed = Bedroom.
[c] Out = Outside.

Table 13
Code 3 summer temperatures (°C).

	No.1			No.2			No.3			No.4		
	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out
Max	25	24.9	22.9	25.4	23.9	22.5	24.8	24.6	23.2	27.5	24.6	29.9
Min	24.3	22.9	14.4	23.3	22.6	13.1	22	22.1	13.2	21.3	21.7	13.8
S.D	0.0	0.5	2.6	0.5	0.5	2.6	0.7	0.7	2.7	1.2	0.7	5.0
Mean	25.0	24.5	17.7	24.5	23.3	17.7	23.8	23.6	17.1	24.1	22.5	19.5

[a] Liv = Living room.
[b] Bed = Bedroom.
[c] Out = Outside.

Table 14
Code 4 winter temperatures (°C).

	No.1			No.2			No.3			No.4		
	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out
Max	27.0	21.8	9.7	26.4	25.3	9.8	26.4	21.9	8.0	26.2	22.2	11.9
Min	18.9	18.1	5.0	21.7	21.7	6.2	22.2	18.3	-2.0	20.9	18.6	8.9
S.D	2.4	0.6	1.0	1.2	1.0	1.1	1.0	0.8	2.9	1.3	0.8	0.8
Mean	22.6	19.7	7.0	24.1	23.4	8.1	23.9	20.0	2.7	23.0	19.9	9.9

[a] Liv = Living room.
[b] Bed = Bedroom.
[c] Out = Outside.

Table 15
Code 3 winter temperatures (°C).

	No.1			No.2			No.3			No.4		
	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out
Max	27.9	23.6	8.4	25.0	22.9	12.1	25.5	23.7	7.6	24.7	21.3	10.9
Min	21.3	20.3	2.5	20.4	19.0	7.4	18.6	16.3	3.2	17.7	18.2	7.9
S.D	1.5	0.8	1.3	1.2	1.0	1.5	1.2	1.3	1.1	1.8	0.9	0.7
Mean	23.9	21.6	4.8	22.5	20.3	9.4	22.9	20.7	5.5	21.0	19.9	9.9

[a] Liv = Living room.
[b] Bed = Bedroom.
[c] Out = Outside.

Table 16
Code 4 summer relative humidity levels (%).

	No.1			No.2			No.3			No.4		
	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out
Max	55.3	56.9	84.6	53.3	54.1	97.5	51.4	53.8	72.8	54.5	50.5	84.4
Min	46.0	50.0	43.8	38.6	38.1	34.4	39.6	44.2	30.7	36.3	41.3	27.9
S.D	1.7	1.9	10.1	3.7	4.7	20.2	2.5	2.1	11.5	2.8	1.9	14.7
Mean	51.1	53.8	67.0	46.3	46.7	69.9	45.2	47.7	56.2	48.7	47.6	64.2

[a] Liv = Living room.
[b] Bed = Bedroom.
[c] Out = Outside.

Table 17
Code 3 summer relative humidity levels (%).

	No.1			No.2			No.3			No.4		
	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out
Max	58.4	59.7	75	63.2	60.1	75.5	70.4	67.2	97.8	57.3	53.4	71.4
Min	41.5	44.2	48.5	47.4	47.3	47.5	53.4	45.6	47.7	39.9	42.8	22.2
S.D	0.9	3.5	7.5	4.1	3.1	6.1	4.4	5.8	16.9	2.8	2.6	13.8
Mean	56.6	54.6	65.2	51.1	51.7	65.9	58.1	57.6	79.7	49.0	49.5	54.8

[a] Liv = Living room.
[b] Bed = Bedroom.
[c] Out = Outside.

Table 18
Code 4 winter relative humidity levels (%).

	No.1			No.2			No.3			No.4		
	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out
Max	33.6	40.9	71.5	45.6	44.7	99.9	46.5	52.7	100	53.2	56.3	83.1
Min	26.2	33.4	62.5	31.5	32.6	76.8	35.6	35.3	71.0	38.1	45.2	72.4
S.D	1.5	1.4	1.8	2.8	2.5	9.2	1.8	2.8	8.2	1.8	3.3	3.0
Mean	30.3	38.0	64.8	38.6	38.2	90.3	41.7	43.9	89.9	43.4	49.5	77.9

[a] Liv = Living room.
[b] Bed = Bedroom.
[c] Out = Outside.

on days away from the home, for example since they spent most their time at home. In these cases, the symptom was still included. Fig. 10 illustrates the prevalence of SBS symptoms in code 3 and code 4 dwellings. The high prevalence of Sick Building Syndrome (SBS) symptoms in Code 3 dwellings suggests further investigation may be needed to identify the cause(s).

9. Discussion

Summer carbon dioxide levels peaked above 1000 ppm in the living room of three out of four Code 4 homes and two out of three Code 3 homes; and in the main bedroom of one Code 4 home and all four Code 3 homes. In two of the Code 3 bedrooms, levels reached above 3500 ppm.

Table 19
Code 3 winter relative humidity levels (%).

	No.1			No.2			No.3			No.4		
	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out	[a]Liv	[b]Bed	[c]Out
Max	52.6	63.8	75.6	55.6	59.5	80.7	62.7	65.9	80.7	52.0	58.3	81.8
Min	41.4	52.8	67.7	44.1	53.4	71.5	42.1	50.4	75.1	40.8	44.2	70.1
S.D	1.8	2.6	1.5	1.8	1.6	2.8	4.3	3.9	1.5	2.3	4.1	2.4
Mean	46.3	58.7	72.6	46.9	55.9	77.4	53.4	60.4	77.9	47.3	52.0	77.5

[a] Liv = Living room.
[b] Bed = Bedroom.
[c] Out = Outside.

Table 20
Summer formaldehyde levels in the living room (ppm).

Descriptive Statistics	Code 4				Code 3			
	No.1	No.2	No.3	No.4	No.1	No.2	No.3	No.4
Minimum	0.00	1.85	0.03	0.18	1.02	0.04	0.10	0.00
Maximum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Standard Deviation	0.00	0.11	0.00	0.01	0.08	0.00	0.01	0.00
Average	0.00	0.01	0.00	0.00	0.02	0.00	0.00	0.00

These results suggest significant problems with ventilation. During the measurement period, trickle vents were opened in the main bedroom of all Code 3 dwellings and the living room of three Code 3 dwellings (C3:No.2, 3 and 4). This suggests that trickle vents alone were not capable of achieving adequate background ventilation under typical conditions, particularly in the main bedrooms. These findings are supported by a recent study by Sharpe et al. (2014), who found significant issues with trickle vents in practice; including insufficient ventilation provision and inadequate occupant use.

In winter, carbon dioxide levels in the living room and main bedroom peaked above 1000 ppm in all Code 3 and Code 4 dwellings, reaching levels as high as 3427 ppm in the living room (9 pm–3 adults) and 4456 ppm in the main bedroom (7 am–two adults) in C3:No.1. Furthermore, average carbon dioxide levels above 1000 ppm were recorded in the living room of one Code 4 and two Code 3 dwellings and the bedroom of three Code 3 dwellings. The occupancy in these homes did not exceed typical levels at any stage of the measurement period. For example, during the winter measurements, the number of people living in the home was exceeded briefly in two homes (one extra person in C3:No.4 and two extra people in C4:No.2). During summer, it was exceeded briefly by one extra person in C3:No.2, C3:No.4 and C4:No.2.

Knowledge of the MVHR system was considerably lacking in Code 4 homes. All households stated that they did not know where the controls for the system were located, or how to change the settings. The MVHR systems were located in the roof-space, which meant access to the systems was difficult. Furthermore, lack of occupant awareness and knowledge of the system could cause significant problems in the future if the system breaks down or maintenance is required. This is particularly problematic in the social housing context as responsibility of maintaining the MVHR system may not be clearly specified. Periodic checks by the housing association therefore may be required to ensure adequate performance and maintenance.

Overheating was reported during the summer in two Code 3 and all four Code 4 homes, with measurements recording peak temperatures above 27 °C in one Code 3 and two Code 4 dwellings. Overheating is emerging as a significant issue in newly built dwellings, with particular concern over lack of solar shading, inadequate ventilation and/or free cooling in low energy homes. The findings from this study suggest greater protection from over-heating may be required in the Code for Sustainable Homes rating scheme, to ensure comfortable interior environments during the summer months. In addition, the results raise questions about the restriction of ventilation rates and the levels of airtightness being sought in the UK housing sector and whether or not it is appropriate considering future climate predictions and current space standards.

In the UK, newly built homes are substantially smaller than in the rest of Europe (Robert-Hughes et al., 2011). Social housing poses a particular problem, which is attributed by the lack of affordable housing and the introduction of the ‘bedroom tax’ policy. For instance, a recent study of English dwellings found that 72% of those receiving Housing Benefit were undersised according to the Greater London Authority standard (Morgan and Cruickshank, 2014). Similarly, lack of national standards for daylighting in England and Wales (highlighted by the RIBA’s ‘Without Light and Space’ campaign RIBA (2014)) has given rise to

Table 21
Occupant activities during the summer measurement period.

House no.	Windows in the living room	Drying clothes naturally	Use of incense/scented candles	Use of air fresheners	Use of cleaning products
C4:No.1	Opened	No	No	Yes	Yes
C4:No.2	Opened	Yes	Yes	Yes	Yes
C4:No.3	Opened	Yes	Yes	Yes	Yes
C4:No.4	Opened	No	Yes	Yes	Yes
C3:No.1	Opened	No	No	No	No
C3:No.2	Opened	No	Yes	Yes	Yes
C3:No.3	Opened	No	No	No	No
C3:No.4	Opened	No	No	No	Yes

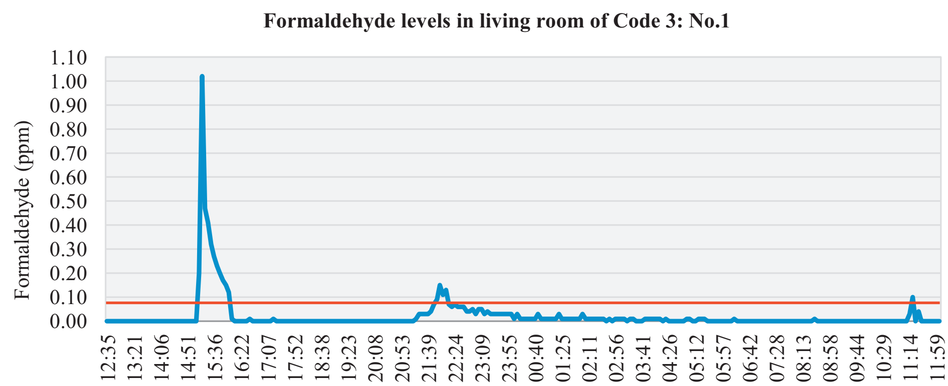


Figure 6. Summer formaldehyde levels in the living room of Code 3: No.1.

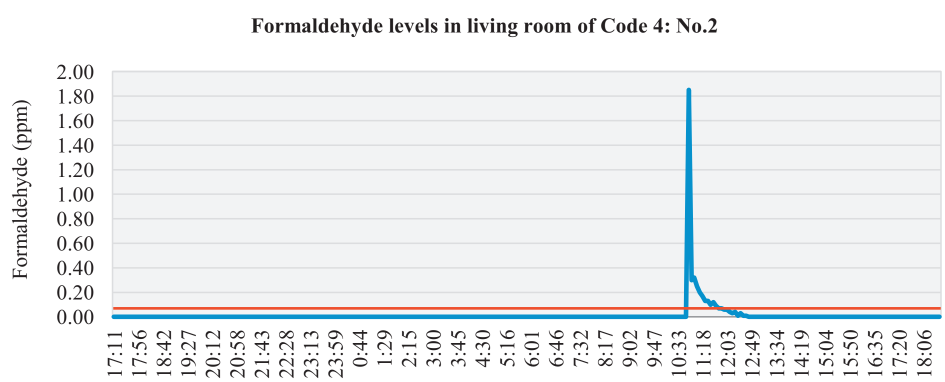


Figure 7. Summer formaldehyde levels in the living room of Code 4: No.2.

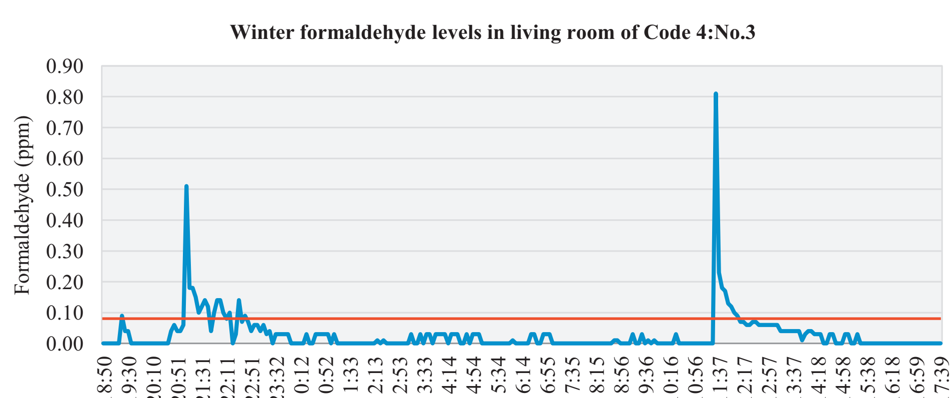


Figure 8. Winter formaldehyde levels in the living room of Code 4: No.3.

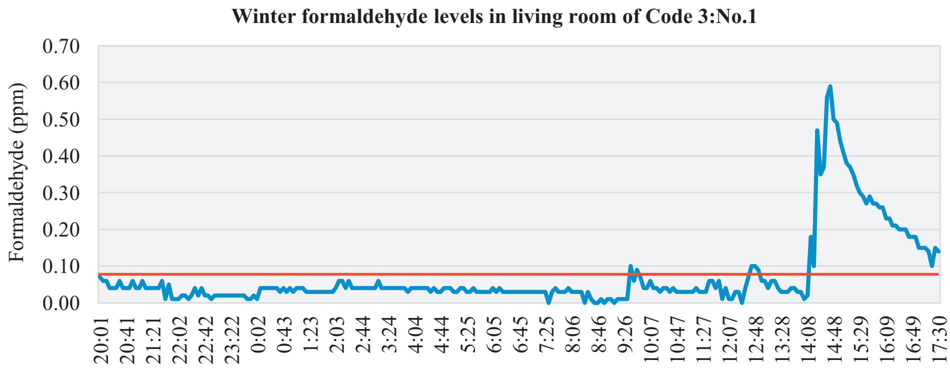


Figure 9. Winter formaldehyde levels in the living room of Code 3: No.1.

Table 22
Winter formaldehyde levels in the living room (ppm).

Descriptive Statistics	Code 4				Code 3			
	No.1	No.2	No.3	No.4	No.1	No.2	No.3	No.4
Minimum	0.04	0.09	0.81	0.18	0.59	0.41	0.24	0.38
Maximum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Standard Deviation	0.01	0.02	0.07	0.02	0.10	0.06	0.05	0.04
Average	0.00	0.01	0.03	0.00	0.07	0.07	0.05	0.01

Table 23
Occupant activities during the winter measurement period.

House No.	Windows in living room	Drying clothes naturally	Use of incense/scented candles	Use of air fresheners	Use of cleaning products
C4:No.1	Opened	Yes	No	Yes	Yes
C4:No.2	Opened	Yes	Yes	Yes	No
C4:No.3	Opened	No	Yes	No	Yes
C4:No.4	Opened	No	Yes	No	Yes
C3:No.1	Closed	No	No	No	No
C3:No.2	Opened	No	Yes	Yes	No
C3:No.3	Opened	No	No	No	Yes
C3:No.4	Opened	No	No	Yes	Yes

Table 24
Perception of indoor air quality in Code 3 homes during the summer months.

IAQ perception scales	Mean	S.D	Mean + S.D	Mean − S.D	Max	Min
Dry–Humid Scale	4.6	1.9	6.5	2.7	7	2
Fresh–stuffy scale	4.8	2.5	7.3	2.3	7	1
Odourless–odorous scale	2.6	1.5	4.1	1.1	4	1
Too still–too draughty scale	3.4	1.3	4.7	2.1	4	1
Satisfactory overall–unsatisfactory overall	2.8	2.2	5.0	0.6	6	1

Table 25
Perception of indoor air quality in Code 4 homes during the summer months.

IAQ perception scales	Mean	S.D	Mean + S.D	Mean − S.D	Max	Min
Dry–Humid Scale	4.9	1.1	6.0	3.7	6	3
Fresh–stuffy scale	5.1	1.0	6.1	4.1	6	4
Odourless–odorous scale	1.0	0.0	1.0	1.0	1	1
Too still–too draughty scale	3.4	0.9	4.3	2.5	4	2
Satisfactory overall–unsatisfactory overall	2.1	1.2	3.4	0.9	4	1

Table 26
Perception of indoor air quality in Code 3 homes during winter.

IAQ perception scales	Mean	S.D	Mean + S.D	Mean − S.D	Max	Min
Dry–Humid Scale	3.6	0.9	4.5	2.7	4	2
Fresh–stuffy scale	5.2	1.3	6.5	3.9	7	4
Odourless–odorous scale	2.4	1.1	3.5	1.3	4	1
Too still–too draughty scale	3.4	0.9	4.3	2.5	4	2
Satisfactory overall–unsatisfactory overall	2.2	1.6	3.8	0.6	4	1

Table 27
Perception of indoor air quality in Code 4 homes during winter.

IAQ perception scales	Mean	S.D	Mean + S.D	Mean − S.D	Max	Min
Dry–Humid scale	3.8	0.5	4.5	3.5	5	3
Fresh–stuffy scale	3.3	0.6	3.8	2.5	4	2
Odourless–odorous scale	1.5	0.7	2.4	0.9	3	1
Too still–too draughty scale	3.8	0.5	4.2	3.3	4	3
Satisfactory overall–unsatisfactory overall	1.6	0.5	2.1	1.1	2	1

Table 28
Scores for Personal Symptom Index (PSI) and Building Symptom Index (BSI).

	Code 4				Code 3			
	No. 1	No.2	No.3	No.4	No.1	No.2	No.3	No.4
Average BSI_8	0	0	0.4	0	1	1.5	1.3	2.5
Average BSI_5	0	0	0.2	0	1	0.5	0.6	2

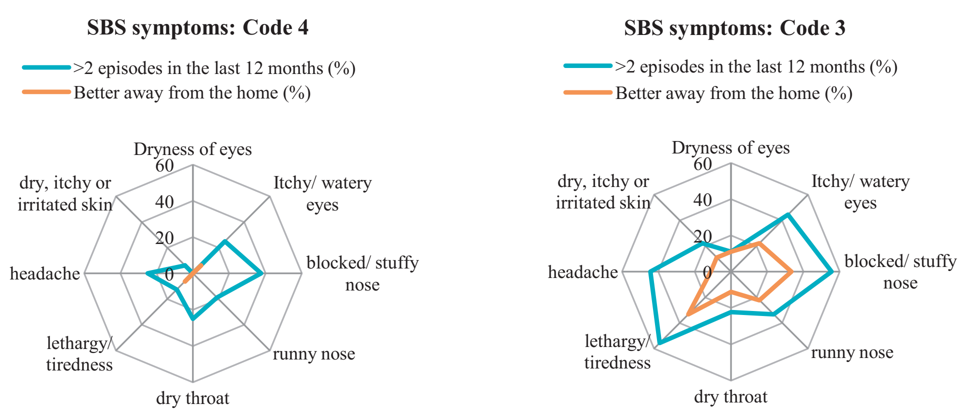


Figure 10. Presence of Sick Building Syndrome symptoms in Code 3 and Code 4 dwellings.

small windows and restrictions to natural ventilation. This may have significant implications on the quality of indoor air and cooling provision in newly built dwellings.

During the winter months, living room temperatures peaked between 26.2 °C and 27.9 °C in all Code 4 dwellings and one Code 3 dwelling, despite low external temperatures. Peak temperatures in the living room were higher than the recommended levels of comfort (18–24 °C) in all Code 4 and three Code 3 dwellings. This suggests excessive use of heating devices and/or significant internal courses of heat. These results may be explained by the rebound effect, where-by relative saving through energy efficiency measures are off-set by higher expectations for comfort and/or higher temperature set-points.

Relative humidity levels in summer rose above 70% in C3:No.3, which corresponds with the results of the interview since the presence of mould was reported in this home in the last 12 months. Levels were recorded above 60% in the living room and bedroom of C3:No.2 and C3:No.3, however all Code 4 homes remained below this level. Outside mean and peak humidity levels were higher during the measurements of all Code 4 dwellings (with the exception of C4:No.3), thus outside conditions did not significantly affect the results. Furthermore, occupant activities did not appear to affect the results. For instance, in two Code 4 homes (C4:No.2 and C4:No.3), occupants stated that clothes were naturally dried indoors during the monitoring period, yet the relative humidity levels were generally lower than Code 3 homes where occupants stated no clothes were naturally dried indoors.

Similarly, during winter months, relative humidity levels in Code 4 dwellings were lower (33.6–53.2%) than Code 3 dwellings (52–62.7%). The presence of MVHR systems therefore may have contributed to the lower humidity levels. In two Code 3 dwellings, peak relative humidity levels exceeded 60%. Higher humidity levels (average and peak) were recorded in the bedroom compared to the living room in all dwellings, (most likely as a result of lower temperatures), with the exception of C4:No.2. Average bedroom humidity levels above 50% are a cause for concern in all four Code 3 dwellings, considering the association with the proliferation of house dust mites.

Summer formaldehyde levels peaked above the recommended limits of 0.08 ppm in two Code 3 and two Code 4 dwellings, with peak levels reaching 1.85 ppm (C4:No.2). However, all mean values were recorded below 0.08 ppm, which suggests intermittent sources may have affected the results. Similarly during winter months, recommended limits were exceeded in all Code 3 dwellings and three Code 4 dwellings, with all 24 h mean values below 0.08 ppm. The results from the occupant diary did not provide possible suggestions for the sources of formaldehyde during the monitoring period.

Results from the occupant interviews suggest problems with indoor air quality perception in both Code 3 and Code 4 dwellings. The perception of freshness of air was a significant issue in both house types, during summer and winter months. However over-all satisfaction scores were good, suggesting occupants did not consider the freshness of air to be particularly important or influential to the overall quality of air. Alternatively, it is possible that the occupants did not consider indoor air quality as a significant issue, therefore were satisfied overall despite concerns with the freshness of air.

Sick Building Syndrome symptoms were reported in all four Code 3 dwellings, compared to only one Code 4 dwelling. BSI_8 for Code 3 dwellings ranged from 1.0 to 2.5 symptoms, suggesting a high prevalence in these homes. The Building Symptom Index (BSI) was taken from the mean values of the recorded Personal Symptom Indexes (PSI), thus Code 3 households recorded an average of at least 1.0 SBS symptom per person. The higher prevalence of Sick Building Syndrome symptoms, higher levels of carbon dioxide and lower overall IAQ satisfaction scores in Code 3 homes present convergence of the results. This suggests that improvements to the Code for Sustainable Homes rating scheme may be required to ensure the provision of adequate ventilation, acceptable indoor air quality and healthy indoor environments. Specifically, the application of trickle vents in newly built UK dwellings with relatively high levels of airtightness requires further attention.

10. Conclusion

This study investigated only a limited number of homes, thus generalisation of the results is not possible. However, the findings suggest inadequate IAQ and thermal comfort in both Code 3 and Code 4 dwellings. For instance, the significantly elevated carbon dioxide levels in both summer and winter months under typical occupancy conditions suggests inadequate ventilation in both the naturally ventilated and mechanically ventilated dwellings. Knowledge of use and maintenance of the mechanical ventilation system was significantly lacking in Code 4 dwellings, which may be particularly problematic in a social housing setting where occupants may not take full control and/or responsibility for the system.

Problems with overheating were highlighted, during both summer and winter months in Code 3 and Code 4 dwellings. This suggests the need for greater attention to overheating in the Code for Sustainable Homes rating scheme, to ensure comfortable interior environments. Furthermore, the re-evaluation of energy efficient design strategies may be required to ensure energy savings achieved through reduction of heating demand during the winter season are not offset by increases in comfort expectations and/or cooling demands during the summer months.

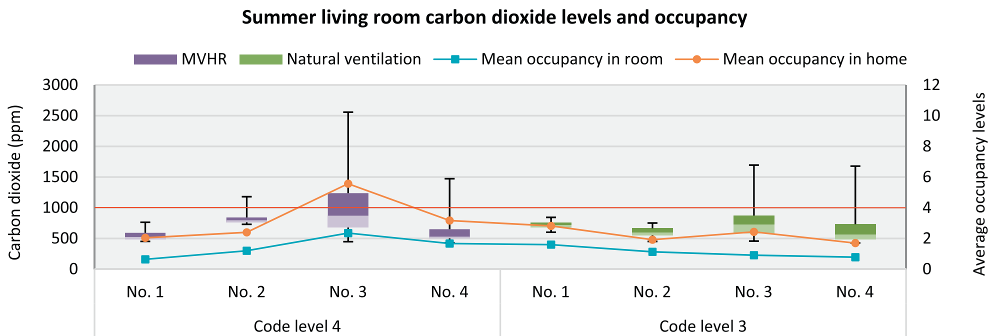
It is suggested that the lower relative humidity levels recorded in Code 4 dwellings during summer and winter may be as a result of the ventilation strategy (use of MVHR). This is beneficial in terms of the potential reduction of the proliferation of mould growth and house dust mites; however levels below 30% may cause sensory irritation. Furthermore, the results of carbon dioxide measurements suggest the ventilation system was not capable of ensuring adequate ventilation. This may be as a result of faults in the system, occupant interference, poor installation and/or lack of maintenance. Further research is required to conduct a comprehensive evaluation of the performance of the ventilation systems in these homes.

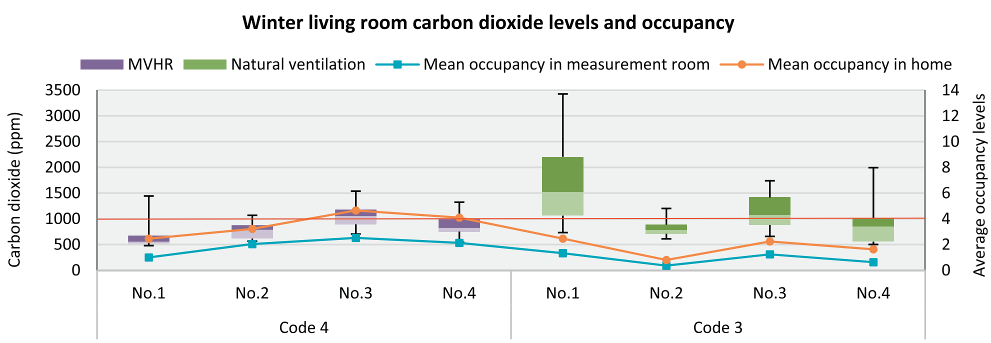
Occupant perception of freshness of air (fresh-stuffy scale) requires further investigation in Code 3 dwellings and is a cause for concern in Code 4 dwellings. Furthermore, the presence of Sick Building Syndrome symptoms in Code 3 dwellings is alarming, and suggests the need for further investigation. In the Code for Sustainable Home's level 3 dwellings, high levels of airtightness can be achieved without the installation of mechanical ventilation systems (such as MVHR) or advanced passive ventilation strategies. The results of this study suggest natural ventilation strategies alone may not be capable of ensuring adequate ventilation in airtight dwellings. Future studies are required to investigate IAQ in low energy social housing on a larger scale, including strategies to ensure IAQ is adequately considered in the design, construction, operation and maintenance of Code 3 and Code 4 homes.

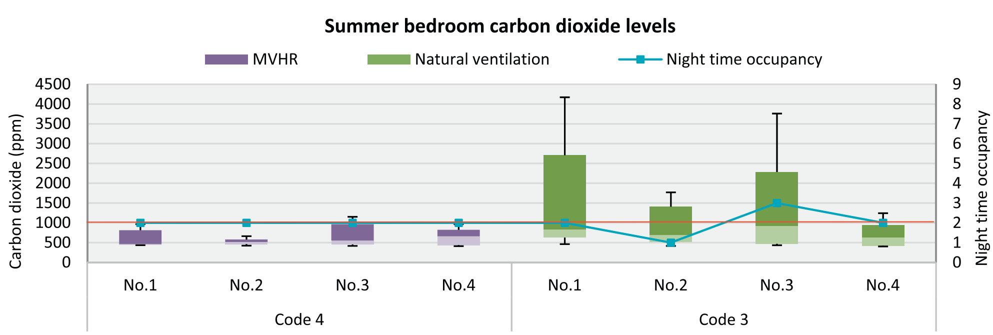
Acknowledgements

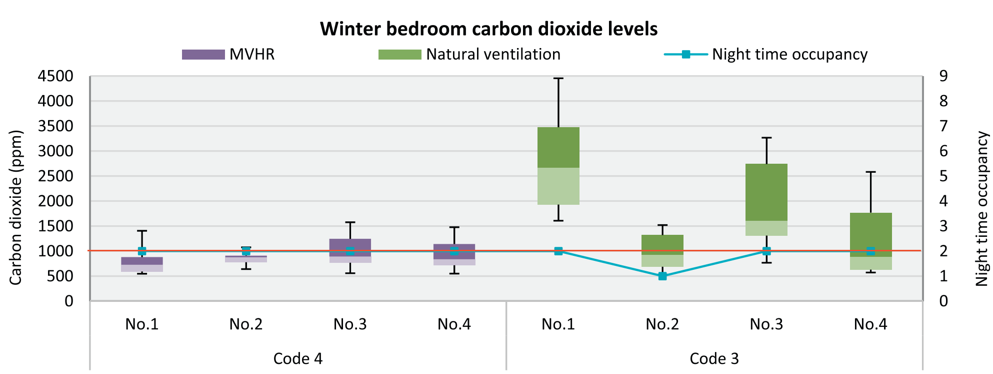
This paper would not have been possible without the assistance of Grove Housing Association and participation of the building occupants, to which the authors are sincerely thankful.

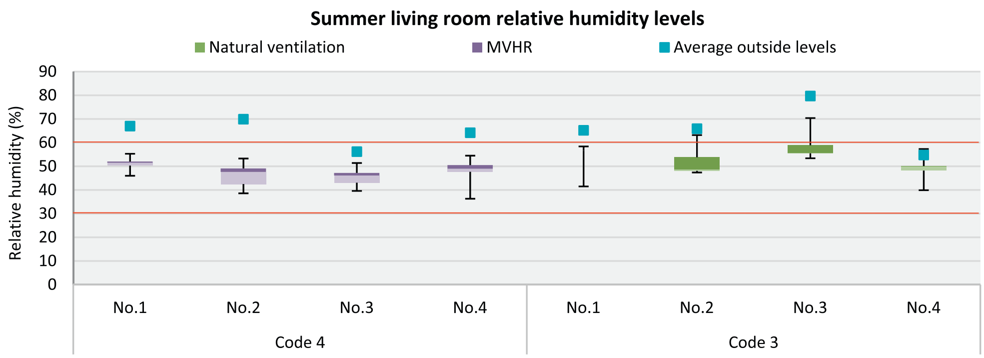
Appendix A. Additional graphs

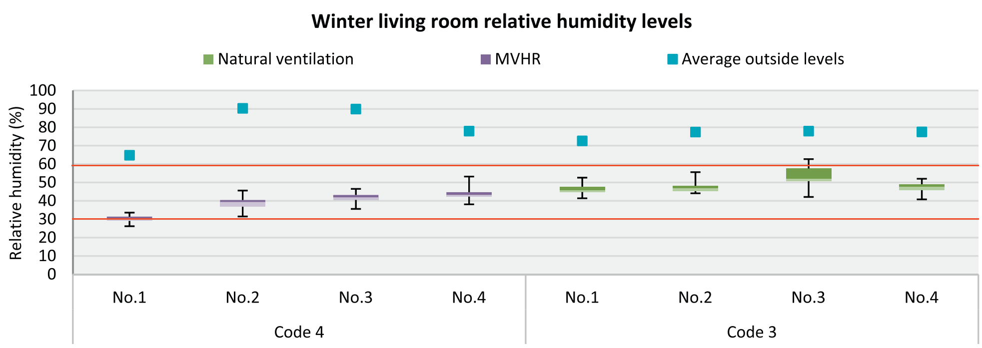


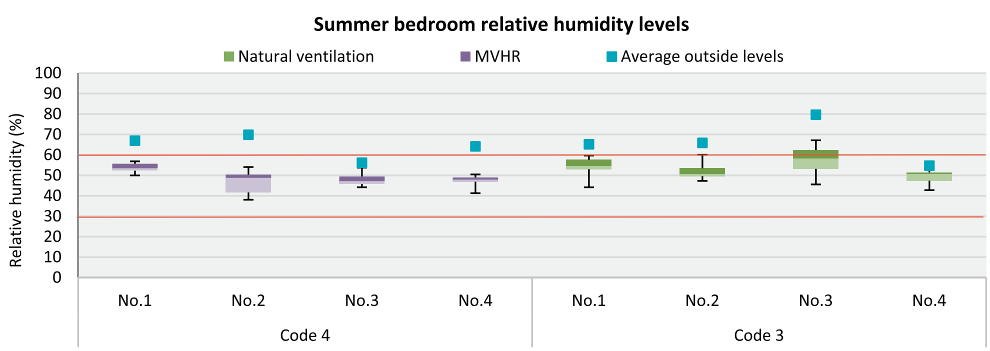


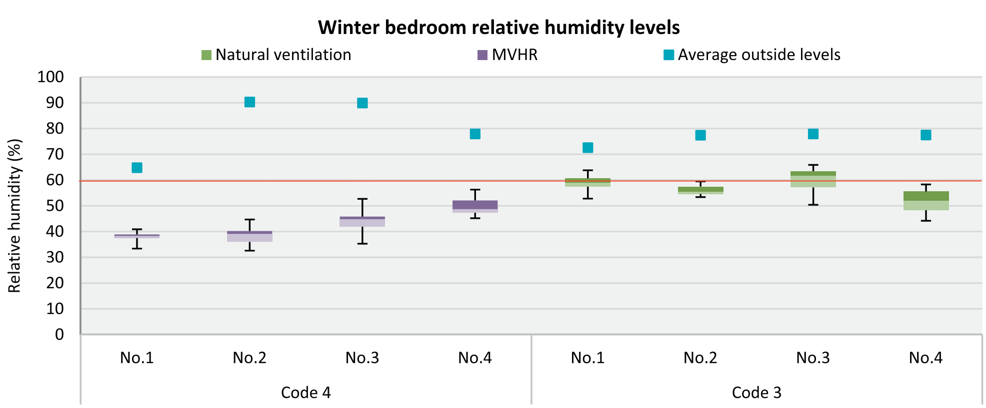


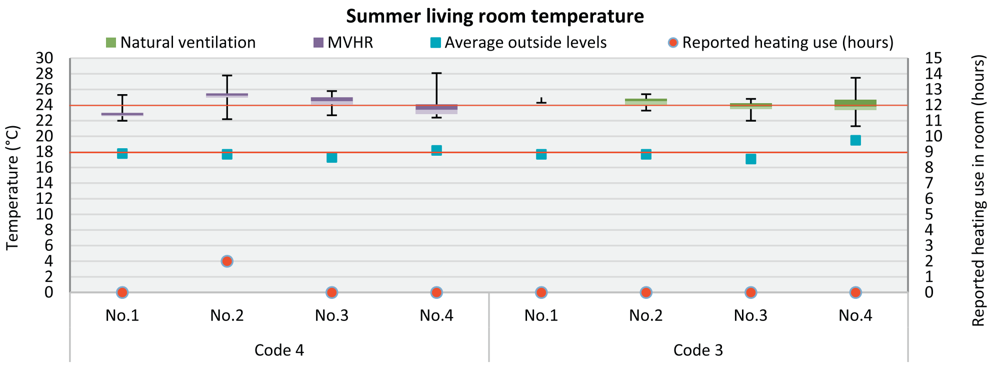


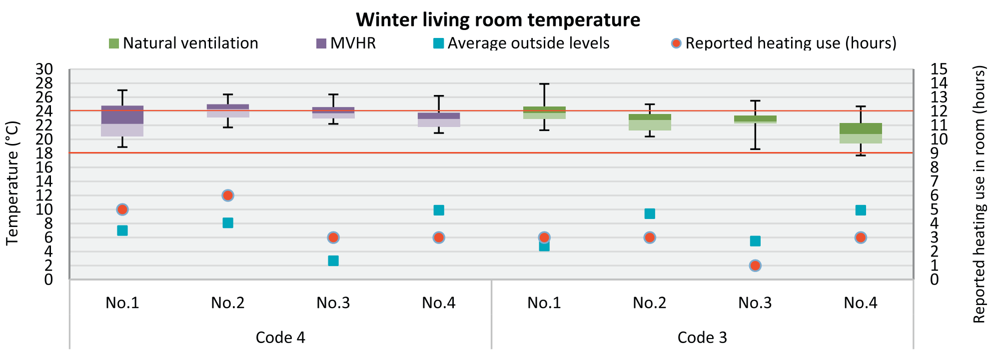

Summer living room relative humidity levels
Natural ventilation
MVHR
Average outside levels
Relative humidity (%)
0
10
20
30
40
50
60
70
80
90
No.1
No.2
No.3
No.4
No.1
No.2
No.3
No.4
Code 4
Code 3

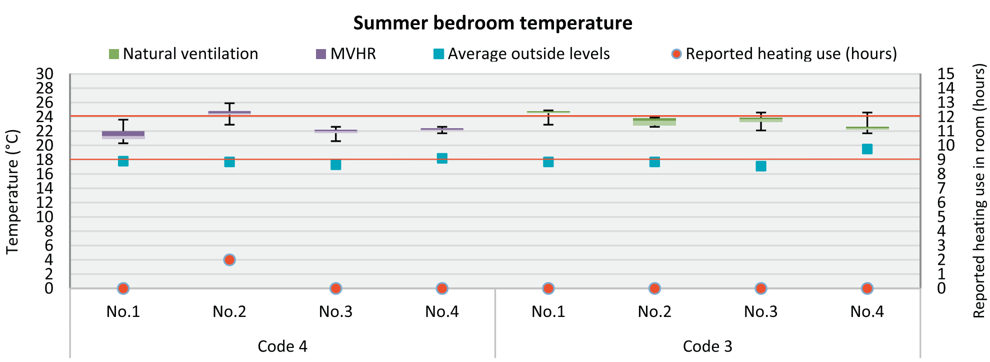

Winter living room relative humidity levels
Natural ventilation
MVHR
Average outside levels
Relative humidity (%)
0
10
20
30
40
50
60
70
80
90
100
No.1
No.2
No.3
No.4
No.1
No.2
No.3
No.4
Code 4
Code 3

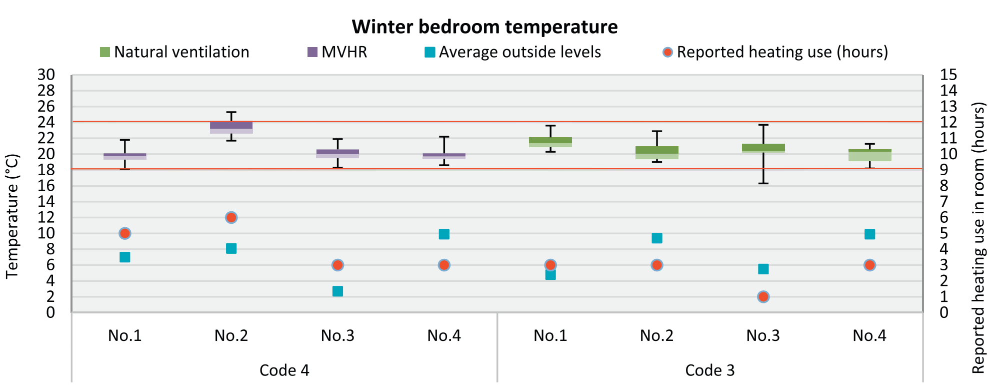

Summer bedroom relative humidity levels
Natural ventilation
MVHR
Average outside levels
Relative humidity (%)
0
10
20
30
40
50
60
70
80
90
100
No.1
No.2
No.3
No.4
No.1
No.2
No.3
No.4
Code 4
Code 3

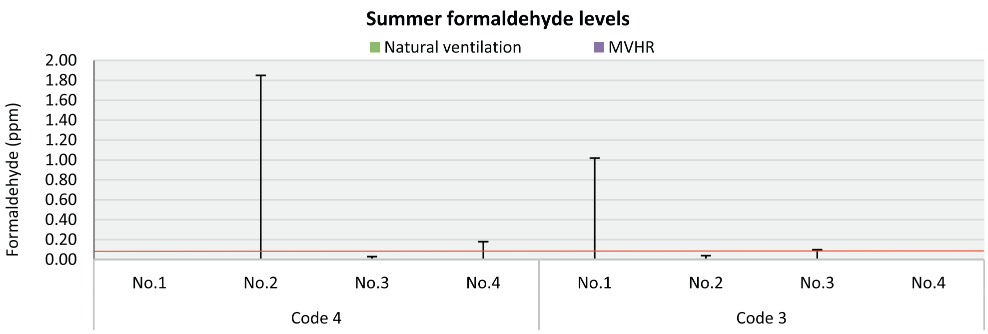

Winter bedroom relative humidity levels
Natural ventilation
MVHR
Average outside levels
Relative humidity (%)
0
10
20
30
40
50
60
70
80
90
100
No.1
No.2
No.3
No.4
No.1
No.2
No.3
No.4
Code 4
Code 3

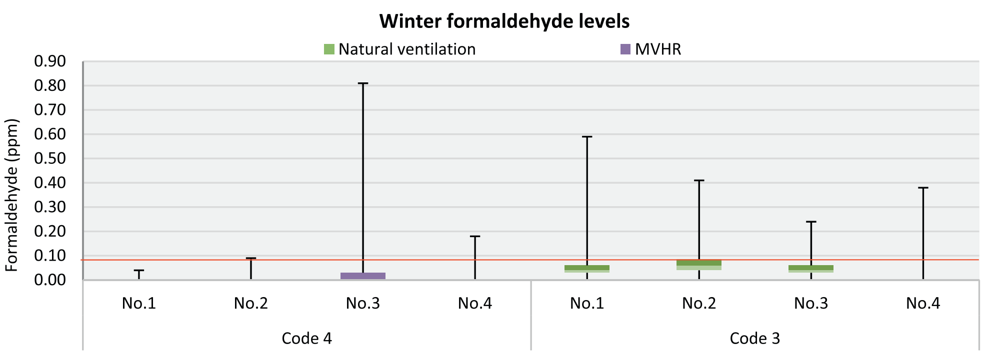

Summer living room temperature
Natural ventilation
MVHR
Average outside levels
Reported heating use (hours)
Temperature (°C)
Reported heating use in room (hours)
No.1
No.2
No.3
No.4
Code 4
Code 3


Winter living room temperature
Natural ventilation
MVHR
Average outside levels
Reported heating use (hours)
Temperature (°C)
Reported heating use in room (hours)
No.1
No.2
No.3
No.4
Code 4
Code 3


Summer bedroom temperature
Natural ventilation
MVHR
Average outside levels
Reported heating use (hours)
Temperature (°C)
Reported heating use in room (hours)
No.1
No.2
No.3
No.4
Code 4
Code 3


Winter bedroom temperature
Natural ventilation
MVHR
Average outside levels
Reported heating use (hours)
Temperature (°C)
Reported heating use in room (hours)
No.1
No.2
No.3
No.4
Code 4
Code 3





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