HÖGSKOLAN DALARNA

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Monitoring air quality indicators and energy consumption in Dalarnas Villa during operation of a demand-controlled exhaust ventilation system

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Abstract

A real-world study was undertaken of the indoor air quality in a recently-built single family home in central Sweden, to establish whether demand controlled ventilation provided superior interior conditions, when compared with other air supply strategies, including the standard used by the Swedish buildings regulator.

The property was highly airtight, with ventilation achieved using a forced exhaust system. Extraction was possible from all rooms of the house, and using a Renson Healthbox air handling unit, the rates of air flow from each room could be adjusted either according to a time schedule, or under demand control according to the unit's sensing of the air quality in individual rooms.

Five ventilation modes were evaluated, each for a period of 24 hours. Occupancy of the house was standardised, with test participants. Two separate air quality monitors were deployed to verify whether measurements made at the air handling unit were representative of the conditions that occupants experienced. Key measurements were the stable level of carbon dioxide overnight in an occupied double bedroom and the time taken for that room to refresh to background CO_2 level the following day. The time taken for a kitchen/living room to similarly refresh was also examined.

The study found that demand controlled ventilation achieved indoor air quality – assessed on carbon dioxide concentration – comparable with rates of fixed ventilation far greater than the regulated standard. In doing so, the air volume exchanged over a representative day was 33 % less than that standard, providing for significant energy savings.

The parallel monitoring of air quality inside the room and via the air exhaust duct showed noticeable variation, but indicated the air handling unit under demand control would never ventilate insufficiently, based on its internal CO_2 sensors.

Contents

1 Acknowledgements

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We would like to thank Healthy Homes AB and Renson for assistance in setting up the Healthbox air handling unit and accessing its data.

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2 Abbreviations

Abbreviation	Description
AHU	Air handling unit
BBR	Boverket Byggregler
DCV	Demand controlled ventilation
IAQ	Indoor air quality
LAQ	Luvian Air Quality monitor
MVHR	Mechanical ventilation with heat recovery
PM	Particulate matter
ppm	Parts per million
UTC	Coordinated Universal Time
VOC	Volatile organic compound

3 Nomenclature

Symbol	Description	Unit
Q	Heat energy	J·K-1·m-3
p	Density of air	kg·m3
Cp	Specific heat capacity	J·kg-1·K-1

4 Introduction

4.1 Background

Different cultures and climates lead to different priorities with regard to maintaining acceptable indoor air quality (IAQ).

In countries such as Sweden, the main issues have traditionally been associated with managing:

- humidity – damp, condensation or mould forming at cold-warm interfaces
- artificial pollutants – biological or chemical, and noxious or just unpleasant, from external activities such as transport, industry, agriculture.
- radon – a naturally occurring radioactive gas that sinks in air and can accumulate in cellars.

Hence the problem had previously been simplified to an outside-in situation [1], which could theoretically be resolved by careful design of air intakes. Consideration of the pollutants generated by a building and its occupants has come to the fore in more recent times.

Outdoor air quality in Scandinavia is related to the local level of emissions from traffic as well as the prevalence of wood burning in the vicinity [2]. Arguably, recent trends away from diesel engines, and the declared ambition of many countries to end sales of vehicles with internal combustion engines will remove some sources of vehicle pollution from residential areas. Road and brake dusts will not be eliminated by any transition to electric powertrains. Outdoor air is cleaner in rural than in urban areas [3] but still not entirely free of particulates, nor of sulfur dioxide and methane gases [1].

What influences indoor air quality?

Relative to 'clean air', indoor air routinely has higher concentrations of carbon dioxide (CO_2), water vapour (H_2O), volatile organic compounds (VOC) and particulate matter (PM). These are all created by the occupants, either directly or by their activities. Items in a home contribute, as does the building fabric itself [4].

- People (and companion animals) are direct sources of all four key indoor air pollutants, through the biological process of respiration, plus all the activities we associate with daily hygiene at the fundamental level (e.g. washing, toilet use) and other more human behaviours (e.g. clothes, wearing scents, smoking). By definition, the pollutants are generated wherever the occupants go.
- Chemicals used in the home – especially those delivered by aerosol (paradoxically, including air fresheners) – are often hydrocarbon-based and therefore noticeable sources of VOC indoor pollution.
- The materials of the building fabric and its furnishings may off-gas VOC from manufacturing residues, or through breakdown of organic compounds due to heat or sunlight. Particulate matter can also be generated.

- Cooking is a strong point source of all four pollutants, especially if a non-electric stove or oven is used [5].
- Wax candles act similarly, albeit on a far smaller scale. They are widely used in Sweden.
- Plants have the potential to marginally reduce indoor pollution, by consuming CO_2 or by interacting with airborne VOC and PM.
- Indoor air quality devices also exist, designed to physically or chemically remove contaminants.

4.2 Ventilation standards

In common with many regions that experience lengthy sub-zero winters, airtightness in modern Swedish homes is very high. Levels of unmanaged air infiltration are low and therefore the *Boverkets byggregler* (BBR) design standards [6] insist upon natural or forced ventilation systems to provide air change rates conducive to a healthy indoor environment. The fundamental requirement is an air change rate proportional to floor area, assuming a standard 2.4 m ceiling height. This ventilation requirement is a minimum of 0.35 litres per second per square metre. Air does not have to be extracted from all rooms. When the property is unoccupied, a lower minimum air change of 0.10 $l/s \cdot m^2$ applies.

The basic approach that complies with Boverket guidance is for fresh air to be admitted to bedrooms and other areas where people are most often present, and to be removed from kitchen and bathrooms areas, where occupants spend less time, and where tangible air quality (odour, moisture) is lowest. Such a system aims to maximise occupants' exposure to fresh air and prevents excess moisture spreading around the home; the atmosphere becomes progressively less fresh until stale air is eventually extracted.

4.3 Policy context

While outdoor air quality is the subject of a European Union directive (2008/50/EC) [7], obliging Sweden and other member states to monitor and reduce contaminants known to be hazardous to health, its remit does not specifically extend to the indoor environment, nor to all the airborne substances that constitute indoor pollution. That said, limitations on VOCs in paints and varnishes are provided for under Directive 2004/42/EC and prevent high solvent emissions associated with some indoor works.

5 Literature review

Literature relevant to the study includes discussion of ventilation strategies, of approaches to measuring IAQ indicators, and of the productivity, health and comfort implications of varying levels of indoor carbon dioxide.

Nielsen and Drivsholm [8] present an approach for a simple demand controlled ventilation system in a single-family house, built in 2002 and having a floor area of 140 m^2. The strategy used in this research was to measure the differences in CO_2 concentration and moisture content between the extracted air and the outdoor (supply) air. Based on that difference, the DCV was switched between a high rate and low rate.
The ventilation rate was set at low mode when the differences of both IAQ indicators, CO_2 and moisture content, were below the respective threshold level. Once the difference in either exceeded a defined level, the ventilation rate switched to the high mode. The high rate (216 m^3/h or 0.43 $l/s \cdot m^2$) is based on the Danish building regulations and the low rate (80 m^3/h or 0.16 $l/s \cdot m^2$) is based on the minimum air quality requirements. The flow rate was controlled by the speed of a fan, where the low flow rate was approximately 40 % of the high.
The house was occupied by four people, two adults and two children. The occupancy schedule followed normal weekday behaviour, with adults in work and children in school. Four series of measurements were taken in the house – each series lasting for five days – to discover the optimal threshold difference of CO_2 concentration and relative humidity with the corresponding fraction of time where low fan speed was able to be used.
The results showed that ventilation heat losses were reduced by 23 % when the fan was running on the low mode 37 % of the time. The fan unit's own electricity consumption was able to be reduced by 35 % without negative impact on the IAQ.

Work by Polet et al. [9] compared four different ventilations systems to evaluate associated indoor air quality, energy consumption and ventilation losses. The systems were:

1. Demand controlled with extraction from utility rooms (DCV 1)
2. Demand controlled with extraction from all zones of the house (DCV 2)
3. Mechanical ventilation with heat recovery (MVHR)
4. Mechanical extraction ventilation (fixed low rate).

The study was assessed in a two-storey detached house, using *Contam* software based on numerical simulations developed by NIST (the US National Institute of Standards and Technology). Three climate zones of Brussels, London and Aberdeen were modelled with outside average temperatures ranging from 5.6–6.6ºC. The indoor set temperature was 18ºC, less than is typical in Sweden. Four occupants (two adults and two children) were assumed, with both weekday and weekend occupancy schedules. Except for natural air supply through

vents in bedrooms, the possibility of air mixing between zones was minimized by shutting windows and internal doors.
The results showed that DCV 2 helped to improve the IAQ level and to decrease the fan electricity consumption and heating energy consumption by 50–65 % compared with system 4 (simple extraction). From an economics standpoint, the DCV had a lower total cost than the MVHR, over a time span of 15 years.

Kruger's 1996 paper [1] outlines a number of considerations in studying air characteristics in a domestic setting. The author notes Pettenkofer's long established baseline (dating from 1858) of a 1,000 ppm CO_2 concentration level, above which people are likely to notice the air is not fresh. In the more modern context, he states that, "Air quality as [it] occurs indoors is largely due to outdoor pollution." That includes, he contends, a noticeable level of naturally occurring methane (1.6–1.9 ppm), even in non-urban areas.
Kruger defines the 'occupation zone' within a room as being at least 0.6 m from any wall and any air-conditioning unit and extending up to 1.8 m from the floor. It is unclear how underfloor heating might interact with such a zone. He further discusses a 'useful occupation zone', i.e. one which is free from draughts.
Working alongside thermal comfort pioneer Fanger, the author outlines units of indoor pollution including the 'olf', the emissions of one standard person performing a sedentary activity, and the 'decipol', the perceived air quality in a room when one olf is ventilated with fresh air at 10 l/s.

Two health-focussed Polish research teams [3] [5] have considered sources and types of indoor air pollution. Carbon dioxide (alongside other chemical and biological traces) was taken as one primary indicator of IAQ, and the set used to compare naturally ventilated public schools at urban/rural sites in Poland. The authors outlined bands of IAQ based on increased CO_2 concentration: high (good) IAQ for ≤400 ppm above ambient; low (poor) for a level raised by 1000 ppm or more; also two intermediate bands. Some classrooms experienced IAQ in the worst band for 91% of the school day, with the highest levels when the children took their collective afternoon nap.
In separate discussion of indoor PM levels, an envious reference is made to the far cleaner air in Swedish schools – although it is not clear whether that may be due to higher rates of (forced) ventilation or to cleaner outdoor air. There was surprisingly little difference between rural and urban locations. Solid fuel stoves were also highlighted as a strong potential source of indoor pollution.

Research carried out in Denmark [10] sought to focus upon occupant wellbeing under different IAQ conditions, by evaluating sleep quality and alertness after nights spent sleeping in rooms with or without systems to limit the carbon dioxide level.
16 students in north Copenhagen slept in single occupancy rooms under one of two conditions. A low noise fan was installed in the room's outside wall, set to supply additional fresh air to the indoor environment when the CO_2 level passed a threshold of 900 ppm. The fan was in use or out of use for a week, providing the two conditions.

The students' sleep quality and their next-day performance was assessed by using a visual analogue scale (a Groningen sleep quality test), the answers being obtained subjectively from students no later than 10 minutes after waking up. Occupants were also asked to wear wrist-watches (of an altigraph type), to measure and record their sleep disturbance. The indoor environment measurements of CO_2, relative humidity, and air temperature were recorded by two sensors.

The final results showed the additional ventilation led to occupants experiencing more comfort and longer resting states, compared to having no additional ventilation. The measurements showed the night-time CO_2 under the ventilation mode averaged 835 ppm. This was compared to a value of 2,395 ppm that arose when the fan was not activated above the 900 ppm threshold. The relative humidity fell within the acceptable range for both modes, although dry skin was a possibility with the additional ventilation.

6 Objective of this study

Applying the BBR standard across many types of houses, regardless of their occupancy levels, prompts obvious questions:

- Is the air supply always sufficient to ensure a healthy indoor climate?
- Is it excessive, and therefore wasteful of energy?

This study aimed to obtain real-life data from a house equipped with a demand-controlled ventilation (DCV) system – a more sophisticated alternative to the BBR minimum – and to investigate whether demand control could reliably achieve the same or better IAQ, and whether it could also save energy.

In addressing those two questions, three key lines of investigation were pursued.

1. Verify that taking measurements at the central air handling unit (AHU) of the air drawn from a room (via an exhaust duct), is a valid way for a DCV system to assess the actual environment inside the rooms of a house, and thereby the conditions as experienced by occupants.
2. Record the variation of indoor CO_2 – in particular its stable equilibrium level during zone occupation and the time taken for the air to refresh once a room is vacant.
3. Record air flows out of the house, as a measure of the unheated replacement air entering the building. From this value, the heat energy required could be estimated, also potentially the cost. The energy used by the ventilation system itself would also be considered.

7 Testing method and protocol

7.1 Dalarnas Villa

Högskolan Dalarna (alongside project partner, Dalarnas Försäkringsbolag) has built a single family home – known as *Dalarnas Villa* and illustrated in Figure 7.1 below – in a low-density rural hamlet between the towns of Borlänge and Falun in central Sweden. There are no significant nearby sources of anthropogenic air pollution.

It is a two-storey wooden construction on a concrete slab foundation. Heating is from a ground-source heat pump with underfloor distribution throughout. The internal footprint is 88 m^2 and the total floor area 150 m^2. Due to the living room being double height, the internal volume is approximately 500 m^3.

Figure 7.1 Southeast side of Dalarnas Villa

The ventilation is *Frånluft* (F-system) in which stale air is extracted mechanically from all rooms and vented to the outside. Supply air is admitted (unwarmed) through window vents and other inlets, into each bedroom and the living room. A *Renson Healthbox 3* air handling unit extracts via ducts from each of seven room zones at rates that can be individually adjusted either manually or by the unit's own algorithms. The Healthbox has sensors at the AHU, monitoring the stale air in each of the incoming exhaust ducts for its levels of CO_2 and other pollutants.

7.2 Ventilation modes

Three different approaches to ventilation management were tested, including the BBR baseline. Five ventilation modes – with specific air extraction rates from the two zones being monitored for IAQ – were used across a number of 24-hour periods. The modes' characteristics are summarised in Table 7.1

Table 7.1 Ventilation modes used in the study

Mode	Overall extraction rate in l/s	Overall extraction rate in $l/s{\cdot}m^2$	Constant, stepped or demand control	Stale air extraction from
1	55	0.35	Constant	All zones
1b	55	0.35	Constant	Only bathrooms and kitchen
1c	70	0.47	Constant	All zones
2	70 or 20	0.47 or 0.13	Stepped	All zones
3	21 - 84	0.14–0.56	Demand control	All zones

- Mode 1: fixed around the clock at the ventilation rate required by BBR regulations for periods of occupation, with air extraction from all zones.
- Mode 1b: fixed around the clock at the same BBR rate, but with no direct extraction from bedrooms, only from bathrooms and kitchen. (See floorplan at Fig 7.2, below.) This represents the Swedish standard for F-system installations.
- Mode 1c: fixed around the clock at a rate 30 % above the Swedish standard, extraction from all zones.
- Mode 2: two fixed ventilation rates, one for periods of occupation, a much lower one for the house being unoccupied.
- Mode 3: each zone ventilated in response to its particular CO_2, H_2O or VOC level, in a range between 30–120 % of the baseline used in mode 1.

7.3 Key measurements

Where occupants are a principal source of indoor air pollutants, CO_2 levels are a useful indicator of stale air, and hence of poor IAQ [3]. The levels are expressed in parts per million, against a background ambient concentration around 400 ppm. In this study, CO_2 levels in room zones were monitored, as well as the time taken for zones to restore the background level, if indeed this occurred.

The air flow rate from the Healthbox (i.e. the total air extraction rate from the whole villa) was measured by the AHU itself as well as independently, downstream of it, using a separate Luvian unit.
Air flow at individual extraction ducts could be checked directly using a hand-held hot wire anemometer. The reliability of this device was uncertain however – a declared error of ±5 % was noted, but experimental error in addition is likely to have occurred.

7.4 Air monitoring equipment

A number of temporary LAQ air monitors were installed, alongside the building's own permanent devices, namely those at the AHU, sampling each air extraction duct.

The focus of the monitoring was on the downstairs double bedroom, as well as the adjacent kitchen. A floorplan is shown at Figure 7.2.

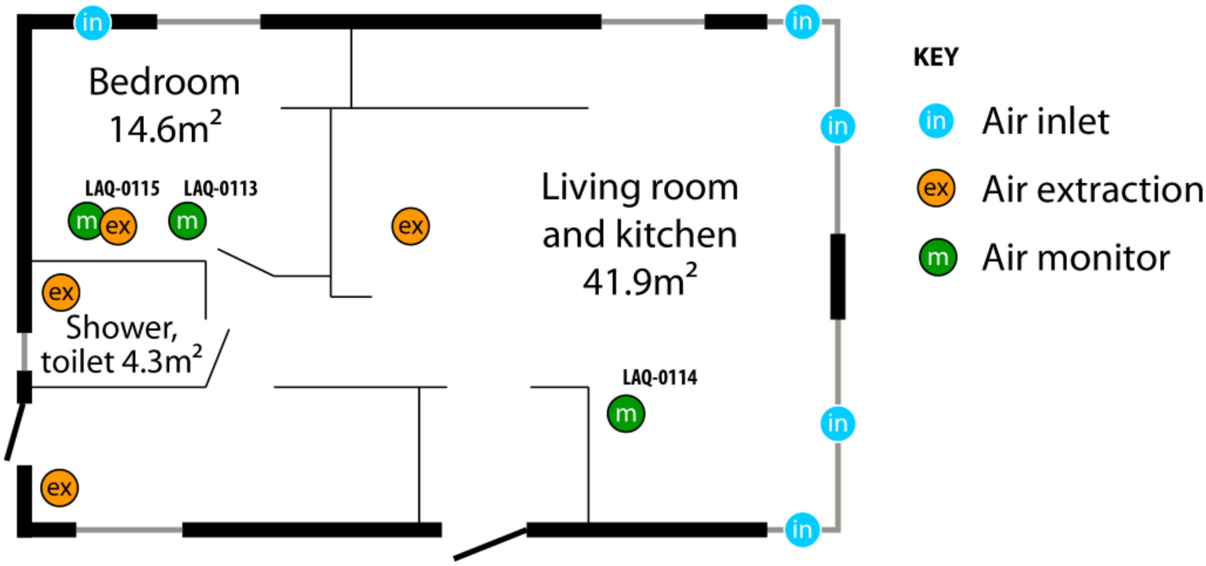

Figure 7.2 Plan of downstairs room layout showing main rooms, permanent air inlets, permanent forced air extraction points and location of additional Luvian air monitors used for the study, with LAQ identifying codes

The LAQs were mounted on tripods at one of two heights about the floor – 1.1 m in the living room, 0.6 m in the bedroom. Being mains-powered and tripod mounted, there was not complete freedom over where to site the Luvian units. The positions were selected based upon earlier work by Kruger [1] and advice received directly from RISE (the Swedish Research Institute). They were located away from sources of incoming air and at least 0.6 m from the nearest wall. Their setup is illustrated in Figures 7.3, 7.5 and 7.6.

The Healthbox (see Figure 7.4) recorded CO_2 ppm values plus the air flow rate for each of the zones. It also stored information about the total air flow and fan power rating, which applied to the entire building.

The LAQs were identified by a three-digit code, allocated by Luvian.

- LAQ-113 was always in the main bedroom at 0.6 m height above the floor.
- LAQ-114 was always in the living room, mounted on a 1.1 m tripod positioned near the sofa.
- LAQ-115 was used in two different locations, one in an upstairs bedroom and one as a second monitor (at 1.1 m elevation) in the main bedroom.
- Two further Luvian LAQ monitors were also in variable sites, allowing up to five readings including outdoor air characteristics.
- A separate Luvian device measured the overall exhaust air flow rate, downstream of the Healthbox outlet.

The air quality data was logged by the Healthbox and Luvian LAQ devices to their respective web servers, at intervals of either 5 or 10 minutes. The Luvian air flow monitor logged at 1-

minute intervals. Log files were downloaded for comparison within Excel, once the timings had been synchronised (the Healthbox adopts UTC as its time zone; the LAQ local time).

Figure 7.3 Luvian sensor on a tripod

Figure 7.4 Renson Healthbox air handling unit, with cover removed for access to connections

Figure 7.5 Luvian sensor in the kitchen/living room

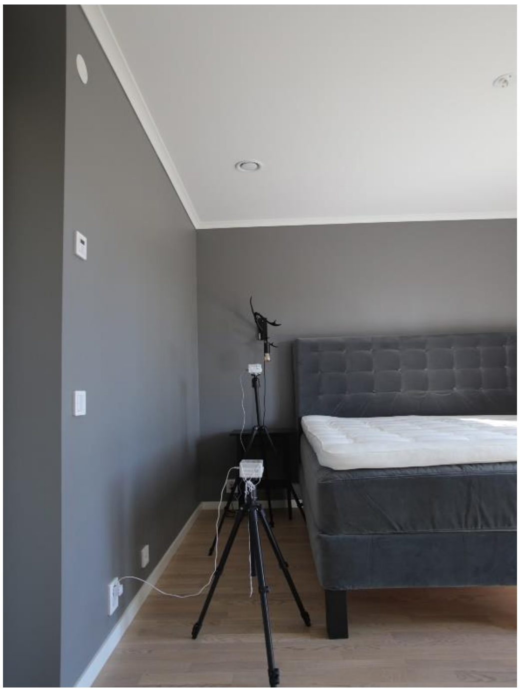

Figure 7.6 Luvian sensors standing at different heights in main bedroom. Ceiling exhaust duct visible above.

7.5 Building occupancy

The house was always occupied for testing between 1800 and 0800. Daytime occupation patterns were devised to replicate a 'weekday', with the house empty, and a 'weekend', with varying numbers of people present at intervals throughout the day.

On every experimental overnight except one, the bedroom had two occupants between approximately 2300 and 0600 hours, the actual times being noted. On most of the experimental nights, the house had four occupants, enabling the large two-storey open-plan kitchen and living room still to register noticeable carbon dioxide increases.
The occupants were adults between 23 and 44 years of age, with no reason to believe their CO_2 output rates were atypical.

7.6 General test procedures

Throughout the testing process, activity in the house that might influence IAQ was noted. Sources of CO_2 other than exhaled air were eliminated; all cooking and heating was electrical, and no candles were lit. External and internal doors were kept closed to minimise exchanges of outdoor air, and to ensure that managed ventilation was used to dissipate stale air.

7.7 Energy evaluation

Further data logging was carried out for heat pump energy consumption and external air temperature. Variability in weather conditions, and uncertainty about the operation of the underfloor heating, meant that this data could not be relied upon for useful energy calculations. Air volumes alone were used as proxy data.

8 Results and discussion

8.1 Presentation of data

The graphs that follow present the CO_2 concentration of the air (in parts per million) in monitored zones against time, for different zones, ventilation modes and periods of the day. Table 8.1 and table 8.2 show the key of each ventilation mode as well as the healthbox, and the LAQ-113, and LAQ-114 sensors that were installed in the downstairs bedroom and kitchen. Their precise locations are shown on the floorplan at figure 7.2.

Table 8.1 Ventilation mode key

Fixed 55 l/s	BBR Standard	Fixed 70 l/s	High-Low	Demand Controlled
Mode 1	**Mode 1b**	**Mode 1c**	**Mode 2**	**Mode 3**
Brown	Blue	Red	Orange	Green

Table 8.2 Device key

Healthbox	LAQ-113	LAQ-114
———	– – – – –	— • — • —

8.2 Indoor air quality

8.2.1. Bedroom overnight CO_2 levels

The key data measured overnight in the main bedroom under various ventilation modes was the level of CO_2 experienced in the room when two people slept inside for a number of hours, with the door closed. There were slight variations in the occupancy schedule, but the room was generally fully occupied between at least midnight and 0600 on every relevant night. A stable (equilibrium) level was typically apparent by 0400 hours.

Mode comparison

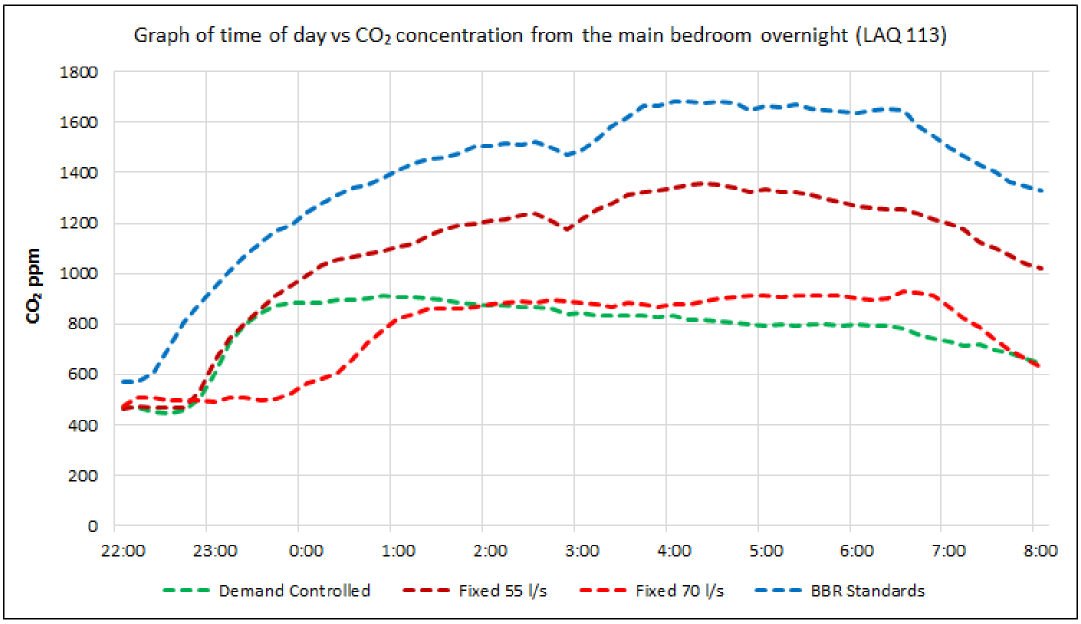

Figure 8.1 Overnight carbon dioxide level as detected by LAQ-113 under four ventilation modes.

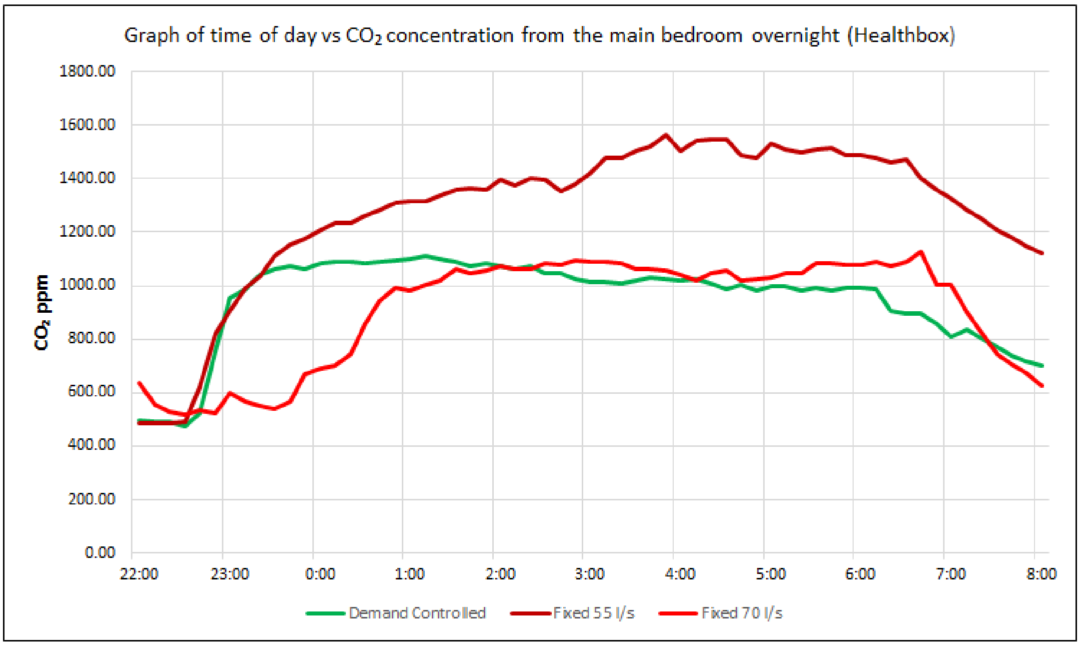

Figure 8.2 Overnight carbon dioxide level as detected by the Healthbox under three ventilation modes.

Figures 8.1 and 8.2 allow comparison between the modes, with data presented from LAQ-113 and from the Healthbox, respectively. Notes about each individual mode also follow.

It can be seen on both graphs, from fixed modes 1 and 1c (55 and 70 l/s), that higher ventilation rates caused the room to reach its equilibrium CO_2 level more rapidly, within 2 hours as opposed to 6 or more. That equilibrium level was also lower.

The contrast between mode 1 and 1b (the latter being the BBR standard) showed the IAQ benefit of removing exhaust air directly from zones that are occupied. The two modes exchanged almost identical volumes of air with the outdoors each hour (see Section 8.3.1). The BBR standard calls only for air extraction points in bathrooms, kitchens and utility rooms, to ensure no air movement from wet rooms into bedrooms. As there are no direct air inlets to the bathrooms (only from the rest of the house) and the Healthbox's background level of extraction would maintain negative pressure, air mixing out of bathrooms into bedrooms was not possible.

The air quality performance of the Healthbox under mode 3 (demand control) was broadly equivalent to mode 1c, i.e. the highest fixed ventilation rate tested.

Mode 1: Fixed 55 l/s

The bedroom was occupied at 2240 and the associated CO_2 was almost immediately detected by the Healthbox. There were two people in the room until 0630 (thereafter just one). The equilibrium CO_2 concentration at the height of the bed (i.e. as reported by LAQ-113) appeared to lie around 1,250 ppm.

A brief period around 0230 saw only single occupation. A dip in CO_2 at that time is visible on all the traces, representing the bedroom door opening and a brief exchange of air with the fresher conditions elsewhere in the villa.

Mode 1b: Fixed - BBR Standard

The occupation pattern was similar to mode 1, with bedtime at 2210 and a period of solo occupancy 0225–0245. The higher starting values shown here (compared to mode 1) are due to activity in the room around 2100, sealing up the Healthbox air outlet.

Note that no Healthbox CO_2 trace is available for this overnight, as the AHU was disconnected from the zone. A second Luvian monitor, LAQ-115 was deployed in the bedroom at 1.1 m height and vertically beneath the exhaust duct (see figure 7.6). Its readings were marginally higher than those from LAQ-113 throughout the night.

The equilibrium CO_2 level was noticeably higher during this period than any other mode. At roughly 1,650 ppm according to LAQ-113, the concentration was significantly above the

1,000 ppm CO_2 level at which it's accepted people may sense a general lack of fresh air. On waking (at 0610), one occupant reported having a headache.

Mode 1c: Fixed 70 l/s

The occupants went to bed between 2330–2400, with room preparations from 2300. They got up at 0630. All this detail is noticeable in the Healthbox data based on air at ceiling level; only a general trend can be discerned at the LAQ, 0.6 m above the floor. The benchmark CO_2 equilibrium was around 900 ppm.

Mode 3: Demand control

The room was occupied by two people from 2240, with one getting up at 0610 and the other at 0645. The equilibrium level settled around 800 ppm CO_2, the lowest of any of the modes.

The rapid rise in CO_2 concentration between 2240 and 2330 hours reflected the Healthbox's operational approach under demand control, in which it supplies background ventilation only (at 30 % of baseline, i.e. approximately 0.1 $l/s{\cdot}m^2$), until it detects occupation via an elevated level of CO_2. This threshold was set to 950 ppm, and its effect can be seen in the levelling out of the green DCV line around 2300 in the Healthbox trace, Figure 8.2.

8.2.2. Bedroom daytime refresh time

Weekday (unoccupied)

The following data series are focused upon the time taken for the main bedroom air quality to return to levels associated with a complete change of air, i.e. for the carbon dioxide level to approach that of the outdoor environment, 400 ppm.

The graphs that follow are presented from time zero (the start hour), which varied according to the day but was in effect the point at which the bedroom door was closed, and no sources of CO_2 were present. The approach was designed to reflect a 'weekday' scenario where all occupants leave home during work/school hours. Hence the maximum time period considered was 8 hours.

The level of CO_2 at each 'time zero' was not standardised. Much of the variation was due to the overnight conditions, which clearly influenced the initial air quality from which the recovery began. Notes and exceptions to this general rule are discussed below, under each individual mode.

Mode comparison

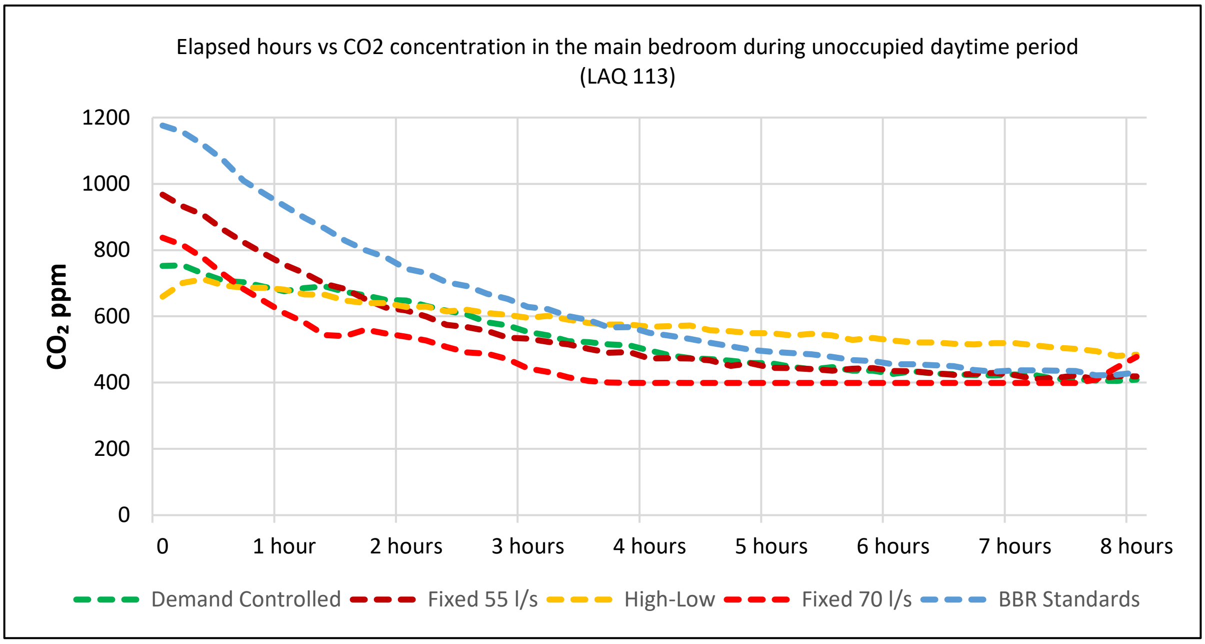

Figure 8.3 Unoccupied daytime carbon dioxide as detected by LAQ-113 under five ventilation modes.

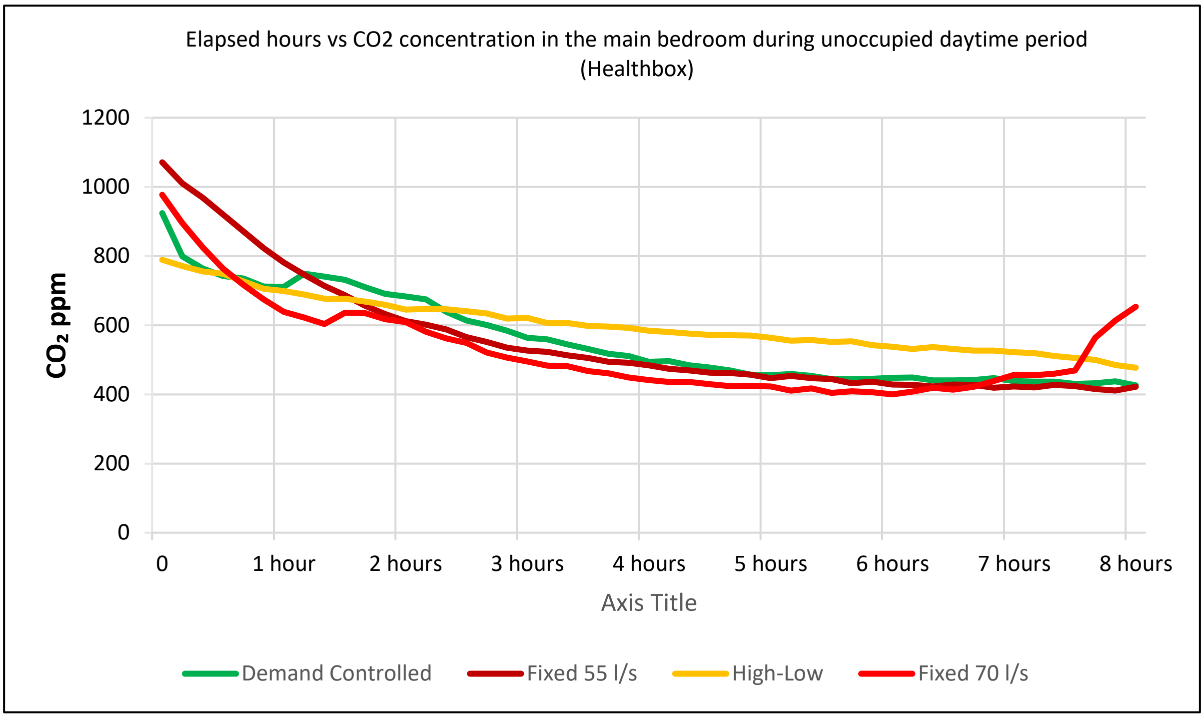

Figure 8.4 Unoccupied daytime carbon dioxide as detected by the Healthbox under four ventilation modes.

Figures 8.3 and 8.4 show no significant differences between the LAQ and Healthbox traces. Those contrasts were more prominent during periods of active occupation.

All modes – except for the stepped High-Low mode 2 – were able to reduce the indoor CO_2 close to outdoor levels within 5–7 hours.

Mode 1: Fixed 55 l/s

The two monitors – the Healthbox and LAQ-113 – showed a steady refresh process, with carbon dioxide at outdoor levels 6 hours after the room was left and the door closed.
As is evident in other traces, when the air became more refreshed, the Healthbox and LAQ values for CO_2 ppm approached each other. This provides some reassurance that the two different units were consistent in their evaluation of the air quality.

Mode 1b: Fixed - BBR Standard

No Healthbox trace was possible during mode 1b periods. Starting from a noticeably higher inherited concentration than mode 1, the bedroom did not quite reach background CO_2 ppm within the available 8-hour period.

Mode 1c: Fixed 70 l/s

The fixed high ventilation mode with no occupation shows a rapid restoration of outdoor CO_2 levels, within 5 hours. The small rise between hours 1 and 2 reflected a person briefly being in the room. The rise after 7 hours is due to people returning to the villa and using the bedroom.

Mode 2: High-Low (70 l/s - 20 l/s)

Mode 2 inherited a relatively low CO_2 concentration in the bedroom, 800 ppm by the Healthbox at time zero, compared to 1000 ppm in comparable mode 1c. Even so, the low ventilation rate used outside hours of occupation (0.13 $l/s{\cdot}m^2$) was not adequate to clear all the carbon dioxide from the room within the following eight hours. This is not necessarily problematic, as an evening uplift to high ventilation rate can still clear the room before bed-time. It is perhaps indicative of the minimum acceptable approach to indoor air quality.

Mode 3: Demand control

DCV was monitored both with a 'weekday' and a 'weekend' occupation schedule. The multi-mode graphs above use the unoccupied weekday data, for comparison with those other modes. Both schedules are presented below in Figure 8.5 and 8.6, just for DCV.

The weekday CO_2 pattern shows a reasonably straightforward reduction to ambient concentration within eight hours. The slight rise between hours 1 and 2 reflects a brief revisit of the room.
The weekend trace shows a very strong spike due to a group visit around lunchtime. The dynamic setting responded to the peak, but then returned to its lower setting around 1pm (hour 5) once the CO_2 dropped below 950 ppm. Although the IAQ continued to improve, it is clear that the low ventilation rate was not adequate in this slightly extreme case to completely clear the room air in the following five hours.

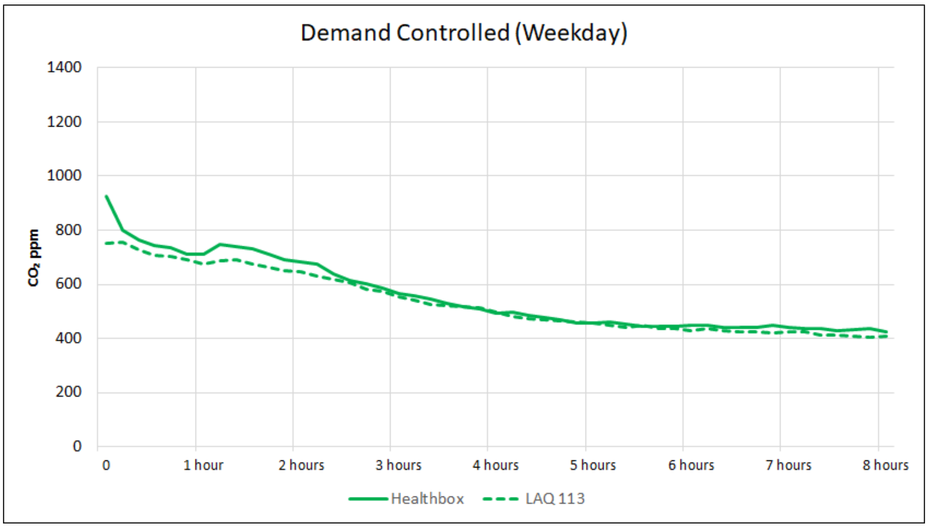

Figure 8.5 Graph of carbon dioxide concentration in main bedroom in unoccupied daytime weekday period, under DCV (mode 3).

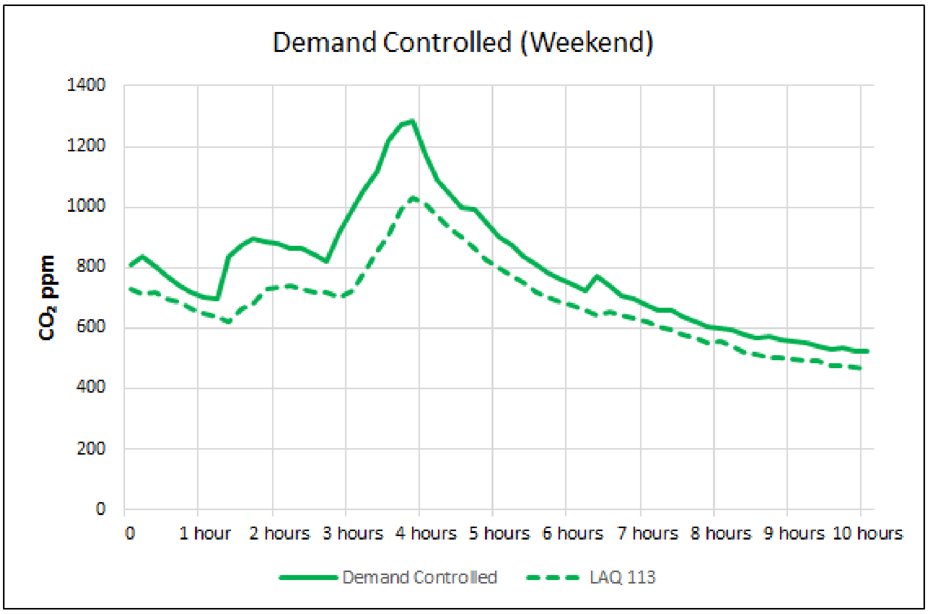

Figure 8.6 Graph of carbon dioxide concentration in main bedroom in partially occupied daytime weekend period, under DCV (mode 3).

8.2.3. Kitchen/living room overnight refresh time

The primary interest in this data was to evaluate the time for the Healthbox in each of two modes to lower the CO_2 level in the open plan kitchen and living room area, after the occupants went to sleep. Due to the occupancy schedule that was achievable, only two ventilation modes were evaluated: modes 1c and 3. Similar to the bedroom refresh time data, the graphs are presented relative to a variable start time at hour zero, for a period of six hours.

Mode 1c: Fixed 70 l/s

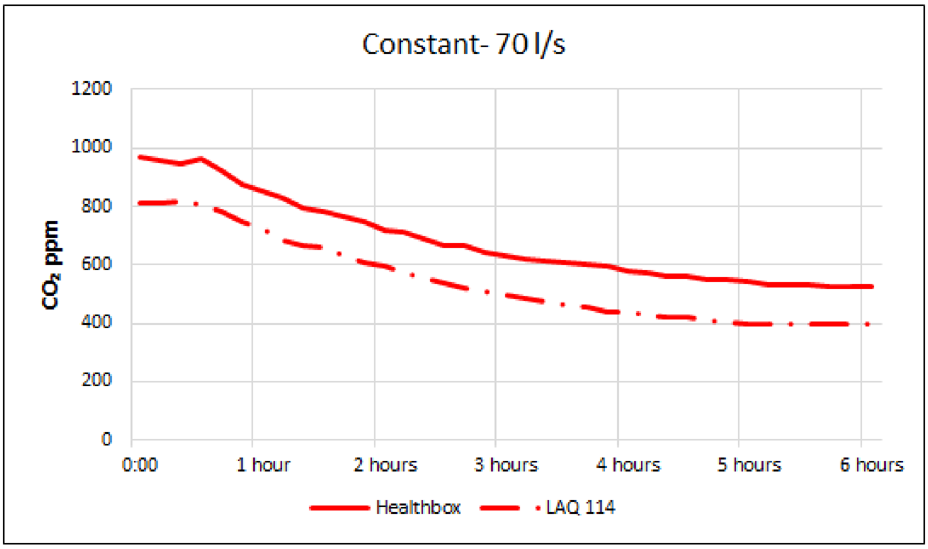

Figure 8.7 Graph of carbon dioxide concentration in kitchen/living room during unoccupied overnight period, under constant high ventilation (mode 1c).

Mode 3: Demand control

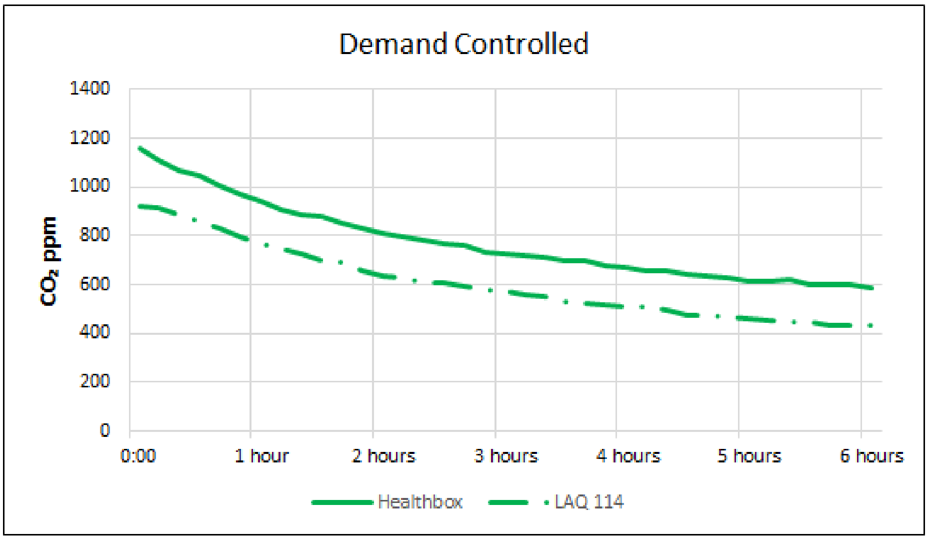

Figure 8.8 Graph of carbon dioxide concentration in kitchen/living room during unoccupied overnight period, under DCV (mode 3).

In both the mode 1c and mode 3 plots, the LAQ-114 trace reaches the 400 ppm CO_2 associated with outdoor air. It is unsurprising that the fixed high ventilation mode showed a faster reduction than the demand-controlled mode, as the latter reduced its extraction rate – potentially down to 30 % – after approximately 1.5 hours, when the Healthbox sensor picked up carbon dioxide concentrations below the 950 ppm threshold.

The location of the LAQ-114 monitor was several metres from the air extraction duct, and significantly closer to the window vents from where the room received its supply air. This may explain why the LAQ reported lower CO_2 concentrations than the Healthbox throughout both test periods. The large room air volume could be expected to exacerbate this potential effect.

It is curious however that they did not converge, as did the analogous bedroom readings (see Mode 3 in Section 8.2.2). Some redispersion of CO_2 from the adjacent bedroom was possible, through internal air paths such as the staircase, and this would have been registered at the Healthbox far more readily than at LAQ-114. But as the bedroom had its own extraction throughout both periods, that does not alone appear an adequate explanation.

The overall outcome, however, is that the Healthbox was seen to be reading higher than the room sensor, thereby avoiding any risk of insufficient ventilation.

8.2.4. Kitchen daytime CO_2 levels

Weekday (unoccupied)

All five ventilation modes were assessed for their effectiveness at refreshing the kitchen/living room air during the unoccupied daytime period associated with the 'weekday' occupation schedule.

As the test occupants departed at different times of day, the 'zero hour' approach was again adopted to compare the rate at which the indoor air quality improved towards outdoor air CO_2 levels.

Mode comparison

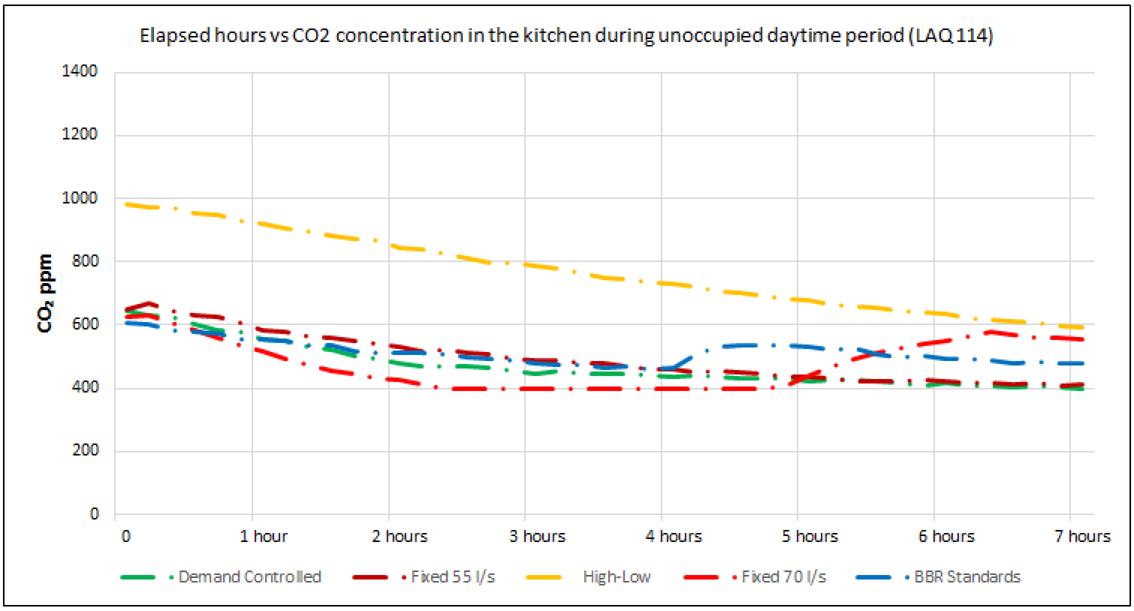

Figure 8.9 Unoccupied daytime carbon dioxide as detected by LAQ 114 under five ventilation modes.

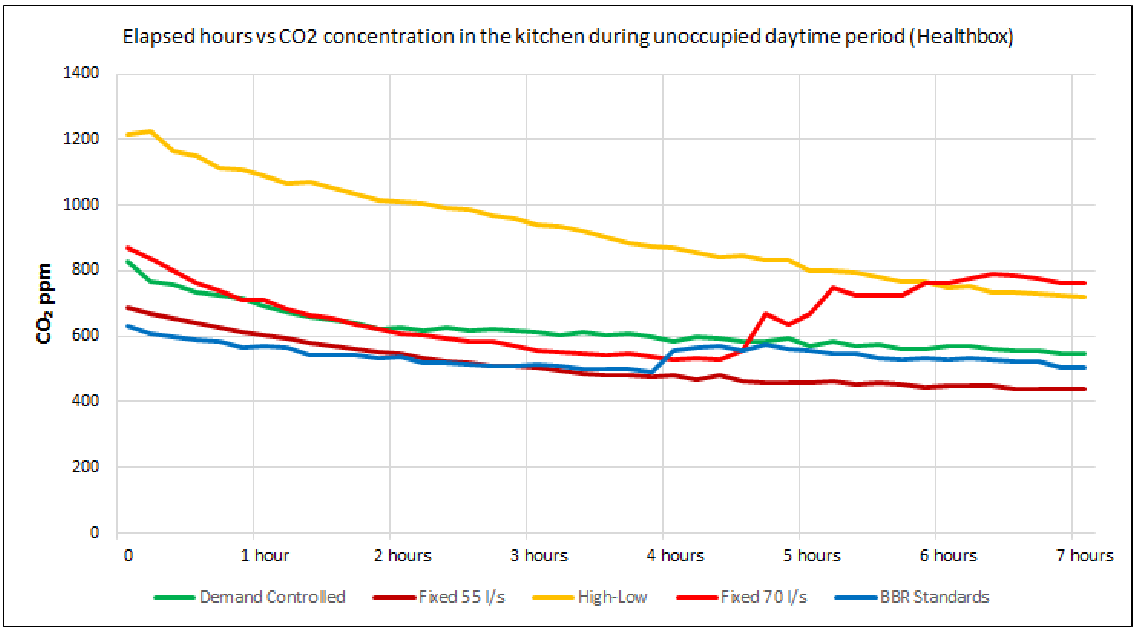

Figure 8.10 unoccupied daytime carbon dioxide as detected by the Healthbox under five ventilation modes

As the above graphs and the following notes outline, all modes were capable of refreshing the air to a significant extent within a period of 5 hours – except for the High-Low mode 2 (running in Low, as the villa was unoccupied).

While CO_2 is only one indicator of poor IAQ, a similar result was separately obtained from the main bedroom (see Section 8.2.2), suggesting that a decision to save energy by lowering ventilation rates during periods a home is empty should only be adopted after careful consideration. Doing so with a DCV approach or some other system that allows variable user input will be healthier and perhaps more comfortable for occupants than one that merely operates a fixed time schedule.

Mode 1: Fixed 55 l/s

The base case showed a simple gradual improvement (CO_2 reduction) with very little difference in the readings of the two different sensors. The background level was achieved in about 5 hours.

Mode 1b: Fixed BBR Standard

Under the BBR standard, the extraction that the bedrooms require is removed via other zones, specifically the kitchen and any wet rooms. Hence the normal (mode 1) kitchen air extraction rate, measured at approximately 10.5 l/s, was boosted to 14 l/s in mode 1b.
The difference in air refresh rate relative to mode 1 did not affect CO_2 significantly. The rise at 4 hours in the mode 1b graph was caused by three unexpected visitors who needed access to the villa.

The LAQ and Healthbox reported very similar CO_2 concentrations to each other during the test periods for modes 1 and 1b. This contrasted with the other modes (see below). The tests for 1 and 1b took place with warmer outside air temperature (+9ºC compared to around 0ºC) helping incoming air to mix when entering through window vents.

Mode 1c: Fixed 70 l/s

The traces from the constant high ventilation mode appear to show the LAQ-114 monitor reaching minimum before the third hour, with the Healthbox sensor continuing to drop for at least a further hour. The 7-hour test period was cut short by the occupants making an early return, at 4.5 hours in.

Mode 2: High-Low (70 l/s and 20 l/s)

The mode 2 (daytime low) ventilation mode started from a high CO_2 concentration, due to activity in the house before departure. The two sensors appeared to converge slightly over time, although neither levelled off within the 7 hours, probably due to that high start point.

Mode 3: Demand control

The demand control (mode 3) test showed a decline with two phases. The initial drop from 800 to 600 ppm CO_2 (as measured by the Healthbox) took 2 hours, at which point the trace suggests the Healthbox lowered its ventilation rate slightly, under its own algorithm.

By the LAQ monitor, the room was refreshed in terms of CO_2 within 6 hours, despite the drop in the air extraction rate. The difference between the two sensors' readings appeared to widen slightly over time.

8.3 Energy

8.3.1. Air flow

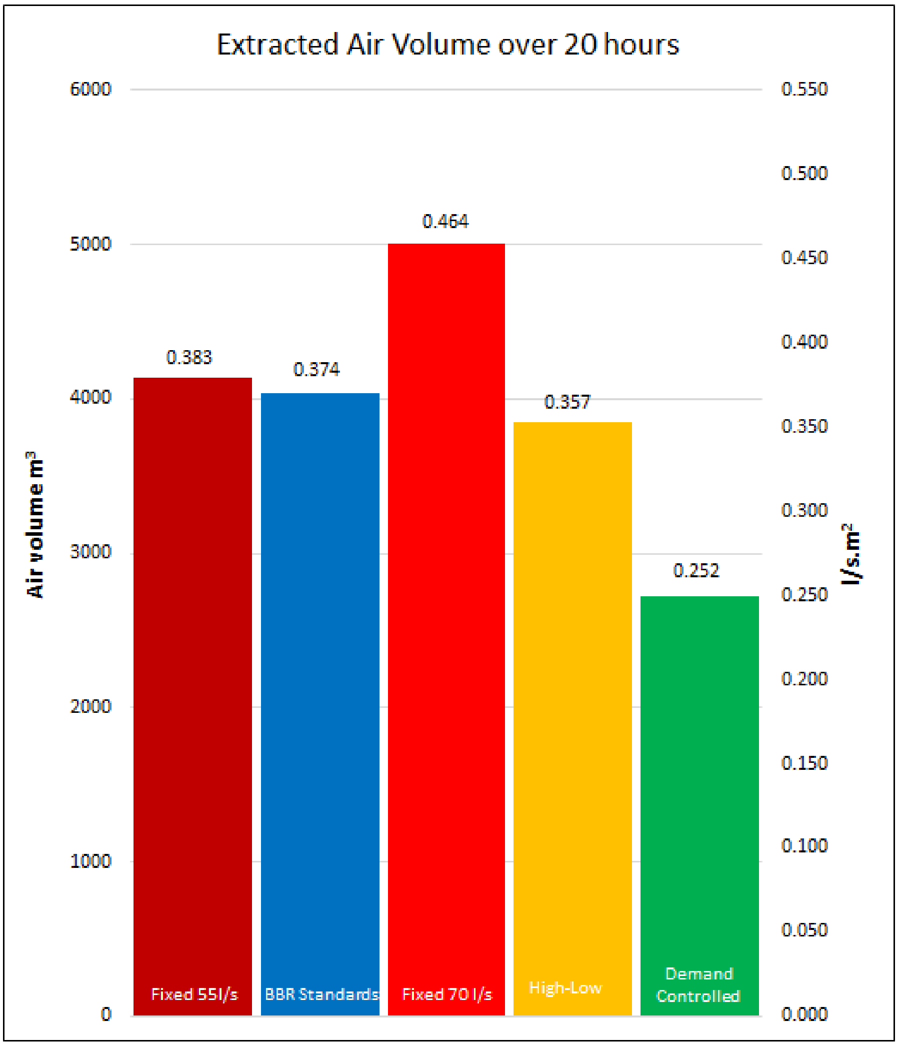

Figure 8.11 Measured air volume extracted from the whole villa in a 20-hour period (one test day) for each of five ventilation modes. Left axis m^3; right axis and bar cap labels equivalent $l/s \cdot m^2$

Total air flow for the whole villa was evaluated using a Luvian differential pressure flow monitor located downstream of the Healthbox AHU, and measuring the air from its outlet. Each ventilation mode was operated for approximately 24 hours, from 1800 overnight to 1800 the next day, but the analysis period for air volume was trimmed at the start and finish to avoid variation caused by recalibration of the Healthbox during changeover time. Hence air volumes extracted in the period between 2100–1700 were summed.

The values presented in figure 8.11 above are therefore not true daily totals. Setting aside the period between 1700–2100 will slightly understate the daily volume of air used by the High-Low and DCV modes (2 and 3) as mid-evening is likely to be an occupied period, and therefore require higher levels of ventilation, raising the average for those modes.

The graph presents the overall extracted air volume from the seven zones – i.e. the entire villa – for the 20 hours that each ventilation mode was selected. (The quality improvements or disbenefits each yielded are discussed earlier in this study.) The left axis presents the 20-hour total in cubic metres for each ventilation mode. The right axis, and the bar cap figures, provide the average air extraction rate from the house, in units of litres per second per square metre of floor area.

Mode 1 (fixed 55 l/s) and mode 1b (BBR standard) had the same nominal flow rate and differed only in where around the building air was extracted from. Hence their measured volumes were closely aligned at 4,140 m^3 and 4,042 m^3 (respectively) per 20-hour 'day'. Mode 1c (fixed 70 l/s) led to air change totalling 5,010 m^3, a 21 % increase over mode 1.

Mode 2 (high-low) was run according to a programmed schedule that saw the high level (70 l/s) used for 13 of the 20 hours and the low level for the remaining 7 hours. The total air volume extracted was 3,852 m^3, slightly below that for mode 1 and 1b.

The only approach that offered significant energy savings relative to the BBR standard (i.e. mode 1b) was the demand control used in mode 3, which extracted 2,726 m^3. During periods of occupation, each zone was ventilated quite strongly. It appeared that the air volume reduction (and therefore the energy saving) was made possible by a significant drop in air change rates in zones where no occupants or other sources of indoor air pollution were detected. The whole house equivalent ventilation rate was approximately 0.25 $l/s \cdot m^2$.
The net balance was a 32.5 % reduction in air extraction; achieved on a nominal 'weekend' schedule day, when there was some daytime occupation. Therefore, the saving could have been greater had the house been empty and the very lowest flow rates been deemed appropriate by the Healthbox's automated system.

8.3.2. Air volume energy considerations

The air volumes evaluated above have an associated energy cost, in terms of the heat required to restore thermal comfort by warming outside air back to the desired indoor level. Readings of the energy consumption of the ground source heat pump that was the villa's primary heat source were taken, but the building's time constant and thermal mass effects of the underfloor heating limited their usefulness. Sharp contrasts in weather conditions exacerbated the matter.
Ventilation energy losses can however be calculated from first principles, according to the equation:

$$Q = \rho \cdot Cp \qquad \text{(Eq. 8.1)}$$

where Q = heat energy per degree Kelvin of temperature gradient and cubic metre ($J \cdot K^{-1} \cdot m^{-3}$)

ρ = density of air ($kg \cdot m^{-3}$)

Cp = specific heat capacity of air ($J \cdot kg^{-1} \cdot K^{-1}$)

Assuming dry outdoor air at 0ºC and standard atmospheric pressure, ρ = 1.29 $kg \cdot m^3$ and Cp = 1,005 $J \cdot kg^{-1} \cdot K^{-1}$. Therefore, the heat energy requirement = 1.296 $kJ \cdot K^{-1} \cdot m^{-3}$

Further assuming an indoor setpoint of 21ºC, the temperature gradient becomes 21 K and the energy requirement 0.0076 $kWh \cdot m^{-3}$. Hence on a day when the outdoor temperature is 0ºC, the BBR standard (mode 1b) would lead to a ventilation energy replacement equivalent to 30.6 kWh in the measured 20 hours. Demand control is variable of course, but on the basis of this study, the comparable energy in mode 3 for the same duration would have been 20.6 kWh.

8.3.3. Fan electricity consumption

Measurements of the electrical load from the extraction fan in the Healthbox showed an extremely low amount of energy being consumed. Running the highest flow rate (mode 1c, fixed 70 l/s) required power of typically 15 W and therefore electricity consumption of less than 0.4 kWh in a 24-hour day. This is almost two orders of magnitude smaller than the energy demand for ventilation losses.

9 Conclusion

9.1 Indoor air quality

The results suggest that an exhaust air ventilation system under demand control is able to monitor and respond to IAQ characteristics in a manner that is beneficial to occupants.

Taking CO_2 as an indicator of overall air quality, no time periods were observed during which the Healthbox – running in dynamic operation (mode 3) – provided air quality that was worse than in a comparable fixed mode (1 or 1b).

When compared against the simple stepped high-low mode (2) – which is potentially an energy saving strategy – DCV was more effective at refreshing the indoor air in the monitored zones while achieving significant reductions in the total air volume exchanged with the outdoors.

Only the fixed high ventilation mode (1c) resulted in CO_2 levels similar to or better than under DCV. There was though a significant penalty in terms of heat losses, which the test occupants experienced more simply as cold temperatures and noticeable draughts.

9.2 Carbon dioxide readings

Two key measures of carbon dioxide were evaluated: the overnight equilibrium level in the main bedroom when occupied by two people, and the time taken (once unoccupied) for the room to return to background level.

There was an inconsistent but general trend for the Healthbox CO_2 reading for extracted air to be higher than that recorded by the LAQ devices in the same vicinity. This could be interpreted as an inaccurate over-reading or be due to the Healthbox sampling the stalest air in the room. That the trend was not consistent, and indeed that the differently sourced readings tended to converge as the room refreshed, suggest the latter is plausible.

The CO_2 data from the Healthbox appeared more granular than from the LAQ, with spikes visible in the Healthbox trace after just brief activity in the zone. This may be due to forced ventilation actively bringing the sample air to the sensor at the AHU, versus the LAQ relying on mixing and natural airflow.

It is reasonable to infer that the Healthbox unit is monitoring CO_2 in such a way that IAQ as experienced by the occupants is adequate or better at all times.

Taking the permanently installed LAQ in each zone as the basis for comparisons of carbon dioxide concentration, it is clear that the equilibrium parts per million level is strongly influenced by the air supply rate. Only the higher ventilating modes, 1c and 3, were able to keep CO_2 below 1,000 ppm, a widely accepted threshold for poor indoor air [1]. Mode 1b ventilation – in line with both Swedish regulations and most common practice – exceeded 1,600 ppm under comparable conditions.

The 'refresh time', i.e. the time for indoor CO_2 in the unoccupied bedroom to approach the outdoor level, showed some variation by mode, although the inherited starting value for CO_2 (the previous night's equilibrium level) was almost certainly a factor. At a practical level, a scenario in which people are away from the building for 8 hours merely requires that the air is refreshed by the time they return.

At that, all ventilation modes bar one performed acceptably. The energy saving High-Low mode 2 failed to reduce indoor CO_2 to the outdoor level in the 8-hour period, even though it was in fact running at a level slightly above the mandated BBR minimum of 0.1 $l/s{\cdot}m^2$. It appears that to opt for scheduled high-low ventilation rates based on periods of zero occupancy in a domestic property is likely to compromise air quality during periods of occupation as well.

9.3 Humidity and VOC

The study's monitoring systems were not designed to provide corroborated data for absolute or relative humidity, nor for levels of volatile organic compounds. The Healthbox reported both characteristics for the villa's bathrooms only.

Despite rain and snow during the study period, the generally cold weather meant absolute humidity in the outdoor air was low. In fact, the Healthbox showed an alert for low relative humidity in the bathrooms throughout. Anecdotally, when running in DCV (mode 3), it was noticeable that the AHU responded rapidly to toilet use. As CO_2 was not monitored for wet room zones, the key indicator for such a change was presumably the detection of increased VOCs.

9.4 Health effects

As previously noted, after a night's sleep exposed to the highest peak and equilibrium CO_2 level (mode 1c), one of the occupants reported waking with a headache. This cannot however be directly attributed to the IAQ.

9.5 Energy use

The programme of daily switching between ventilation modes allowed for only one full 24-hour period under each approach. For air volume measurements, the time window was trimmed to 20 hours, in order to avoid the transition periods. DCV demonstrated a clear reduction in air volume – made possible by reducing the flow rate in zones that were unoccupied. As noted, this air change reduction was achieved without a deterioration of IAQ.

The baseline volume (modes 1 and 1b) was around 4,100 m^3 of air extracted in 20 hours. DCV reduced this volume by 33 %. To achieve comparable IAQ with a fixed ventilation rate (mode 1c) required 22 % more air exchange than the baseline.

The thermal energy loss in a home with no heat recovery from exhaust air is approximately 1.3 $kJ \cdot K^{-1} \cdot m^{-3}$. The projected ventilation energy loss on a day with an outside temperature of 0ºC is 24.7 kWh. A 33 % saving by using DCV represents 8 kWh in a 20-hour period.

Energy usage by the Healthbox itself is insignificant by comparison. The maximum observed during the study was 0.4 kWh per day. By lowering fan operation levels (as evidenced by the overall air volume moved) DCV will reduce this figure, but even the maximum amount is trivial compared to the thermal energy ventilation losses.

9.6 BBR regulations

The findings suggest that the IAQ obtained when following the BBR standard can indeed be improved upon (in F-system, exhaust ventilation homes) by installing more sophisticated controls, coupled to ducting that allows variable extraction rates from occupied and unoccupied zones. The Healthbox is one such solution, but the fundamental requirement is an AHU – or independent fans – with the capacity to ventilate strongly only when and where there is need to do so.

The minimum ventilation rates prescribed under BBR extracted more air than did the Healthbox under DCV. By inference, the home might be expected to experience similar (or better) IAQ levels. This was not the case, although the study was not able to investigate whether this logic relied upon internal doors being left open. However, by testing the bedroom both with and without direct extraction (modes 1 and 1b respectively), some experience was obtained. Not extracting from the bedroom and keeping the door closed led to the highest overnight CO_2 levels of any ventilation mode tested. Closing a bedroom door prior to sleeping is arguably a normal behaviour in households, except perhaps families with young children. Previous work [11] in Swedish apartment homes suggested closing of doors made a difference, but that adequate IAQ could be achieved in either situation.

The findings imply that whole house ventilation rates are too simple a measure. The kitchen recovery time studies carried out showed that by around 0400 hours in the morning, ventilation of the living room was not replacing stale air with fresh; merely drawing in more outside air, cooling and desiccating the indoor environment. This would only generally be beneficial in conditions of summer overheating.

A further matter is the inability of the BBR guidance to accommodate in any way how the building is used. The number of people (and potentially house pets), their schedules of room absence/occupation and levels of activity, would all be expected to influence IAQ.

9.7 Experimental design

9.7.1. Study limitations

CO_2 as representative indicator

The focus of this study was upon indoor carbon dioxide. The LAQ air monitors available were not equipped to measure VOC levels, and a newly built and furnished house would not necessarily provide representative data in any case [4]. With regard to humidity, the study team made no use of the laundry and did only limited cooking, showering etc. Therefore, the IAQ impact was largely a reflection only of people's exhaled air, with its moisture and CO_2 characteristics. The weather was insufficiently cold or damp for condensation to become noticeable.

Measurement uncertainty

The contrast between CO_2 as detected by the Healthbox and by the LAQs was noticeable at times. The Healthbox always reported the same or a higher carbon dioxide level than the LAQ in the same zone. This may have been due to systematic variation between the two detector types. But as the readings did coincide, a rational interpretation is that the air at the point of extraction would be the most polluted in an otherwise largely airtight room.

There was also uncertainty about calibrating the air flow rates; the study team gave preference to the Luvian flow meter that had provided stable readings for a number of weeks, over a hand-held device that was known to exhibit variability.

Standardisation of occupancy

While the study team did its best to standardise periods of occupation and of indoor activity, this was not always practical, due in part to bus timetables and to the needs of other users of Dalarnas Villa. Significant variations were noted and are discussed where relevant.

The original intention had been to undertake both a 'weekday' and a 'weekend' test in all ventilation modes to which they were relevant. (On a 'weekend', mode 2 has no unoccupied low rate period, and is the same as mode 1.) Scheduling meant that not all permutations could be trialled for 24 hours. In addition, the 'weekend' periods were out of the control of the study team, with no direct records of the number of visitors, timings or activities.

Placement of LAQs

The study team had access to a number of Luvian LAQ air quality monitors which were placed around the villa in accordance with advice received directly and with literature precedent. There were occasions when it appeared stratification, poor mixing and/or strong convection airflows occurred. but this was not possible to ascertain. For example, three people who were sitting within 2 m of LAQ-114 in the living room for two hours registered a CO_2 level of just 843 ppm – perhaps due to the inflow air rate, or their relatively low respiration rate (static, watching a film), or due to their exhaled air rising rather than mixing in a cool room with a high ceiling.

An opportunity, recognised too late in the programme, would have been to cross-check the Healthbox's CO_2 sensor by placing an LAQ as close as physically possible to the extraction duct in the bedroom or kitchen. Both ends of the same pipe would have had their CO_2 level gauged by different sensor devices.

9.8 Suggested future work

9.8.1. Dalarnas Villa

A more advanced study, that attempted to monitor seasonal changes and sought a fuller picture of household activities and family life, would benefit from recording IAQ characteristics across CO_2, humidity and VOCs.

The experiment took place during the first year of the villa's commissioning. Accordingly, the VOC emissions from the furniture and house materials would be expected to be relatively high compared to a normal case, with an older property. Therefore, a further study in the future could investigate the correlation between each ventilation mode and the VOC dispersion behaviour.

An opportunity may also arise to examine IAQ and energy conservation in an FTX system that combines heat recovery with either fixed or demand-controlled ventilation.

9.8.2. Elsewhere

Other approaches to refining the BBR guidelines could be investigated, to identify possible adjustment factors relating to how a fixed ventilation rate (expressed as litres per second per unit floor area) might better serve the occupants as a balance between health, comfort and energy consumption. Such an investigation might expand the real-world usage of the home, to include sources of carbon dioxide and indoor pollution such as pets or the burning of candles.

10 References

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