Impact of occupant behaviour on indoor environment of A-rated dwellings

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ABSTRACT: An increase in energy efficiency and airtightness in the absence of adequate ventilation in A-rated energy efficient houses has brought about an increase in indoor environment quality (IEQ) issues which can lead to health hazards. Relative humidity above 80% for prolonged periods can result in mould growth on any cold unventilated surfaces. Humidity can also affect an occupant's well-being. For example, low levels of humidity can lead to throat irritations, particularly for those who are susceptible to such conditions. Similarly, high carbon dioxide levels can also make occupants feel lethargic and drowsy. Therefore, proper and adequate ventilation is needed to supply fresh air and remove indoor pollutants. Building occupants play an important role in this because it has been observed that their interactions with the ventilation system can lead to poor IEQ conditions within airtight dwellings. In order to improve the knowledge of the IEQ in A-rated dwellings, a two-year study is being carried out on a total of 100 A-rated homes. This paper presents two contrasting examples of modern airtight houses selected from 44 A-rated houses in the current part of the overall study with the same orientation and layout, which experience quite different indoor environments due, ostensibly, to human behaviour. Three IEQ parameters (temperature, relative humidity and CO_2 levels) are monitored in cohorts of dwellings with similar design but with different family profiles to establish the influence of user behaviour on the IEQ. The variability of IEQ over time is explained episodically by human activities during occupancy.

KEY WORDS: IEQ monitoring; Ventilation; Occupancy; User behaviour

1 INTRODUCTION

Energy use in residential and non-residential buildings accounts for 40% of primary energy use and 36% of greenhouse gas emissions in Europe [1]. Ireland was identified as one of the least energy efficient in Northern Europe in the housing sector [2] because traditional houses in Ireland, built prior to the introduction of Irish building regulations in the late 1970s, have been considered draughty and difficult to heat. Due to these issues, energy consumption in domestic buildings constructed prior to 1979 reflected poor thermal performance [3] and carbon dioxide (CO_2) emissions were 92% higher than the average EU home [4, 5]. There were no regulations in terms of energy efficiency of new dwellings in the Republic of Ireland until 1979 [6] and, therefore, the thermal performance of domestic buildings in Ireland started from a low baseline [7]. The evolution of improving thermal performance of domestic buildings in Ireland is evident from the ever-increasing standards dictated in the evolving Part L regulations [8, 9]. With the latest version of Part L, in order to obtain a high energy rating, modern homes are highly insulated with a well-sealed external fabric [10]. One of the desired consequences of these energy efficiency improvements is the delivery of domestic buildings capable of being operated with lower energy usage. However well-constructed the building is, occupant behaviour is still one of the key factors that affects energy usage in buildings [11]. Heating regimes in a house can be affected by personal preferences. Poor operation of ventilation systems by occupants in effectively sealed homes can lead to sub-optimal thermal efficiency [12]. At the same time, subsequent large variations in moisture and Carbon Dioxide (CO_2) in the air can also occur in airtight dwellings. High levels of moisture can have many adverse consequences, including causing condensation on walls, windows, mirrors, swelling of timbers, absorption by paper, etc, but most importantly, in sheltered areas in the house, mould growth can be an aesthetic or, worse, a health problem [13]. Occupant behaviour can largely impact the overall energy efficiency in high performance dwellings, reflecting the way they control the indoor environment, such as opening windows, open/closing vents or changing their thermostat settings [14].

In this paper, results from two contrasting examples, out of 44 A-rated homes, are discussed. These homes were constructed and occupied in 2019 and meet the Irish building regulation Part L (2011, 2017 amended).

1.1 Objective

The objective of the study is to explore examples of how occupant actions can influence the internal environmental quality in a recently constructed A-rated home.

2 METHODOLOGY

2.1 Building type and characteristics

Two A2-rated homes, located in Dublin, have been selected as good examples of differing occupant behaviour. They have identical construction forms and geometry, both with a floor area of $101m^2$. They are both end-terrace houses, with South West orientation, cavity wall with a brick façade and double glazed windows. Indoor temperature, relative humidity (RH) and CO_2 were monitored for all four seasons in five rooms and gathered over 12 months. Surveys were carried out with the residents to investigate their perceived thermal comfort and air quality. Questions were also asked to better understand how they operate the heating, trickle vents and mechanical ventilation system, corroborating the potential causes of the observed indoor environments.

Table 1 gives details of the building and householder characteristics of the case study homes. The homes are 2-storey, natural gas heated with photovoltaic (PV) solar panels. The homes are ventilated by continuous mechanical extract in wet rooms and natural ventilation with trickle vents in the bedrooms and living room. The constant-pressure four port Demand Controlled Ventilation (DCV) system is ducted to room ceiling vents and the extract-only fan installed in the attic produces little or no noise. The ceiling extract units are located in the kitchen, downstairs toilet, main bathroom and ensuite. Windows in both houses are fitted with trickle vents but only in rooms which do not have a ceiling vent. Manually, these trickle vents can be set to the “closed” position (10% open), “open” position (100% open) or “auto” position which is RH activated, yielding a 10% open position below 65% RH, rising to 100% open at 95% RH.

For clarity in this study, the homes are designated A01 and A04. A01 is occupied by a couple with three children and A04 is occupied by a couple.

2.2 Monitoring system

Three indoor environment parameters were measured, temperature, RH and CO_2, using LoraWan-enabled IoT sensors (Figure 2) with an accuracy of ± 0.5 °C, ±2% RH and ±30ppm, a resolution of -0.1 °C, 0.1% RH, 20 ppm, and a range of 8km, with a 2 x 3.6V AA lithium battery. The sensors are connected to a LoraWAN gateway located on site and can provide coverage of up to 40 km line-of-sight or up to 800 metres within buildings. Data is gathered in a cloud-based LoraWAN Network Server and is downloaded to IES iSCAN, a cloud-based data management and analysis platform. Outside conditions were monitored using a full weather station.

Measurements are recorded in five rooms – the living room, kitchen, ensuite bathroom, master bedroom and bedroom 2 for 12 months (April 2019-March 2020). A labelling system was used to designate the sensors, for instance, A01SW3E5E, where A01 represents a house reference number, SW is the orientation, 3 is the number of bedrooms, E is the end terrace, 5 is the number of occupants and E is the zone considered (Ensuite). The last character refers to the physical quantity being gauged. All sensors have been labelled thus to assist in interrogating the data: K (kitchen), L (living room), E (ensuite bathroom), M (master bedroom) and S (bedroom 2) are the zone labels given to the rooms in the figures presented in the result section. All data was stored privately and anonymised in compliance with GDPR. Two face-to-face sessions were held with the residents during occupancy, responses were collected as to their normal actions in controlling the IEQ in these homes.

Plans of the houses, with the five sensor locations, are shown in Figure 1. All the sensors are consistently placed on the ceiling (Figure 2) to reduce location variability and to stop people tampering with it.

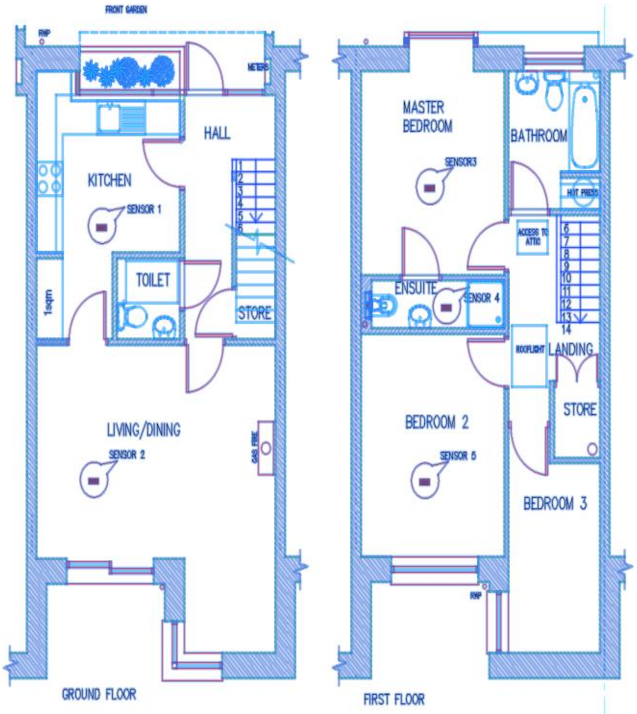

Figure 1. Layout plan and sensor locations

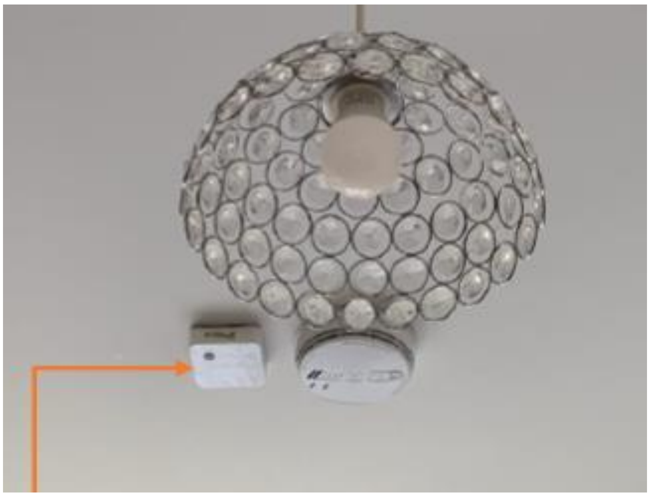

Figure 2. Placement of sensors

3 RESULTS AND DISCUSSION

Indoor air temperature, RH and CO_2 values were measured for 12 months with the average and maximum values during summer and winter for both houses given in Table 2 to Table 5.

3.1 Temperature trends

Average indoor temperatures are different between the two dwellings. This is largely related to different thermostat setpoint schedules, as set by the users, determined by the house occupancy pattern.

In A01, indoor temperatures peaked at 30 °C and it was more than 25 °C for 41% of the time in July (Table 2). An occupant can define the building’s environment, for example,

Table 1. Household characteristics

House Ref.	**Primary heating fuel (space and water)**	**Household description**	**Avg. weekday occupancy**	**Avg. weekend occupancy**
A01	Gas	Couple and 3 children	00:00-23:59	17:00-09:00
A04	Gas	Couple	17:00-08:00	00:00–23:59

by opening windows, which will help in dissipating extra heat in summer. However, as evidenced by the data, the occupants of A01 may prefer not to do that.

Exceedances of recommended indoor temperature were also seen in specific rooms due to their orientation, for example, in the kitchen and master bedroom of A01. Both houses have the same orientation, but differences in temperature range in summers can be observed (Tables 2 and 4) which is likely to be due to the fact that (as CO_2 evidence corroborates) occupants in A04 tend to open their windows and vents, which prevents the house from overheating.

Winter is a time of particular interest given that the occupants are less inclined to open windows and may even tamper with

Table 1. Indoor conditions in House A01-Summer

	TEMPERATURE			RELATIVE HUMIDITY				CARBON DIOXIDE			
Room	Avg. Temp	Max Temp	% > 25ºC	Avge RH	Max RH	>60% RH	> 80% RH	Avg. CO_2	Max CO_2	>1000 <1500	>1500
Living	21.9	26.7	4%	51.4	68%	13%	0%	658	2506	17%	1%
Kitchen	23.0	29.9	41%	49.1	83%	3%	0%	645	3202	17%	1%
Master Bed	22.2	28.2	17%	51.6	77%	9%	0%	772	2574	34%	14%
En-Suite	22.2	26.8	4%	53.6	91%	19%	1%	-	-	-	-
Bedroom 2	22.0	25.8	6%	52.2	66%	13%	0%	852	2931	65%	25%

Table 3. Indoor conditions in House A01-Winter

	TEMPERATURE			RELATIVE HUMIDITY				CARBON DIOXIDE			
Room	Avg. Temp	Min Temp	% < 18ºC	Avge RH	Max RH	>60% RH	> 80% RH	Avge CO_2	Max CO_2	>1000 &<1500	>1500
Living	20.4	15.9	13.8	47.5	68	0.7	0	848	2883	24.7	15
Kitchen	21.8	16.8	6.6	44.8	84	1.8	0.01	772	3547	14.4	8.8
Master - Bedroom	19.2	14.9	42.8	49.4	73	3.3	0	735	2982	16.6	14.1
En-Suite	20.5	15.6	24.5	49.3	91	4.7	0.5	-	-	-	-
Bedroom - 2	19	15.3	37.5	48.8	68	0.6	0	772	3732	14.2	19.4

Table 4. Indoor conditions in House A04-Summer

	TEMPERATURE			RELATIVE HUMIDITY				CARBON DIOXIDE			
Room	Avg. Temp	Max Temp	% > 25ºC	Avge RH	Max RH	>60% RH	> 80% RH	Avge CO_2	Max CO_2	>1000 &<1500	>1500
Living	20.7	24.4	0%	54.33	70	47.73%	0%	561	1216	3.43%	0%
Kitchen	20.32	23.7	0%	56.54	86	43.31%	.07%	504	1231	2.68%	0%
Master - Bedroom	20.63	27.3	1.73%	54.56	85	31.79%	.02%	578	2295	1.34%	0.47%
En-Suite	20.50	26.1	0.43%	58.25	92	64%	1.84%	-	-	-	-
Bedroom - 2	20.54	24.8	0%	56.88	70	41.67%	0%	828	3555	25.14%	16.27%

Table 5. Indoor conditions in House A04-Winter

	TEMPERATURE			RELATIVE HUMIDITY				CARBON DIOXIDE			
Room	Avg. Temp	Min Temp	% < 18ºC	Avge RH	Max RH	>60% RH	> 80% RH	Avge CO_2	Max CO_2	>1000 &<1500	>1500
Living	20.9	16.9	9.6	45.1	58	0	0	616	2177	2.3	0.3
Kitchen	19.7	16.6	19.7	49.4	76	0.4	0	580	1884	1.7	0.06
Master Bedroom	19.2	15.9	37.2	52.6	76	1	0	699	2231	7.5	0.4
En-Suite	20.2	16.1	15.6	51.6	91	8.9	0.5	-	-	-	-
Bedroom - 2	18.8	16.2	38.3	56.6	68	15	0	1259	4588	12	25.8

the ventilation system's automatic operation in order to avoid draughts. To demonstrate this behaviour, a typical day during winter is considered. From the data, the radiators are left permanently on in every room monitored in both the houses. Indoor temperature is well maintained despite the outside average temperature being about 5 ºC for lengthy periods (Figures 3-5). These figures suggest that the natural infrastructure of the house allows temperature to increase at a rate of about 2.0-2.5 ºC per hour when heating starts, but it dissipates slowly at about 0.3 ºC per hour.

The behaviour of the occupants can be deduced as being different in both homes. For example, no heating control is being exercised over some spaces in A01 (Figure 4). The temperature upstairs is set lower, but the heating is never switched off. In A04 (Figure 5), heating is turned on in both the bedrooms upstairs despite occupants not using those rooms (as CO_2 remains static). Further, Figure 6 shows the minimum/maximum temperature range in both the houses for one week. It shows that the second bedroom in A04 is set at a lower temperature as compared to other rooms in the house, although occupants use the same bedroom for sleeping. In A01 (occupied by 5 occupants), all the rooms are equally heated during this winter period.

It has also been observed that bedroom temperatures are set lower in both the houses compared to their living rooms. The CIBSE Guide A recommends operative temperature range of 20-22°C in winter for living rooms. The average living room temperature in both the houses falls in this range but the thermostat setting is kept at 23 °C on most occasions in both houses. This suggests that the designed thermal efficiencies arising in an A-rated home may not be realised and thus both cost and carbon savings may not occur.

3.2 Relative Humidity trends

The RH values are strongly related to human presence and behaviour. Due to the high indoor temperatures and lack of cooking/showering activity in A01 on this particular typical day (14/01), the RH is low (Figure 7), varying between 40-45% RH, spiking to 55% RH in the kitchen when probably preparing an evening meal.

High humidity levels in this winter period are observed in the second bedroom of A04. Diffusion of RH from the ensuite to master bedroom was also observed in A04 (Figure 8) which was probably due to the residents leaving the ensuite door open whilst using the shower and afterwards. Keeping the bathroom door open during showers will raise the RH level of the bedroom as humidity diffuses quickly from the shower area to the bedroom. If sustained, this may lead to higher average RH levels and condensation leading, potentially, to mould growth, though none was observed in the first year of occupation. After a shower or cooking, the humidity levels in the bathroom/kitchen are clearly at a peak and need to be dissipated because the building is especially airtight and occupants cannot perceive this sustained high RH normally, unlike high temperatures. Closing the door during and after using the shower or cooking will allow any excess moisture to disperse through the extractor fan in these areas without significantly affecting the RH of the air in the rest of the house. Evidence for this exists in low RHs in other rooms.

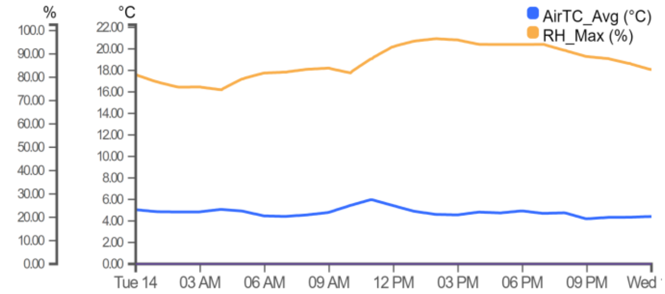

Figure 3. Data from external weather station

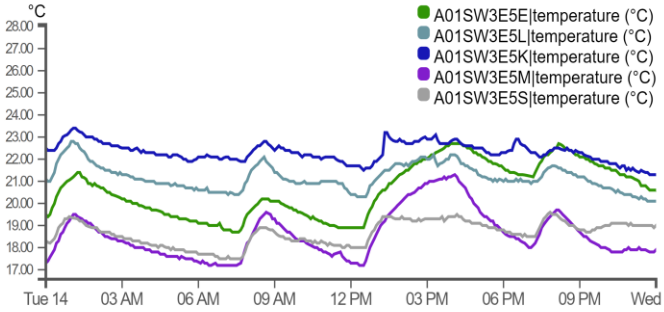

Figure 4. Temperature variations in House A01 on 14/01

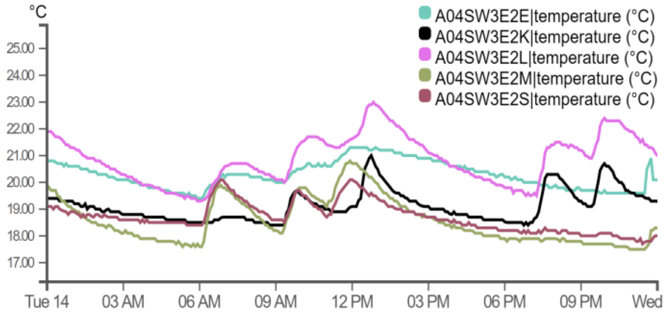

Figure 5. Temperature variations in House A04 on 14/01

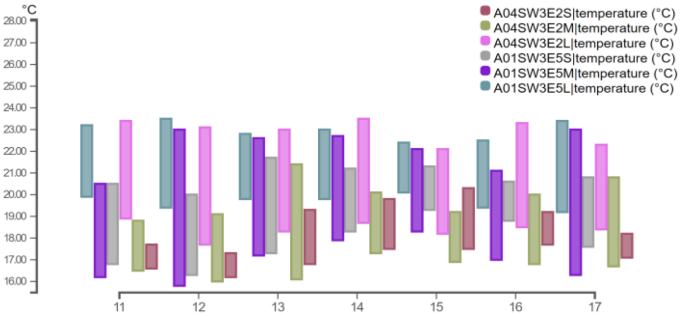

Figure 6. Avg./min/max T comparison for bedrooms and living rooms for a period of 1-week

In the short term this will prevent condensation on windows, walls and ceilings which otherwise could lead to mould problems. Due to the airtightness, the dissipation rates of RH (and CO_2) are much lower in rooms with doors closed where

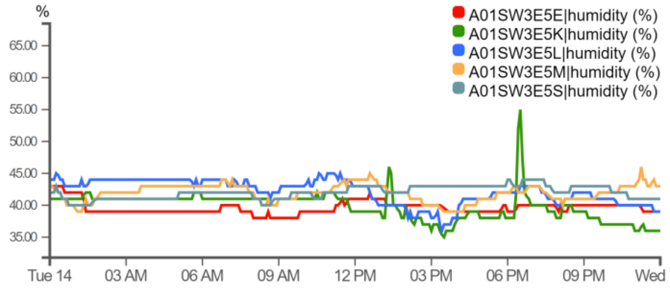

Figure 7. RH variations in House A01 on 14/01

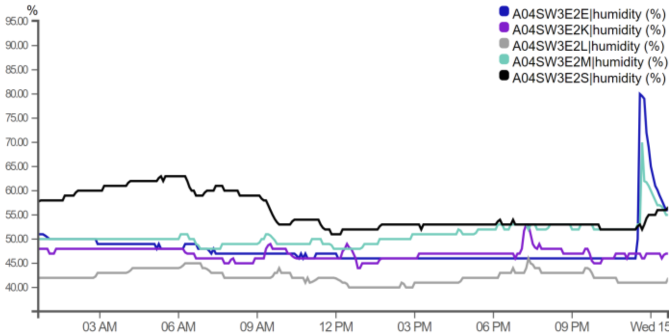

Figure 8. RH variations in House A04 on 14/01

the room is in use, potentially leading to exacerbated IEQ related problems for occupiers.

3.3 Carbon Dioxide trends

The CO_2 levels in A04 indicate that occupants are sleeping in their second bedroom rather than using their master bedroom, but heating is on in all the rooms. High levels of CO_2 during night-time in the second bedroom of A04 suggests that occupants may be closing their trickle vents in the bedroom (Figure 9). In A01, CO_2 levels are high in both the bedrooms, kitchen and living area (Figure 10). CO_2 levels peaked above 1000 ppm in both the houses, reaching levels as high as 3200 ppm in the kitchen of A01 and 3555 ppm in the second bedroom of A04 – where recommended values [16] are of the order of not more than 1000ppm normally or 1500ppm exceptionally. These results suggest issues with occupant-controlled ventilation. High levels of CO_2 can be due to closed trickle vents leading to an absence of ventilation. As was observed on site, this may be precipitated by other issues with trickle vents in practice including improper occupant use (typically by taping up the vent due to cold air ingress during high winds, particularly in winter).

Figure 11 shows a comparison of CO_2 levels in bedrooms of both houses over a one-week period in winter. This figure shows the difference between a well- ventilated and un-ventilated bedroom which can arise in a well-sealed house. The fact that CO_2 is not normally perceptible to people, unlike temperature, means that these excessive CO_2 levels largely go undetected. Therefore, providing advice concerning the need to utilize the designed ventilation system properly by occupants of homes is imperative if a high IEQ is to be achieved in tandem with thermal efficiency.

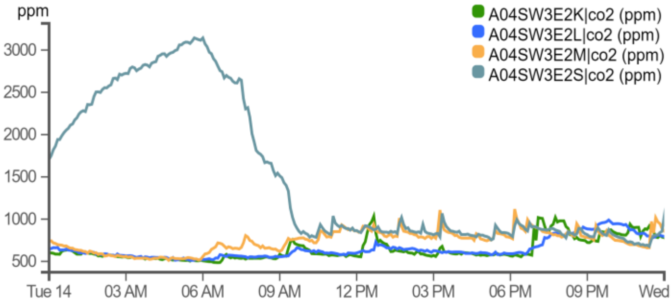

Figure 9. CO_2 levels in House A04 on 14/01

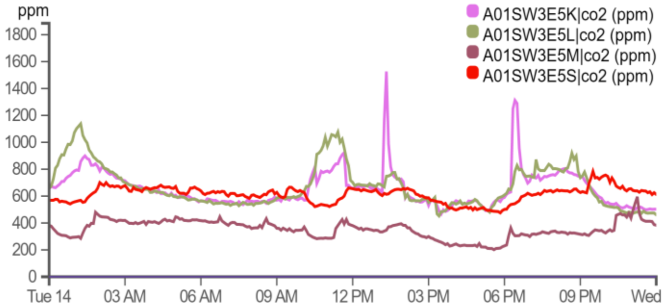

Figure 10. CO_2 levels in House A01 on 14/01

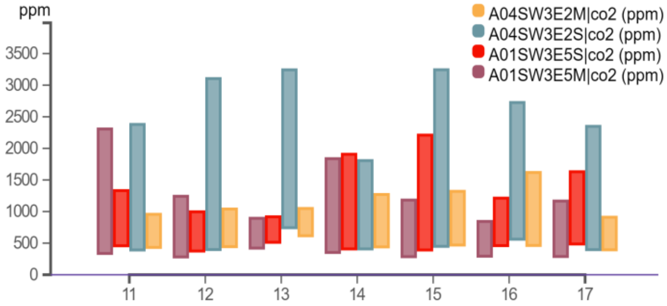

Figure 11. CO_2 comparison in bedrooms of both houses

4 CONCLUSIONS

In this study, two similar houses with different occupancy profiles were studied, considering the interaction between users and their dwellings. The user's habits/behaviour influencing the indoor environment were analysed. Based on the results collected in this small subset of all available data, it can be observed that temperature, humidity and CO_2 levels were not in the range which was anticipated [16] during the design phase of these homes. A problem of occupants' preferences for open/closed trickle vents seems to be a large influence in both houses.

Findings from the study suggest inadequate IEQ and diminished thermal comfort exist in many instances, which was as a result of family behavior related to their perceived comfort levels and existing habits. For example, both the families prefer to close their bedroom doors and trickle vents in winters due to cold breezes entering through the bedroom windows, which can be observed by elevated levels of RH and CO_2 during occupied hours and after showering in their bedroom, hence seriously affecting the IEQ environment. A04 has closed trickle vents only in its bedroom while the family tends to ventilate the rest of the rooms in the house. In A01, elevated CO_2 levels are found in most of the areas, suggesting that the occupants keep their ventilation inlets off. Findings from the study suggest how minor actions by a user (for example, keeping their bathroom doors open during and after showering, causing high RH levels) can have a significant impact on the IEQ environment of the house, not all of which are immediately perceptible to the occupants.

A demand controlled ventilation system is designed to provide suitable indoor air quality, if used correctly. However, if the ventilation system results in cold air draughts in winter, as evidenced in this study, occupants will experience discomfort and, as is known from CIBSE Guide A [16], they will take action to solve that problem with potential deleterious effects on the IEQ. It is, therefore, vital to provide occupants with suitable guidance when they move into retrofitted or new A-rated homes.

ACKNOWLEDGMENTS

This paper would not have been possible without the participation of the residents, for which the authors are sincerely grateful.

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