Chapter 6

# The Role of Building Users in Achieving Sustainable Energy Futures

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Additional information is available at the end of the chapter

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## 1. Introduction

In the drive to provide a sustainable energy strategy the reduction of energy use by buildings is a crucial component as they provide the majority of energy use and carbon emissions. In an attempt to mitigate the damaging effects of greenhouse gas emissions, international governance has legislated for the reduction of energy use and CO2 emissions. In Scotland (the setting for this research) the Government has identified target reductions in domestic regulated energy use of 30% by 2010 and 60% by 2013 (compared to 2007 technical standards) and the ambition of whole life zero carbon by 2030 [1]. A low carbon economy is now a strategic priority for the Scottish Government. As domestic energy use represents 30% of total national energy use [2] there can be little doubt over the role this sector has to play in helping to achieve the targeted reductions. Whilst for new buildings this may be addressed through building standards, a more pressing problem is that an estimated 70% of the stock currently in existence will still be standing and in use by 2050, and much of this stock has a very poor performance [3]. Therefore the role that existing dwellings will have to play in helping to meet these ambitious targets cannot be underestimated.

The primary mechanism to affect change has been improved building regulations, for which compliance is achieved at design stages. Although standards have improved significantly in recent years, it is becoming increasingly apparent that these are not being translated into energy savings in practice [4]). In situations where thermal improvements are made there is emerging evidence that the drive for energy reduction is resulting in other unintended negative consequences, for example poor indoor air quality which as well as being problematic in its own right, also leads to rebound behaviours which undermine energy strategies [5].

Problems of energy consumption and carbon emissions apply to both new and existing buildings. Existing buildings are in many ways a more significant problem, in that they tend to have very much worse energy performance; make up a much larger proportion of the stock; can have physical, economic and cultural barriers to major improvements; and are not subject to the same regulatory requirements as new building as current building standards are not applied retrospectively.

The use of Building Performance Evaluation (BPE) is a crucial tool in assessing the tangible performance of buildings, and identifying the positive and negative factors that lead to actual consumption. The Mackintosh Environmental Architecture Research Unit (MEARU) has been at the forefront of developing and promoting forms of BPE [6] and has undertaken a range of evaluations in both new build and existing buildings. BPE includes both qualitative and quantitative methods to gather data on energy use, environmental performance and occupant behaviour and attitudes. From this is it possible to identify actual energy consumption, patterns of occupancy and behaviour, and the environmental conditions that are being achieved and from these determine process changes in design, management, procurement, construction and use that can improve building performance. The use of BPE is crucial to sustainable urban futures is as it identifies the gaps that occur between design, construction and occupancy. Wider use of BPE in the future may place more of an onus on designers to consider actual performance, as opposed to designing for regulatory compliance. It is a technique that can be applied to both new build and existing buildings.

Of these, the issues of occupancy are attracting the most interest. The potential impacts of occupant behaviour on energy consumption are significant, with some studies identifying variation in consumption by a factor of 4 and 5 times between identical dwellings [7]. Of equal importance however is the question of the impacts *on* occupants of low energy design in respect of environmental performance, especially indoor air quality, and what the implications are for energy consumption and health.

This chapter will describe and compare two case study projects that have used BPE to investigate performance in use, as a comparison of two very different building types. The first of these is the refurbishment of a 19th century Grade A listed tenement building in Edinburgh; the second is the 'Glasgow House' a prototype low energy housing development for Glasgow Housing Association.

The former is an existing 19$^{th}$ century stone built tenement in Edinburgh's Grassmarket that was refurbished to a high standard, including improved fabric performance through internal insulation and secondary double glazing, sun spaces, a ground source heat pump supplying underfloor heating, and a mechanical heat recovery ventilation system (MVHR) system.

The 'Glasgow House' is a new build project developed by Glasgow Housing Association (GHA), one of Europe’s biggest landlords, as a prototype for future housing developments in the city. The design proposed a thermally heavy clay block system, with high thermal performance, glazed sun spaces, MVHR, solar thermal hot water heating; high efficiency gas boiler and low energy lighting equipment. Due to uncertainties about this type of construction, two test houses were constructed by GHA’s partner organisation, City Building one of which uses a more standard form highly insulated timber frame.

Although very different house types, built over 120 years apart, both are attempting to meet contemporary standards in terms of energy use. In the evaluation several common factors relating to ventilation and indoor air quality (IAQ) were apparent in the performance of both projects and the question that this chapter addresses is how these factors affect building occupants, their subsequent behaviour, and how this in turn affects energy consumption.

## 2. Indoor air quality

IAQ is an important, but neglected aspect of sustainable design, which more commonly emphasises energy use and carbon reduction. However, achieving good IAQ is important for a number of reasons. Firstly it is crucial for health and well-being of occupants. Secondly, it is increasingly evident that poor IAQ can lead to detrimental energy performance, for example, users opening window to control temperature, humidity, stuffiness and smells, even when mechanical systems are intended to address these issues. Thus the tension that exists between low energy design, which attempts to minimise ventilation loss, and good IAQ, which seeks to maximise ventilation, needs to be addressed.

The majority of the world's population spends 90% of their lives indoors [8], [9]. Its quality is of recognized concern [10] and can be affected by many factors, most noticeably air temperature (Ta), as well as surface temperature (Ts), humidity and pollution levels. IAQ affects how inhabitants perceive a space, to the same extent as the availability of space and light do. Through sound and well tested ventilation design a healthy living environment can be achieved.

Globally, indoor pollution has been related to respiratory illnesses [11]; has resulted in an increase in childhood asthma [12] and poor levels of IAQ have been linked with mechanical ventliation and sick building syndrome [13]. Factors that contribute to IAQ can be considered in various ways and calculated using different indicators. Allard defines optimum IAQ as,

"...air which is free from pollutants that cause irritation, discomfort or ill health in the occupants." [14].

Scottish Building Standards (SBS) states that indoor air quality should not endanger the health of the inhabitants [15]. It suggests a temperature range of 18 - 21°C, relative humidity (RH) of below 70% as well as specifying trickle vent sizes to maintain air quality. Although clearer than the previous definition, the standards expediency is debatable, producing only the minimum levels of IAQ needed, whilst focusing on maximising energy efficiency [16]. Temperature and RH ranges are not room specific, and with indoor pollution varying over time, the advised levels of ventilation should be adaptable [17].

$CO_2$ is an appropriate indicator to measure when assessing IAQ and was used in these studies as its importance as an environmental indicator is invaluable. The concentration of $CO_2$ is very rarely found at hazardous levels indoors, but levels of $CO_2$ represent the presence of other contaminants in the air, such as bio-effluents, which relate directly to health issues [18]. Increased levels of $CO_2$ are indicative of occupancy and inadequate ventilation [19]. Pettenkofer first tested air for the presence of $CO_2$ [20]; consequently Pettenkofer's Max, of 1000ppm, was established and the current consensus of opinion is that levels above 1000ppm are linked to poor occupant health [21]. Where concentrations greater than 1000ppm are experienced the rate of air change is insufficient and the potential for culmination of internal pollutants is increased with an associated impact on occupant health. Examples within domestic contexts include volatile organic compounds (VOC), which act as allergens and respiratory and dermal irritants [22].With low air change rates there is also a well-defined risk of interior moisture vapour build up which brings with it its own set of health implications. Vapour pressures over 1.13kPa have been identified as promoting the growth of dust mite populations [23] which have, in turn, have been found to have a causal relationship with development of asthma in susceptible children [24]. With high vapour pressures there is also an associated risk of fugal growth and an increase in the levels of fungal spores, microbial bodies and other pathogens which can be detrimental to the health, particularly to the ever increasing atopic portion of the population. In addition to this, increased relative humidity has also been found to increase health impact from non-biological aerosols as it increases the rate of off gassing of water-soluble chemicals such as formaldehyde [25].

In both these case studies a key component to address the issue of ventilation and energy use was the inclusion of Mechanical Ventilation Heat Recovery Systems (MVHR). The principle of these systems is that poor quality, but relatively high temperature internal air is mechanically extract from spaces in the dwelling, typically spaces which contain ‘problem’ air such as high moisture content or smells from kitchen and bathrooms. This air is passed through a heat exchanger during which colder fresh air from the outside is warmed by the recovered heat before being delivered to the dwelling. In theory should satisfy the needs of both energy conservation and IAQ to produce a sustainable solution. Accordingly the discussion below makes particular reference to the performance of these systems.

## 3. BPE methodology

The methodology in both case studies was broadly similar. Quantitative data on temperature, humidity and $CO_2$ levels was collected using Eltek GD-47 Transmitters linked to Eltek RX250AL1000 Series Squirrel Data Loggers. This was supplemented by Gemini TinytagPlus Data Loggers for temperature and humidity some rooms without a power supply (bathrooms and toilets).

The Glasgow House was unusual in that as demonstration houses they did not have occupants. MEARU in conjunction with GHA developed a methodology for scenario testing whereby volunteers occupied the houses for two-week periods during which they were asked to follow set occupancy ‘scripts’ for behaviour. Heating and environmental controls were fixed in the script and users were asked not to change these. Thus occupancy and behaviour could be tightly controlled, allowing an examination of the environmental performance under known conditions

In the Glasgow House, additional qualitative information was gathered using occupant diaries, record sheets for key activities such as fan operation and boost switch use, cooking, and window opening. The inhabitants of the house were each given diaries to record their day-

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to-day activities. This included the documentation of house occupancy periods, personal sanitary routines, and the use of individual electrical equipment. Cooking periods and kettle use were recorded separately, as well as instances when the boost switch was used on the extract for the MVHR system, usually in association with showering or food preparation. Room occupancy levels and window opening was also documented. Participation in post occupancy evaluation (POE) questionnaires allowed for the occupants qualitative and functional responses towards the houses to be gathered.

In Gilmores Close, due to the more vulnerable nature of the occupants (a high proportion of which have special needs), a semi-structured interview was conducted with residents and office users to query patterns of occupancy, user behaviour and comfort. This was supplemented by surveyors observations, photographs and thermographic imaging

## 4. Case study 1: The Glasgow house

### 4.1. Construction

The two semi detached houses were built in 2010 by City Building (CB) in partnership with the GHA. They were designed to provide comfortable and flexible living for low income families with an aim of costing no more than £100 per year to heat. The houses are of similar layout and consist of a porch, kitchen/dining/living area, a utility room/WC, four bedrooms, a bathroom and garden.

The design incorporated high levels of thermal efficiency using a Thermoplan clay block with external insulation, highly insulated roof cassettes and high performance windows, thermal mass, airtight construction (0.4 ach), sunspaces, solar thermal hot water collectors, mechanical ventilation heat recovery, low energy lighting and high efficiency appliances (House A). The comparison house is identical house except the clay block is replaced with a more conventional highly insulated timber frame system which is the standard form of construction used by City Building.

A series of scenarios were proposed to examine how these houses performed in use with actual occupants. Findings from two separate periods of BPE, in February and December 2011 are described here. In both cases four occupants inhabited each dwelling. They were to simulate an average family living pattern and were given prescribed scripts on occupancy.

Heating is by a high efficiency gas boiler and radiators. Hot water heating is supplemented by the use of a solar hot water system. Ventilation is by a MVHR system, extracting air from the kitchen and bathrooms spaces and supplying a balanced flow of air to the living room and bedrooms. The temperature of the house was pre-set using the main thermostat and by the individual thermostats on the radiators in each room. The MVHR system was inspected visually and the filters changed if necessary. Electricity and gas meter readings were made at the start and end of the monitoring process in each dwelling to record energy consumption.

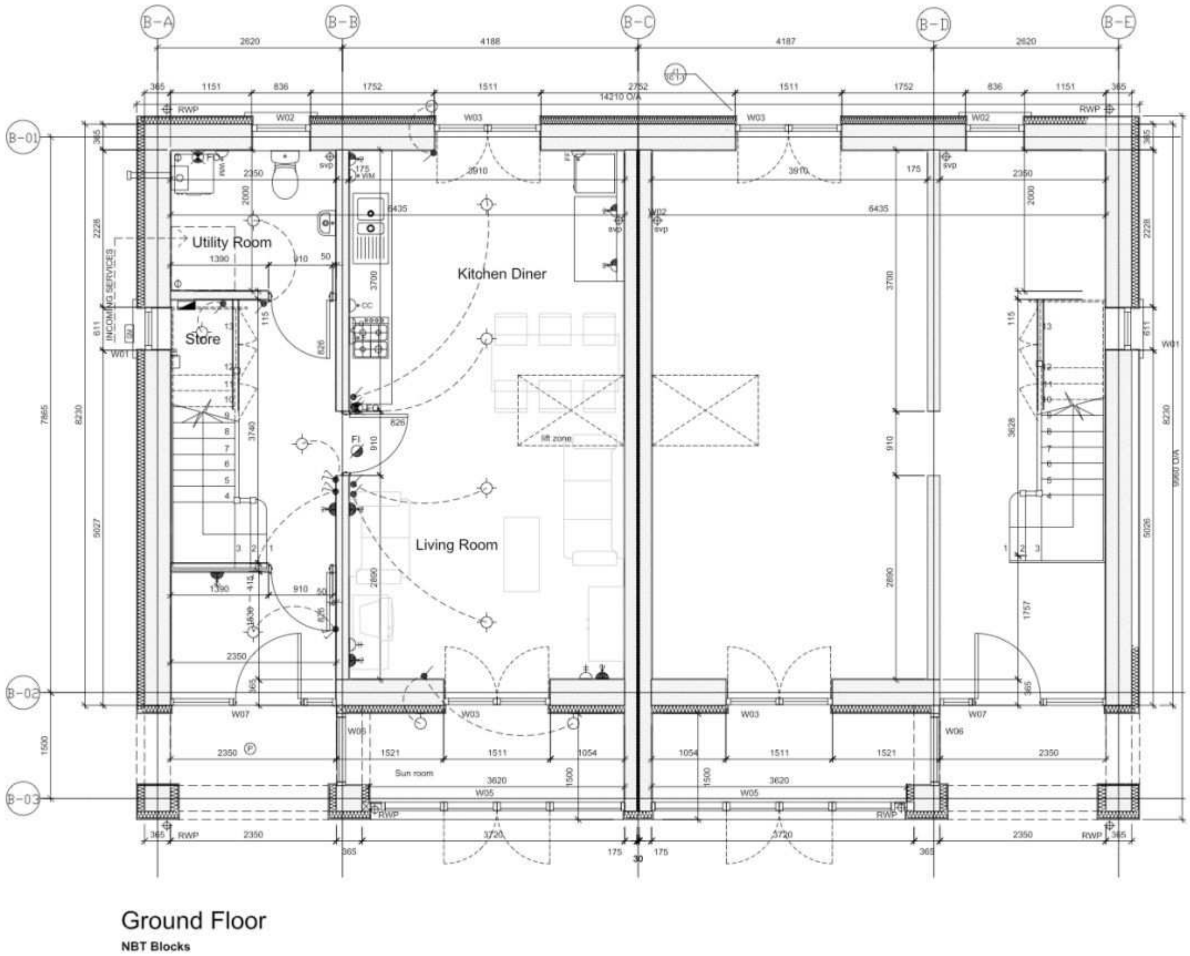


**Figure 1.** The Glasgow House, Ground Floor Plan

### 4.2. Data review

When assessing IAQ in relation to the specified Ta, RH and $CO_2$ criteria, the maximum and minimum values recorded are of most significance as well as the subsequent range produced. A graphical output, visually representing the continuous change in these values over time is appropriate for analysis and discussion. Mean values calculated from these indicators can sometimes be of use to give an overall representation of the data. However, this statistic can overlook significant individual moments, diluting the importance of some data, and thus failing to give an accurate depiction of performance. Mean values may be more appropriate for other IAQ indicators, such as VOCs and plasticisers, which have constant background levels. The data collected was subject to certain variables and limitations.

#### *4.2.1. Occupancy*

The first study period in February (SP1) ran from 15/02/11 at 00:00 until 27/02/11 at 23:55. In December study period two (SP2), ran from 06/12/11 at 00:00 to 15/12/11 at 23:55. Ideally both study periods would be for the same duration, however, it was determined that the se-

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lected periods (SP1 and SP2) from each study were sufficient to provide adequate data for analysis and comparison.

The February study monitored a period of non-occupancy prior to SP1 commencing. This data provides a valuable 'control' period (CP) which can be utilised to understand how the house performed in relation to IAQ when uninhabited. Although the studies were run during different months, they were both in the winter period of the same year. Average external temperatures during this period were 5.5 $^0$C in SP1 and 3.3 $^0$C in SP2. The studies can be compared reasonably accurately in relation to this slight inconsistency.

During study periods occupancy levels in the houses remained constant. The houses' flexible layout resulted in sleeping arrangements varying depending on how the show home had been set up. (Table 1).

| | House A | | House B | |
|---|---|---|---|---|
| | **Type** | **Occupancy** | **Type** | **Occupancy** |
| Bedroom 1 | Double | 1 | Double | 1 |
| Bedroom 2 | Double | 1 | Double | 1 |
| Bedroom 3 | - | 0 | Single | 1 |
| Bedroom 4 | Twin | 2 | Double | 1 |

**Table 1.** Occupant Sleeping Arrangements, SP 1 & 2, House A

When assessing the results it should be noted that in House A, Bedroom 3 was set up as a study/office and was not used for sleeping. As a consequence, the occupancy of House A, Bedroom 4 was double that of House B. Data collected from House A, Bedroom 3 is still relevant, although the results will not warrant accurate comparison with House B, Bedroom 3. The data can be viewed to see how the room performs when uninhabited, similar to the control period mentioned previously. House A, Bedroom 3 can be compared between the two study periods, however. It is worth mentioning that each occupant will not have spent the same amount of time in their bedroom and sleeping patterns will have varied. Similarly, room occupancy level throughout the house may have varied from time to time, depending on occupant activities and interaction. High occupancy room levels ≥ 3 inhabitants.

When evaluating the data it is essential to consider each bedrooms qualities, in order to make fair comparisons. (Table 2).

The room on the 2nd floor, in the attic space, is the largest of the bedrooms. Bedroom 3 is the smallest. Bedroom sizes vary slightly between the two houses. This is due to the construction types, which alter the wall build up, affecting internal space a little. The houses have identical plan configurations.

| | | House A | | House B | |
|---|---|---|---|---|---|
| | Location | Floor Area ($m^2$) | Volume ($m^3$) | Floor Area ($m^2$) | Volume ($m^3$) |
| Bedroom 1 | 1st Floor | 11.89 | 28.41 | 12.02 | 28.74 |
| Bedroom 2 | 1st Floor | 11.89 | 28.41 | 12.02 | 28.74 |
| Bedroom 3 | 1st Floor | 7.33 | 17.52 | 7.28 | 17.41 |
| Bedroom 4 | 2nd Floor | 18.69 | 39.43 | 18.69 | 39.43 |

**Table 2.** Bedroom Information

The MVHR system was serviced and its installation altered between SP1 and SP2.The studies had prescribed occupancy patterns to achieve specific goals and were scripted to accurately represent the airtight dwellings' IAQ performance using the MVHR system. The occupants were asked to refrain from naturally ventilating the dwellings, by opening windows and doors, and not to alter temperature thermostats. However, during SP1 windows were opened by the occupants in both House A and House B. (Table 3).

| SP1 - House A | No. of Openings | Total Duration of Openings (min) |
|---|---|---|
| Bedroom 1 | 4 | 225 (3hr 45min) |
| Bedroom 2 | 7 | 1779 (29hr 39min) |
| Bedroom 3 | 0 | 0 |
| Bedroom 4 | 2 | 578 (9hr 38min) |
| Total | 13 | 2582 (43hr 2min) |
| **SP1 - House B** | **No. of Openings** | **Total Duration of Openings (min)** |
| Bedroom 1 | 1 | 33 |
| Bedroom 2 | 2 | 215 (3hr 35min) |
| Bedroom 3 | 0 | 0 |
| Bedroom 4 | 0 | 0 |
| Total | 3 | 248 (4hr 8min) |

**Table 3.** Frequency of Window Opening, SP1, House A and B

The consequence of this natural ventilation will have more of an impact on the data collected in House A, simply due to the greater over all duration in which the windows were open, than in House B; 43 hours compared with 4 hours, respectively. Conclusions drawn from the particular data in both houses should acknowledge these variances in terms of their effect on Ta, RH and CO2 levels within the specified rooms.

During SP2 window opening was more tightly controlled and no natural ventilation was recorded, however, an occupant in House B increased the radiator thermostats in the kitchen, living room, utility and attic bedroom from one to four, over a period of 18.75 hours on 06/12/11. This change may have affected the data collected for House B, in particular in Bedroom 4. Any conclusions drawn from the particular data should take into account this variance.

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Whilst this project is focused primarily on investigating $CO_2$ levels, it is worth including the analysis of the other monitored indicators, Ta and RH. Observing several IAQ components provides a greater understanding of how the MVHR system is functioning. Over the study periods all three of the indicators contributed to unhealthy IAQ within the bedrooms. $CO_2$ levels were of significant concern.

### *4.2.2. Air temperature data*

The graphical output produced, as well as the statistics calculated, shows that Bedroom Ta fell out with the preferred parameters, defined as 18-20$^0$C, during both studies. The houses failed to sustain a constant bedroom Ta, within the optimum 2$^0$C range. The temperature related IAQ was unsuitable for sleeping on occasions. (Table 4) Within the data, an apparent difference is visible between the SP1 and SP2 results. Although ranges are similar, SP2 bedroom Ta was lower than the previous study, resulting in a reduced overall Ta. House A and B appear to function very similarly to one another in the studies.

| Bedrooms | Max (°C) | Min (°C) | Range | Mean (°C) |
|---|---|---|---|---|
| SP1 – House A | 23.30 | 16.60 | 6.70 | 20.01 |
| SP1 – House B | 22.40 | 16.70 | 5.70 | 19.82 |
| SP2 – House A | 20.40 | 14.50 | 5.90 | 16.95 |
| SP2 – House B | 19.30 | 13.50 | 5.80 | 16.25 |

**Table 4.** Overall Bedroom Ta Statistics

### *4.2.3. Relative humidity*

Similarly, RH failed to maintain the standard defined as 40-70%. With corresponding to Ta values, maximum RH values are within the prescribed range, but the minimum values recorded fall below. This resulted in the occupants experiencing reduced IAQ during these intervals. (Table 5)

| Bedrooms | Max (%) | Min (%) | Range | Mean (%) |
|---|---|---|---|---|
| SP1 – House A | 59.30 | 31.10 | 28.20 | 43.37 |
| SP1 – House B | 67.50 | 32.50 | 35.00 | 43.25 |
| SP2 – House A | 56.40 | 35.30 | 21.10 | 43.96 |
| SP2 – House B | 61.20 | 36.90 | 24.30 | 45.40 |

**Table 5.** Overall Bedroom RH Statistics

There appears to be little difference in RH between SP1 and SP2. Also, House A's performance does not differ from that of House B.

#### *4.2.4. Carbon dioxide data*

Both study periods reveal comparable trends in $CO_2$ levels, highlighting a strong diurnal range. It is also clear that there is an identifiable difference between the general $CO_2$levels in SP1 compared with SP2. Comparing identical bedrooms in House A and House B is also of interest.

| Bedrooms | Max (ppm) | Min (ppm) | Range | Mean (ppm) |
|---|---|---|---|---|
| SP1 – House A | 2007.00 | 478.00 | 1529.00 | 872.50 |
| SP1 – House B | 2006.00 | 445.00 | 1561.00 | 921.06 |
| SP2 – House A | 1300.00 | 367.00 | 933.00 | 605.26 |
| SP2 – House B | 1478.00 | 375.00 | 1103.00 | 633.82 |

**Table 6.** Overall Bedroom CO2 Statistics

In SP1 $CO_2$concentration reaches levels double the maximum recommended value highlighting unhealthy IAQ. SP2 produced healthier results; however maximum values in each house still rose above Pettenkofer's Max. (Table 6) In general, bedrooms in House A and House B appear to function similarly in relation to $CO_2$.

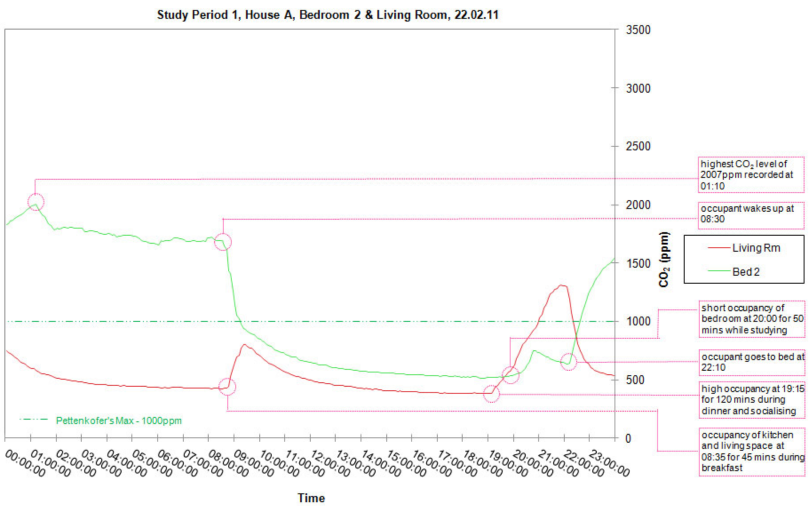


**Figure 2.** Comparison $CO_2$Levels, SP1, House A, Bedroom 2 & Living Room

The diurnal range is clearly visible on the graphical information produced for the study periods. (Figure 2) This day to night change can be attributed to the bedrooms occupancy pattern, prescribed by their function. A graph showing a 24 hour period within a bedroom allows the rise in $CO_2$levels to be identified as occurring during the night, and can be associated with periods of sleep, and therefore occupancy. When $CO_2$ levels are lower the room is most likely to be empty because respiration is not taking place. Occupancy patters within the living room, also identifiable through $CO_2$ levels, are quite different to that of the bedroom.

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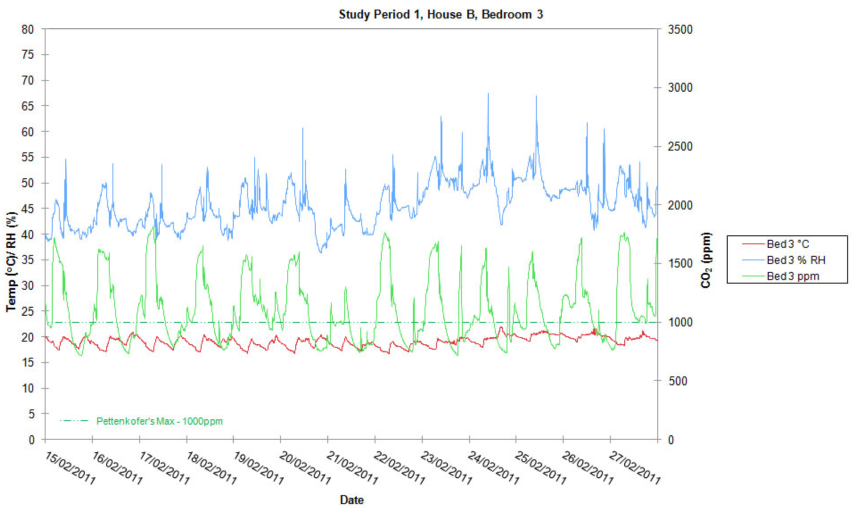


**Figure 3.** Unhealthy Bedroom Performance, SP1, House B, Bedroom 3

The most unacceptable levels of $CO_2$ found by the studies were recorded during SP1 in House B, Bedroom 3. (Figure 3) There was one occupant sleeping in this room. Levels of $CO_2$reached over 1000ppm for approximately 13 hours of each day, more than half of the total study period. The maximum level recorded was 1819 and the minimum being 713ppm (Table 7). The range of 1106 is evidence of the occupancy pattern, however, the diurnal range is less defined in this instance and may show that the room was also occupied at times during the day. When the room was in use $CO_2$levels in the air indicated a potentially harmful IAQ. When discussing IAQ, Ta and RH data recorded for this example support poor conditions, with max. and min. of 21.9°C and 16.7°C, 67.5% and 36.4% respectively. There is strong instability evident within all three indicators.

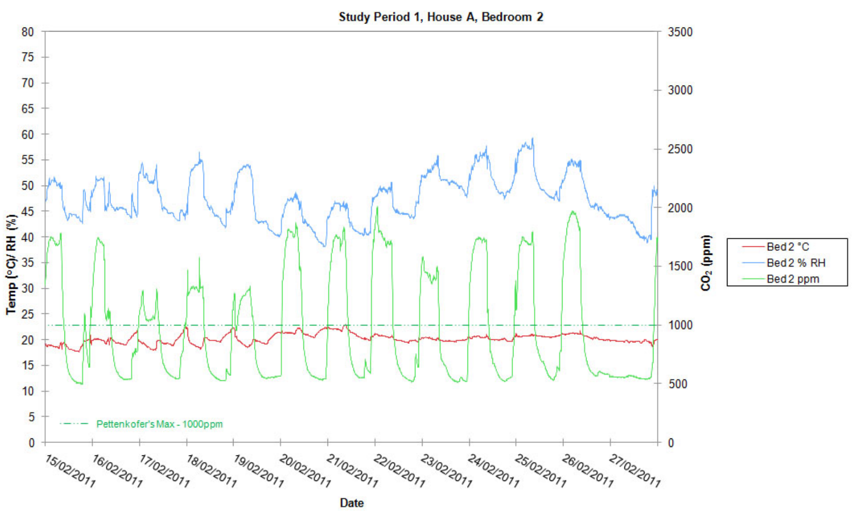


**Figure 4.** Unhealthy Bedroom Performance, SP1, House A, Bedroom 2

Another bedroom performing particularly poorly was House A, Bedroom 2, again during SP1 (Figure 4).Although levels of $CO_2$ were less frequently above 1000pm, compared with the previous example, it did have the highest level of $CO_2$ recorded over the whole investigation. The room was also occupied by one person but, it is worth noting that this bedroom was subject to approximately 30 hours of natural ventilation over the duration of the study period. The maximum level recorded was 2007ppm and the minimum level was 497ppm, giving an excessive range, of 1510 (Table 7). Air quality in relation to $CO_2$ levels was poor. Ta and RH data recorded max. and min. values of 22.9°C and 17.6°C, 59.3% and 38.1% respectively.

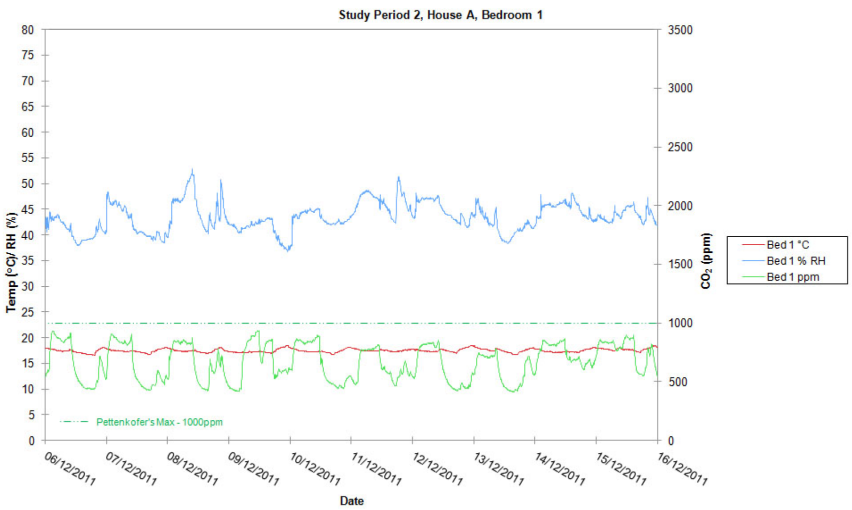


**Figure 5.** Healthy Bedroom Performance, SP2, House A, Bedroom 1

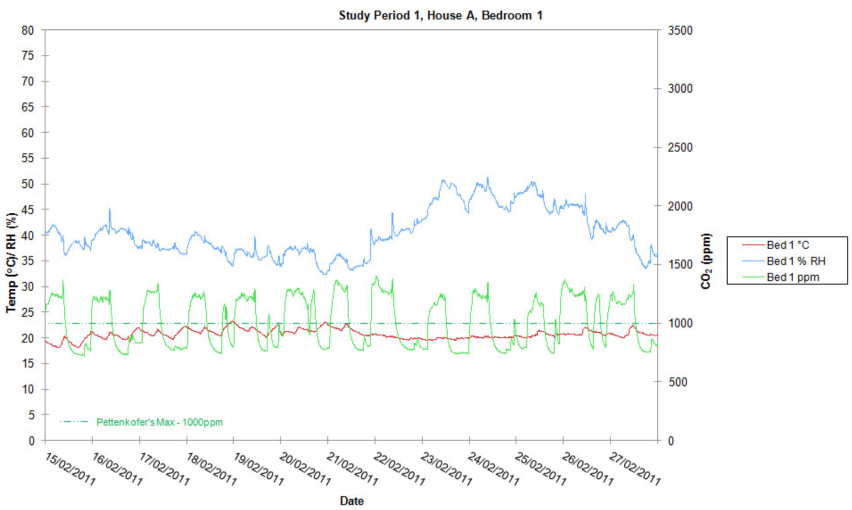


**Figure 6.** SP1, House A, Bedroom 1

The healthiest levels of $CO_2$ were recorded during SP2 in House A, Bedroom 1. (Figure 5) This room had one occupant and was not subject to any natural ventilation. Data recorded

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for this bedroom was continuously below 1000ppm. The maximum level recorded was 939ppm and the minimum was 386ppm (Table 7). This produced an overall range in $CO_2$ levels of 553ppm. Importantly, the room appears to respond better to occupation that in previous examples, with $CO_2$ levels remaining within the prescribed limits.

With reference to the two latter examples, (Figures 4 and 5) both bedrooms are in House A and therefore have the same construction. They also have identical floor area and volumes, (Table 2) and appear to differ only in orientation. An influential disparity between the two examples is the study period in which the data was collected.

| **SP1** | **Min (ppm)** | **Max (ppm)** | **No. > 1000ppm** | **Time > 1000ppm (hr& min)** | **Mean Time/Day > 1000ppm (hr& min)** |
|---|---|---|---|---|---|
| House A – Bed 1 | 713 | 1398 | 1847 | 153hr 55 | 11hr 50 |
| House A – Bed 2 | 497 | 2007 | 1513 | 126hr 5 | 9hr 42 |
| House A – Bed 3* | 681 | 1316 | 197 | 16hr 25 | 1hr 16 |
| House A – Bed 4 | 478 | 1176 | 711 | 59hr 15 | 4hr 33 |
| Bedroom Total | 2369 | 5897 | 4268 | 355hr 40 | 6hr 50 |
| House B – Bed 1 | 585 | 1569 | 1317 | 109hr 45 | 8hr 27 |
| House B – Bed 2 | 445 | 2006 | 690 | 57hr 30 | 4hr 25 |
| House B – Bed 3 | 713 | 1819 | 2085 | 173hr 45 | 13hr 22 |
| House B – Bed 4 | 550 | 1907 | 1220 | 101hr 40 | 7hr 49 |
| Bedroom Total | 2293 | 7301 | 5312 | 442hr 40 | 8hr 31 |
| Total | 44662 | 13198 | 9580 | 798hr 20 | 7hr 41 |
| **SP2** | **Min (ppm)** | **Max (ppm)** | No. >1000ppm | Time >1000ppm (hr& min) | **Mean Time/ Day>1000ppm (hr& min)** |
| House A – Bed 1 | 386 | 939 | 0 | 0min | 0min |
| House A – Bed 2 | 393 | 1151 | 467 | 38hr 55 | 3hr 54 |
| House A – Bed 3 | 374 | 1044 | 352 | 29hr 20 | 2hr 56 |
| House A – Bed 4 | 367 | 1300 | 265 | 22hr 5 | 2hr 13 |
| Bedroom Total | 1520 | 4434 | 1084 | 90hr 20 | 2hr 16 |
| House B – Bed 1 | 417 | 1226 | 334 | 27hr 50 | 2hr 47 |
| House B – Bed 2 | 460 | 1075 | 56 | 4hr 40 | 28min |
| House B – Bed 3 | 433 | 1478 | 774 | 64hr 30 | 6hr 27 |
| House B – Bed 4 | 375 | 1055 | 18 | 1hr 30 | 9min |
| Bedroom Total | 1685 | 4834 | 1182 | 98hr 30 | 2hr 28 |
| Total | 3205 | 9268 | 2266 | 188hr 50 | 2hr 22 |

**Table 7.** $CO_2$ Levels, SP1 and SP2 (*House A – Bed 3 was not slept in, see Table 4.)

With this in mind, an obvious difference can be shown between the two study periods by comparing the best performing bedroom from SP2 with its counterpart in the first study. (Figure 5 and 6). SP2 shows much lower levels of $CO_2$ than that recorded in the same bedroom in SP1. In fact SP1 results indicate unacceptable levels of $CO_2$ within all the bedrooms of House A and B (Table 7). In SP2 only two of the eight bedrooms recorded levels above 1000ppm on a regular basis (>3 hours a day). Further to this, SP2's maximum levels are not as high, and the minimum levels were also lower.

Although a crude representation, looking at the mean time per day that bedrooms spend above 1000ppm clearly strengths the visible difference shown in the graphs, between the CO2 levels in both study period.

### 4.3. Discussion

The most important inconsistencies are highlighted below and will be considered when discussing the results.

House A and B had different occupancy distributions

Natural ventilation occurred during SP1

Thermostat increase occurred in House B during SP2

MVHR system was serviced in the interlude following SP1

#### *4.3.1. Air temperature*

The temperature thermostats were possibly set too high in SP1. It is possible that the Ta recorded for SP1 House A would have been considerably higher if the occupants had not opened the windows in the bedrooms so frequently. The need to naturally ventilate to different degrees between House A and House B, but with similar temperature outcomes, supports the observation of a difference in IAQ between the two houses. Likewise, it can be assumed that the thermostats in SP2 were set too low, resulting in one of the occupants altering the settings in House B to compensate. This evidence further identifies a difference between House A and House B. Whether the difference in Ta is due to construction type, a variation in MVHR system or a study limitation, the unacceptable Ta experience highlights the need for a greater degree of occupant control in order to achieve the ideal sleeping temperature.

#### *4.3.2. Relative humidity*

RH levels remain constantly poor throughout both study periods and suggest that the MVHR is producing air that is too dry, 30-40%. The reason for this unacceptable RH is unclear.

#### *4.3.3. Large diurnal range*

A diurnal $CO_2$ range is normal and can be expected to be evident in the results due to the occupancy pattern of a bedroom, as described previously. It is however the size of the range

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produced, such as that seen prevalent in SP1 (Figure 3) is a concern. The bedrooms have acceptable $CO_2$ levels when empty but when they are occupied they fail to adapt. This observation leads to an assumption that there is very little or no ventilation taking place during SP1. This conclusion is supported by unstable Ta and RH levels also presented in the CP. Reasons for poor ventilation could be attributed to the MVHR system not functioning as required to produce the sufficient amount of air changes per hour needed for each room. There was no CP prior to SP2 to gain clarification from, however, a reduction in the diurnal range in SP2 shows that better ventilation must be taking place.

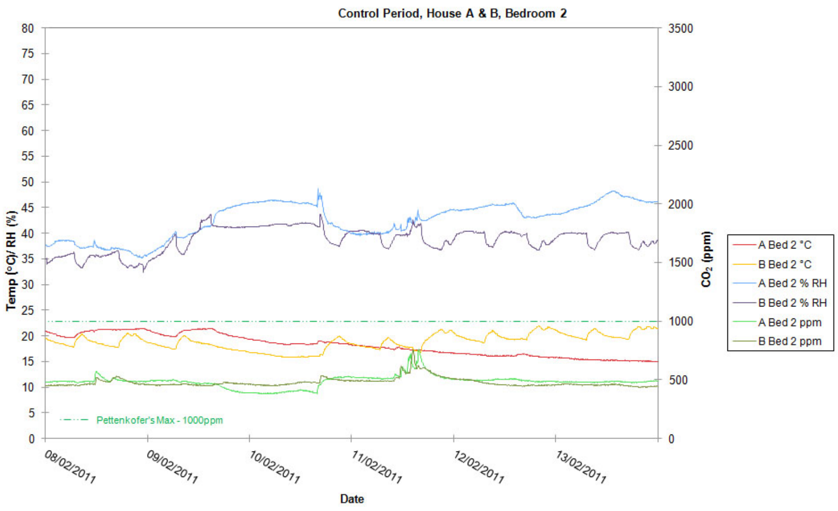


**Figure 7.** CP, House A & B, Bedroom 2

*4.3.4. Bedroom performance variation*

Other than the probable identification of a poorly performing MVHR system, there are other factors for varying bedroom performance.

As highlighted in Figure 3, Bedroom 3 in House B SP1 produces unhealthy $CO_2$ results. The room's size could be a contributing factor resulting in poor IAQ. Bedroom 3 has a volume less than half that of the largest bedroom (Table 2). It has no additional system design requirements, such as a larger supply vent or increased flow rate to provide more air changes. With the same occupancy levels the air will become polluted more rapidly than in a bedroom of a larger size, due to the smaller volume of air available for respiration.

It is also worth considering that the occupant slept with the door shut, magnifying the IAQ problem. There are no trickle vents between rooms and with the door shut there is no way of stale air leaving the room, this in turn inhibits supply flow.Bedroom 3's performance is of specific interest because it has the most potential to be used as a nursery. As previously mentioned in the IAQ of these spaces must be excellent as it is a time when childhood illness/IAQ related health issues are most common.

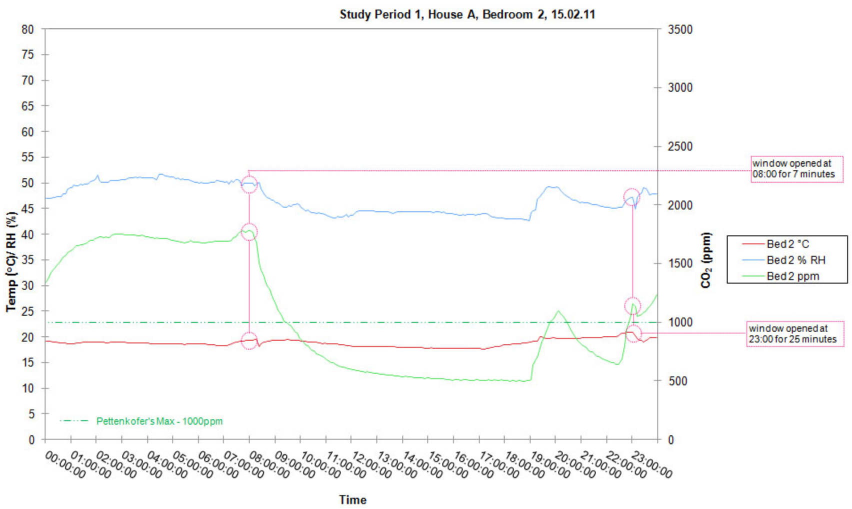


**Figure 8.** Window Opening, SP1, House A, Bedroom 2

In the same study Bedroom 2 in House A also performs poorly in relation to IAQ. Bedroom 2 has a volume of approximately 28m$^3$ compared with 17m$^3$ in Bedroom 3. This room was heavily ventilated naturally over SP1 (Table 3). By looking at how conditions changed during each recorded window opening period it is assumed that without this additional natural ventilation Ta and $CO_2$levels would have been considerably higher. Its counterpart in House B was only subject to roughly four hours of natural ventilation compared with 30, but performed considerably better, although maximum and minimum values were similar. It is possible that in House B the occupant slept with their bedroom door ajar opposed to that of House A. This is unconfirmed. The results produced for this room during SP1 would lean towards House B having producing more acceptable IAQ and are backed up by qualitative assessment which found occupants rated House B's IAQ to be superior to that of House A.

In addition to the examples discussed it is worth noting that the attic rooms seem to perform relatively well in each case, even with House A having double the occupancy level. This could be due to Bedroom 4's large volume and also its proximity to the MVHR unit resulting in shorter duct lengths and therefore better flow rate. The room's location near to the unit may also explain why in the qualitative assessment made by an occupant it was stated that the fan was very obvious and noisy in the attic bedroom. With this is mind, the position of MV supply vents and the noise levels they produce should be considered to the same extent, especially as the air tight construction results in the home being extremely quiet in general.

### *4.4.4. Study period variation*

The substantial difference shown in the results, between the chosen examples, highlights a clear improvement in $CO_2$levels between SP1 and SP2.The qualitative IAQ results recorded support the quantitative results. The inhabitants deemed the air to be of greater satisfaction, freshness and circulating more frequently within the second study period.

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Significant evidence explaining reasons for the improvement in $CO_2$levels can be sought from a report written following an inspection of the MVHR system in both houses, by the installer, subsequent to the completion of the first study period. The report identified a number of defects, which were rectified between SP1 and SP2.

In House A it was observed that 125mm ducting had been used in the roof space, but that the majority of ducting installed was only 100mm. This potentially led to the unit running at higher pressure than it was designed to, although no increase was specifically noted. In House B, however, the system was measured to be running at an increased pressure. Higher pressures impact on air flow and created the potential for fans to stall, resulting in reduced ventilation.

There were several reasons for the high pressure within the system of House B. As well as the extensive use of 100mm ducting, there were also additional bends compared to that of the ducts in House A. In addition the ducting had been connected in the wrong position to the MVHR unit. This contributed to the high pressure as well as reducing the performance of the system. Areas of ducting were also found to contain remnants from the internal fix out of the house, hindering air flow. Other ducts had been squashed. Both faults increased pressure within the system. The filters within the unit were seen to be dirty and in need of cleaning/replacement. This factor would have resulted in increased resistance adding to the high pressure within the system. The build up of dirt would have reduced the filters air purifying efficiency resulting in increased levels of contaminants being circulated throughout the house. Extract flow rates in the rooms were measured at low levels because the system was running poorly, this would result in polluted air being removed from rooms at a much slower rate than necessary during inhabitation.

It seems reasonable to conclude that these works have improved the performance of the system, but that concerns remain in regard to the levels of IAQ that are experienced by occupants, particularly during peak conditions.

## 5. Case study 2: Gilmores close

This project was a building performance evaluation of an adaptive rehabilitation project on a Category B listed 19th Century stone tenement located within the World Heritage Site of Edinburgh’s Grassmarket. Working within the constraints of its historical significance and limited budget (a registered social landlord as Client) and end user group, this project has sought to create an energy efficient solution for its sustainable rehabilitation.

To assess the performance of this building MEARU undertook a programme of monitoring and evaluation over a three-week period during March 2011(from 17.03.11 to 12.04.11). Average external temperatures during this period were 9 $^{o}$C. Environmental monitoring was supplemented with an analysis of energy demand and acquisition of qualitative data through semi-structured interviews of the occupants, and observations by the surveyors to provide an overview of building performance.

This project was undertaken over a limited, albeit very focused, period. As such the information derived provides a 'snapshot' of building performance, rather than a more extensive review of performance over the course of an annual climatic cycle. The study collected data on 6 properties (5 dwellings and 1 small office) out of a potential 17 properties.

### 5.1. Construction

The measures used in the refurbishment of the block incorporate specific approaches to design and specification to reduce the on-going environmental impact of the building and to improve the living conditions of the potential residents. Working within the constraints (both physical and statutory) of the existing blonde ashlar and random rubble sandstone façade and structural cores, a new internal layout was constructed to provide flatted accommodation. The new insertions within this masonry skin are generally lightweight timber construction. Figure 9 shows the general flat arrangement.


**Figure 9.** Typical Plan Gilmore Close

The thermal performance of the building was improved by bringing the fabric up to contemporary standards through a process of internal dry lining and insulation to achieve a U-value of 0.25W/m$^2$K.The thermal performance of the historic timber sash and case windows was also improved through the use of secondary internal glazing improving U-values to 1.8W/m$^2$K. Both of the above strategies adhered to the design principles dictated by the building's historic status in that they did not materially affect the principal elevation. To the rear a south facing, semi-glazed (approx. 50%) sunspace with an average U-value of circa 1.0W/m$^2$K has also been incorporated into 12 of the dwellings to provide additional amenity and to make use of passive solar gains.

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The principle active technology employed throughout the development is a vertical ground source heat pump (GSHP), which, along with an electric back up heater, provides for the hot water and space heating demands of the full building. Delivery of the space heating is through a wet under-floor heating system. Due to limitations of the timber intermediate floor structure this is provided within proprietary insulated trays rather then being contained in a screed.

Ventilation of 13 of the dwellings also allows for the use of heat recovery through proprietary mechanical ventilation with heat recovery (MVHR) units. In the 1 bedroom apartments (without sun spaces) a conventional system of opening windows, background trickle ventilators and mechanical extraction from wet spaces has been installed. Elsewhere a whole house MVHR system draws air from the kitchens, bathrooms and sunspaces, and after recovering waste heat, delivers fresh warmed air to the hall spaces, with the intention that this will dissipate to adjacent spaces. Note that MVHR relates to an energy strategy but is viewed primarily as a ventilation aspect with the heat recovery aspect being secondary.

### 5.2. Occupancy

The building has three distinct groups of occupants, all of who were represented in the data collection process. The first user group is that of the mainstream social rent tenants. They occupy one of the building's two closes. The second user group, occupying the second close, is made up of residents who require supported living. The third group of users are the care staff who occupy the building's office space and provide support to user group two.

Following completion and occupation of the building there were reports from residents of poor performance and problems with the heating system. Through a process of further commissioning and alteration this system was brought up to a standard where resident complaints were dramatically reduced but where continued problems were evident. Anecdotal evidence suggested over-heating was common and this was be supported by visual inspections of window openings.

In response to these issues MEARU was asked by the architects to undertake a building performance evaluation to identify issues relative to the building performance in general with a specific focus on internal comfort. The project was funded by the CIC Start Online academic consultancy fund. The key question posed was what energy performance and environmental conditions are being achieved, and if these are below requirements what lessons may be learned for this, and other similar projects.

### 5.3. Data review

Research into the building performance and user satisfaction was undertaken using a variety of approaches and techniques for data collation and analysis. This was designed to primarily provide a resource of quantitative (empirical) data but which was supported by qualitative data providing a greater depth to the analytical process. Over a 3½ week period the internal temperature, relative humidity and $CO_2$concentration were monitored in all apartments, the hall and kitchens of five flatted dwellings and throughout one office space (noting that in each case the bathrooms/ WCs were omitted).

Although not a longitudinal study, there are significant benefits in a short, intense period of monitoring. The relatively brief duration led to limited intrusion on the occupants, ensured continuity in data collection relative to both dwellings and occupants and allowed a fine granularity, which helped to identify specific events within the flats.

### *5.3.1. Thermal comfort*

Due to the anecdotal evidence on overheating, this was the initial focus of initial research. A review of physical data at the macro level (Table 8) confirmed that the mean and absolute maximum temperatures within all apartments (office space excluded) were - often significantly - beyond the accepted comfort range. The mean values confirmed the suspicions held at the project outset but did not provide any information on cause or potential solutions.

| Room | Mean Temp (°C) | Comfort Temp (°C) | Δ T 1 (°C) | Absolute Max (°C) | Δ T 2 (°C) |
|---|---|---|---|---|---|
| Living Rm | 22.62 | 21.00 | +1.62 | 28.00 | +7.00 |
| Kitchen | 22.87 | 18.00 | +1.87 | 29.10 | +11.10 |
| Hall | 23.45 | 18.00 | +5.45 | 31.20 | +13.20 |
| Sun Space | 21.24 | | | 40.90 | |
| Bedroom 1 | 22.58 | 18.00 | +4.58 | 27.20 | +9.20 |
| Bedroom 2 | 21.41 | 18.00 | +3.41 | 26.20 | +8.20 |

**Table 8.** Mean and absolute maximum thermal conditions over project duration

To identify this, a more focussed review was undertaken of each dwelling relative to the profile of physical parameters on a diurnal basis.

Figure 9 illustrates a typical daily example where a living space is heated to a degree of discomfort and then is rapidly cooled by the occupant behaviour of liberal window opening. This behaviour was found to be repeated throughout the development and was supported by the survey responses in which 60% of residents noted they opened windows every day throughout the year.

Recorded data from an unoccupied dwelling had shown that a relatively stable temperature profile could be maintained internally which demonstrated that despite the loss of thermal mass necessitated by insulated dry-lining and timber construction the fabric was capable of facilitating thermal comfort. Further investigation using thermal imaging provided an insight to problems of frequent overheating. Figure 11 shows the surface temperature of a typical apartment floor at two different points in time. In the first (T1) the thermostat was set at its lowest level yet a temperature of 28.9°C was evident. Immediately after this image was

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taken the thermostat was turned to it's highest setting with the same image being taken one hour later (T2).

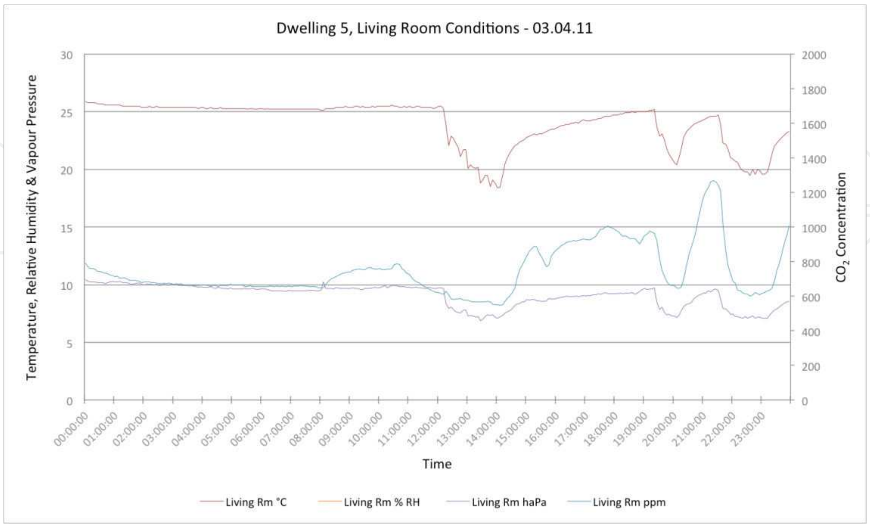


**Figure 10.** Physical parameters in Dwelling 5 living room – fluctuating thermal comfort

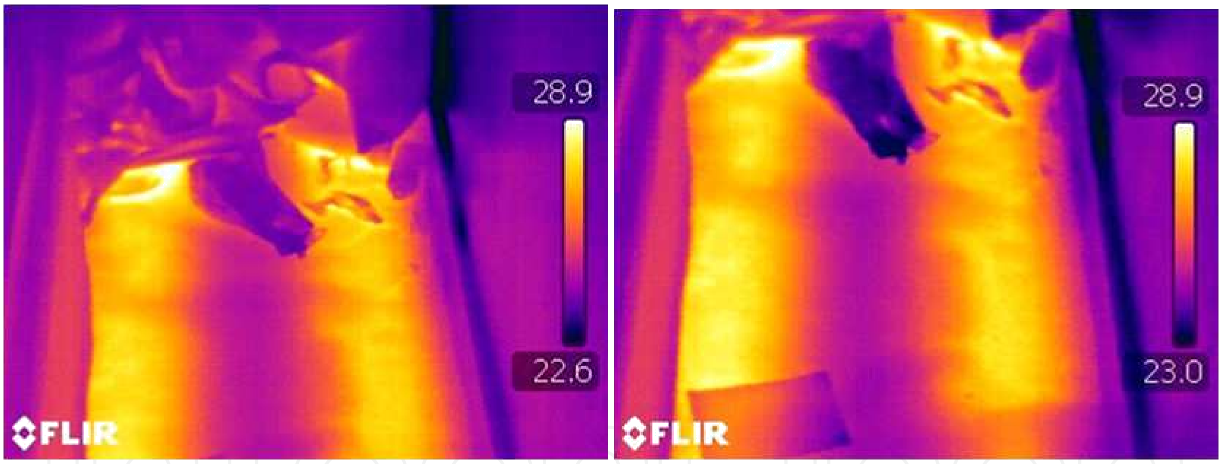


**Figure 11.** Floor surface temperature T1 and T2

The level of the initial reading suggested that the control of the heating system was ineffective. This was confirmed by the lack of response over the subsequent sixty-minute period. Poor performance of heating controls, allied to a poor user interface, were identified as factors that consistently resulted in the creation of sustained internal temperatures exceeding the comfort range. In addition to this, the lack of thermal mass in the structure, an outcome of the approach to thermal upgrade of the historic fabric, results in high rates of heat gain and loss; a process which is difficult for residents to stabilise once the cycle of window opening has commenced. Ultimately, having windows open when heating is on leads to an increase in the energy required for space heating and undermines the thermal efficiency of the building. This also provides an explanation for the disparity in predicted and measured energy loads for space and water heating.

*5.3.2. Internal air quality*

Monitoring identified several spaces with very good IAQ. Given the prevalence of window opening this result was hardly surprising, but will of course have a thermal penalty. In circumstances where window opening is common, the use of an MVHR system is not only ineffective but is also an additional primary energy burden on the dwelling as the fan continues to run at the same rate regardless of IAQ conditions. Where window opening was not prevalent, maximum values of $CO_2$concentration were frequently found to rise and be sustained above recognised maximum desirable levels of 1000ppm. Figure 11 illustrates a particular situation from a bedroom in Dwelling 2 over the monitoring period but this is typical in monitored apartments throughout the project.

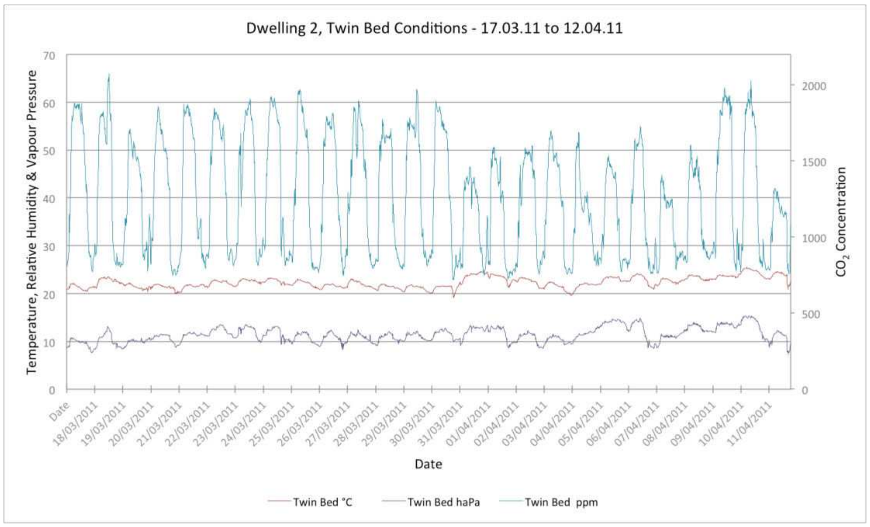


**Figure 12.** Physical parameters in Dwelling 2 twin bedroom – high CO2 concentrations

The bedrooms are of particular interest as windows are generally closed at night due to issues of external noise and as the occupants are asleep no further occupant intervention occurs. Accordingly these spaces are entirely reliant to the MVHR system to deliver ventilation and good IAQ.

*5.3.3. Discussion*

A contributory factor to the poor performance is the layout of the system, with the two air delivery registers focussed into the hall space only.The intention behind this design was that air would migrate from this central location into adjacent apartments. However, fire regulation requirements for self-closing fire doors and smoke seals prevent such air movement. The situation appears to have been exacerbated post-construction, as carpet installation has further reduced the air spaces under doors.

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With the potential health impacts, the importance of good IAQ cannot be a secondary concern and it must not be undermined by attempts to improve thermal efficiency and air tightness. Not withstanding this position, the level at which poor air quality is perceptible has the potential to cause occupants to manually seek improved ventilation. With a $CO_2$concentration of 1000ppm poor air quality is perceptible to humans with the stress initiated behavioural response invariably being one of window opening and the result being, as was evidenced with the poor thermal control, one of high energy loss. Instances of this were identified through in the monitoring of this project and the outcome of poor air quality is (entirely rational) behaviour that counteracts the approach to energy conservation central to a contemporary design ethos.

A further issue of note in relation to the MVHR system is that of maintenance. The MVHR system contains air filters to screen for dust and particulate and the need ensure these are cleaned on a regular basis is critical to the functionality and energy consumption of the system. In this instance limitation on the space available has led to the placement of the unit in a location above a dropped ceiling where access for maintenance and filter replacement is physically very difficult.

The study identified that through the refurbishment considerable improvement has been made in the thermal performance of the buildings and there should be no doubt that overall it has been successful in terms of the improvement of the flats and the maintenance of the cultural heritage of these buildings.

However, the study also found that there are some problems that lead to a reduced energy performance and some unintended negative consequences, particularly in respect of indoor air quality. These are due to some design issues, for example the fire protection measures over-riding the ventilation strategy; the desire to increase living space in the sun-spaces undermining the energy strategy (not discussed in this Chapter); the loss of thermal mass through the provision of internal insulation and lightweight sub-division; and the design integration of elements such as the MVHR and sunspaces. There are also issues of installation, commissioning and maintenance, including the lack of proper control of the heating system, and MVHR specification and installation.

The study identified a number of measures for improvement, both remedial measures in these flats, but also lessons for similar developments elsewhere.

Options for improvements in this development that are currently being explored include: the re-commissioning and improvement of the heating control systems; an extension of the MVHR supply ducts to deliver air directly into living spaces and bedrooms; provision of additional control over the sunspace extract system.

These findings are also relevant to future developments in this building type. The original building would have had an energy strategy relying on open fires with chimneys providing significant levels of radiant and convected heat, which would engage with the thermal mass of the building. Sash and case windows, although relatively draughty by contemporary standards, provide high and low level openings, which, when combined with high ceilings give very good ventilation regimes. The literature review for this project has highlighted a significant gap in the understanding of the standards of IAQ in energy efficient dwellings and this is a key area for further study. This is relevant to new build energy efficient dwellings and particularly to retrofit schemes as contemporary approaches may actually reduce IAQ and undermine attempts to improve thermal efficiency and reduced $CO_2$output.

The necessity of removal of some of these characteristics (thermal mass, volume of dwellings through sub-division, high ventilation rates) needs to be considered in taking a holistic approach to refurbishment of these dwelling types which addresses environmental performance as well as energy targets.

These questions have wider implications for the profession and identify areas for further research if we are to achieve the desired sustainable future.

## 6. Conclusions

Both these projects clearly illustrate the challenges for sustainable energy futures that can arise if environmental strategies are not successful. Both of these projects have produced low energy buildings, of high architectural quality, but these studies have identified that unless environmental strategies are carefully designed, implemented and maintained, unintended negative consequences can arise. As well as producing potentiall harmful environments which can have detrimental effects of occupants health, poor ventilation design can undermine strategies for energy conservation as occupants attempt to achieve comfort by conventional means such as window opening.

In both projects the role of building users is two-fold – as operators and as consumers. In the former role, building users have a part to play in ensuring the efficient and effective performance of the buildings, but this role is significantly moderated by their environmental experience, the effectiveness of the systems and their control over them. Thus a system that cannot effectively control comfort leads to behaviours that can increase energy consumption. In the latter role, building users are subject to the environmental conditions of the buildings and may experience discomfort or even detrimental health effects if the environmental strategies are ineffective.

The results and discussions from both projects conclude that the design of mechanical ventilation heat recovery systems does require further consideration in order to provide healthy levels of IAQ in both projects whilst maintaining good energy efficiency. In the Glasgow House the considerable improvement in $CO_2$levels between the study periods indicates that the design itself is reasonably good, however, there is still need for improvements within the bedroom areas and poor IAQ was still experienced. Remedial measures are also proposed in Gilmores Close and it is hoped that there will be an opportunity to monitor the results of this. The projects also illustrate the need for holistic environmental design, which takes into account a range of design requirements, including obvious environmental factors such as heating, ventilation, lighting, and controls, but also relating these to other design parameters such as the nature of occupants, maintenance and fire safety.

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The studies also illustrate the value of information revealed by the use of BPE. Underperforming systems which potentially endangers the health of the occupants will not be apparent unless the buildings are evaluated in use. Without these studies the conditions in these dwellings would not be known, nor would the knowledge about the issues and how they may be addressed be revealed to the industry in general. In the current low carbon environment most new buildings are experiments – it is vital that we go back and check the results. Collectively, the design, installation, maintenance and the need for BPE require further consideration in order to provide exemplary indoor air quality in Scotland's future housing stock.

## Author details

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## References

[1] Sullivan, L. (2007). A Low Carbon Building Standards Strategy for Scotland, Arcmedia, Scotland.

[2] Shorrock, L. D., & Utley, J. I. (2003). Domestic Energy Fact File 2003. BRE Bookshop, Watford, England

[3] Boardman, B. (2007a). Home truths: a low-carbon strategy to reduce UK housing emissions by 80 per cent by 2050. Report to the Friends of the Earth and the Cooperative Bank.

[4] Steemers and , K., & Yun, G. Y. (2009). Household energy consumption: a study of the role of occupants', Building Research and Information, doi.org/10.1016/j.enbuild.2010.09.021., 38, 625-637.

[5] The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency.A report produced by the Sussex Energy Group for the Technology and Policy Assessment function of the UK Energy Research Centre, Steve Sorrell, October (2007). 1-90314-403-5

[6] http://www.cicstart.org/content/home/1,1,276/FS01DevelopmentofPostOccupancyEvaluationforevaluationofinnovativelowcarbonsocialhousingprojects.html

[7] Energy, , Buildings, Volume. 4., Issue, ., & January, . (2011). Measured energy and water performance of an aspiring low energy/carbon affordable housing site in the UK, 117-125.

[8] Mazzeo, Nicolás A, ed., Chemistry, Emission Control, Radioactive Pollution and Indoor Air Quality, (Croatia, 2011), p. 447

[9] M. Jantunen, J. J. K. Jaakkola and M. Krzyzanowski, eds., "Assessment of Exposure to Indoor Air Pollutants," in WHO Regional Publications, European Series, no. 78, (1997), p. 1

[10] Raymer, Residential Ventilation Handbook, p. 2.4, McGraw Hill, ISBN: 9780071621281
2009

[11] Mazzeo, ed., Chemistry, Emission Control

[12] Stirling Howieson, Housing and Asthma,Oxon, (2005).

[13] Jantunen, Jaakkola and Krzyzanowski, eds., "Assesment of Exposure to Indoor Air Pollutants,"

[14] Allard, ed., Natural Ventilation in Buildings

[15] Scottish Government, Scottish Domestic Building Regulations, Section 3.14

[16] Porteous, "Sensing a Historic Low-CO2 Future," p. 238

[17] Allard, ed., Natural Ventilation in Buildings

[18] Michael G. Apte, Joan M. Daisey, William J. Fisk, "Indoor Carbon Dioxide Concentration and SBS in Office Workers," in Proceedings of Healthy Buildings(2000). http://senseair.hemsida.eu/wp-content/uploads/2011/05/6.pdf, 1

[19] Dearden, "Ventilation and Air Quality," p. 21

[20] Mosley, "Fresh Air and Foul," p. 8

[21] Ibid., p. 21; London Hazards Centre Handbook, Sick Building Syndrome, p.43

[22] Crump, D., Dengel, A., & Swainson, M. (2009). Indoor Air Quality in Highly Energy Efficient Homes- a Review, IHS BRE Press, Watford, England.

[23] Platts-Mills, T. A. E., & De Weck, A. L. (1989). Dust Mite Allergens and Asthma- A worldwide Problem, Journal of Allergy and Clinical Immunology, , 83, 416-427.

[24] Heinrich, J., Int, J., Hyg, Environ., & Health, . (2011). Jan;Epub 2010 Sep 18.Influence of indoor factors in dwellings on the development of childhood asthma., 214(1), 1-25.

[25] Arundel, A. V., Sterling, E. M., Biggin, J. H., & Sterling, T. D. (1986). Indirect Health Effects of Relative Humidity in Indoor Environments,. Environmental Health Perspectives, , 65, 351-361.