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Research Project To Investigate Occupier Influence On Indoor Air Quality In Dwellings

21 August 2014

A8460492

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1. Research Outline

Overview

Indoor Air Quality (IAQ) in dwellings is important because people spend a substantial amount of time in their homes. The quality of the air that people breathe in their homes can therefore have a significant effect on their health and wellbeing. The air quality inside a building can also have an adverse effect on the building itself.

There is concern that in some instances indoor air quality in recently constructed dwellings can decline to levels that may be detrimental to the health of the occupants as well as to the construction of the dwelling. Poor indoor air quality is one of the main suspects driving the large increases in diseases such as asthma and allergies.

In 2011 the Building Standards Division (BSD) commissioned research to identify the effect that increasing air-tightness may have on air quality within dwellings [1]. This research concluded that the Domestic Technical Handbook guidance to Standard 3.14 on natural ventilation was fit for purpose down to an air-tightness level of 5 $m^2/m^3.h$ @ 50 Pa. The research did, however, assume that trickle ventilators and internal doors were all open, but did not consider when and why occupants interact with trickle ventilators and windows in dwellings.

These subjects were discussed in detail at a 'Ventilation Workshop' held by BSD in October 2013 which brought together representatives from academia, construction, architecture, building standards and social housing to discuss the issues pertinent to ventilation rates and indoor air quality. The outcome of this is that research on occupant interaction with the natural ventilation provisions in dwellings is required to inform when trickle ventilators and possibly windows are opened and closed and what motivates these actions. Additionally, it is important to know why natural ventilation equipment is available but it is not utilised by the occupants at all or only at limited times.

The conclusions from the workshop highlighted two issues that are presently unknown relating to the occupant use of natural ventilation equipment available within their dwelling. First and foremost is to investigate the frequency that dwelling occupants open and close trickle ventilators in the normal course of their daily lives, if they do open them at all. Secondly, when dwelling occupants do open and close trickle ventilators (or indeed windows) what is the trigger for this action?

The main aim of the study is to gather information on occupant use of natural ventilation and to relate this to indoor air quality. This requires fieldwork to a), gather quantitative data on occupant interaction with ventilation provision within the homes and b) undertake more detailed investigations into the effects on indoor air quality.

[1] BRE (2012). The effect that increasing air-tightness may have on air quality within buildings. http://www.scotland.gov.uk/Resource/0040/00402329.pdf accessed 1/6/14

This project was commissioned by Building Standards Division (BSD) in December 2013 and was undertaken between December 2013 and May 2014.

Work Packages

The work packages were as follows:

WP1 Project setup and literature review. This provides an understanding of the current context relative to national and international regulation, policy, case studies and academic papers on the implications of increased air tightness in dwellings. The review provides a contemporary understanding of the issues and draws a significant body of evidence that the team has obtained through related research projects and findings of work on internal air quality.

WP2 Overview Survey. This was a survey of 200 homes conducted between January and March 2014 to gather information on the use of trickle ventilation and window opening. The project identified candidate addresses for the survey, from partner organisations, Building Standards departments and other contacts in the field. A professional survey company, Research Resource, conducted the doorstep survey, with the surveyors being briefed and trained by the project team. The survey was also used to identify locations for follow-up sample monitoring.

WP3 Sample Monitoring. The overview survey has identified 40 houses for a follow-up survey. For logistical reasons these were confined geographically, but included representation of ventilation strategies identified in WP2. This survey required access to the houses, with a more detailed survey and includes a checklist of observations (e.g. window condition, trickle opening use, occlusion of openings, etc)., photographs of ventilation issues, etc. Environmental monitors that record temperature, humidity and CO_2 were left in place for a 24-48 hour period. This monitoring took place between February and May 2014.

WP4 Detailed Monitoring. This section of the project has accessed data being gathered from ongoing studies funded through the Technology Strategy Board Building Evaluation Programme. This includes more detailed longitudinal information about ventilation and also undertook sample monitoring of IAQ. A specific week long period of monitoring was undertaken in February 2014, during which detailed information was collected through occupant diaries on occupancy, heating and ventilation habits was undertaken.

WP5 Analysis and report production. On completion of all three assessment methodologies analysis of the findings was undertaken and formed the basis of the following report.

2. Literature Review

Sources and scope of Literature review

There are several primary sources of research into Indoor Air Quality (IAQ). The International Academy of Indoor Air Sciences (now renamed as the International Society of Indoor Air Quality and Climate [2] was founded in 1992 and has organised 18 international conferences each producing over 5 volumes of research papers. Although this represents a substantial and comprehensive body of work, much of the specific data is tangential to the unique aspects of the Scottish climate in combination with the construction techniques now prevalent (timber frame with polythene vapour barriers). The United Kingdom Indoor Environments Group [3] has also been active since 2003.

The scope of the literature review covers the following points:

- The role of CO_2 as a marker for IAQ
- The relationship between CO_2, health, and ventilation
- CO_2 levels and airtightness of construction
- Non CO_2 pollutants and IAQ
- Guidelines for IAQ
- Studies examining occupant interaction with ventilation

The role of CO_2 as a marker for IAQ

There are many studies in which CO_2 is being used as an indicator of ventilation rates and IAQ. As CO_2 is emitted by metabolic processes of humans, levels of CO_2 correlate well with human occupancy and human-generated pollutants, but may be unrelated to pollutants not related to occupancy, such as off-gassing from building materials, carpets and furniture and can be produced by non-metabolic processes e.g. gas cooker hobs; portable liquid petroleum gas (lpg) heaters, and candles.

CO_2 is present in the outside air at concentrations between 350 and 575 ppm (0.035 and 0.057%) together with O_2 (21%) and N_2 (79%). When people breathe they absorb atmospheric O_2 into the bloodstream to fuel the body's metabolic processes, and CO_2 and H_2O are exhaled. The level of CO_2 in exhaled breath is around 3.6 – 4.3% (36,000 – 43,000 ppm), H_2O around 6% and $O_2$15%[4] [5].

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[2] www.isiaq.org

[3] www.ukieg.org/

[4] Hasselar E. (2006) Health Performance of Housing Indicators and Tools, Delft University Press. Sustainable Urban Areas Series.I ISBN 10: 1586036890 / ISBN 13: 9781586036898 (pdf free download from Delft University repository

[5] Hasselar E. et al. (2006) How Healthy Is The Bedroom? Healthy buildings , HB 2006, Lisboa, 4-8 june 2006, Vol I, p 185-188

CO_2 was historically viewed as a naturally occurring environmental substance and therefore not included in lists of environmental pollutants in normal situations[6 7 8]. Humans are the primary source of CO_2 in the indoor environment and are also a source of heat, moisture (H_2O), smells and other bio-emissions which can influence perceived indoor air quality. This common source with other people-generated emissions is a clear and direct link, and CO_2 is a useful proxy for these human sourced elements of indoor air quality. CO_2 levels set at 1000 ppm in communal areas such as offices and schools have been set as indicators of sufficient per person ventilation rates to provide perceived good indoor air quality and counter the human sourced emissions including moisture [9 10]. (Note: the moisture content of the indoor air, calculated from relative humidity and temperature, can also be a useful indicator for per person ventilation rates.) This metabolic production of CO_2 by humans (and other animals) naturally leads to higher than background CO_2 concentrations. Where humans are present, the CO_2 concentration level depends on the number in a given area, their activity level, and the rate at which the local air is diluted and replaced by fresh air (ventilation rate).

CO_2 does not have the same simple relationship with pollutants from non-human sources. There are numerous non-human sources for pollutants impacting on IAQ, these sources include building materials, furnishings, cooking, cleaning and electrical products [11 12].

Low CO_2 concentrations do not necessarily ensure good IAQ where there is an alternative source generating indoor pollution. A recent Californian study found low CO_2 levels in conjunction with dangerously high levels of formaldehydes [13].

While the relationship is less direct for non-human pollutants, where occupancy rates and non human pollutant emission rates are known or can be assumed to be at some standard rate, then CO_2 levels can be used to indicate relative levels of ventilation and as a proxy for non-human pollutant levels.

Therefore, in the context of concerns over ventilation rates, CO_2 measurements can provide a useful indicator of ventilation rates and their use in this study has allowed a comparative analysis across a number of dwelling types.

The relationship between CO_2, health, and ventilation

There is a general acceptance that CO_2 keeps ‘bad company’ and that levels above 1000 ppm are indicative of poor ventilation rates. The provenance of this is well

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[6] Crump D et al. (2001), BR 450: A protocol for the assessment of indoor air quality in homes and office buildings

[7] Coward S K D et al. (2001), BR 433: Indoor air quality in homes in England

[8] WHO. (2010), WHO guidelines for indoor air quality: selected pollutants, ISBN 978 92 890 0213 4

[9] BS EN 15251:2007 (2007)

[10] ASHRAE 62.2 FAQs (2014) http://waptac.org/Additional-Pages/FAQ-ASHRAE-62002E2.aspx (accessed 23/02/2014)

[11] EU EnVIE (2006) WP3 Technical Report: Characterisation of spaces and sources.

[12] Project no. SSPE-CT-2004-502671. http://www.envie-iaq.eu/ (accessed 15 apr 14).

[13] Offermann, F. J. (2009). California Energy Commission: Ventilation And Indoor Air Quality In New Homes

evidenced [14] and corresponds well with a ventilation rate of 8 l/s per person[15] (Figure 3). This figure is also relevant in comparison with the findings of a review of the literature looking at the associations between ventilation rates and CO_2 levels with health outcomes which concluded "Almost all studies found that ventilation rates below 10 l/s per person in all building types were associated with statistically significant worsening in one or more health or perceived air quality outcomes" [16]. Associations between health and CO_2 levels have been found in office buildings [17] and a study by Batterman and Peng [18] identified associations between CO_2 levels and total volatile organic compounds (TVOCs). A recent paper by Wargoki identified associations between CO_2 levels and health and concluded "The ventilation rates above 0.4 h-1 or CO_2 below 900 ppm in homes seem to be the minimum level to protect against health risks based on the studies reported in the scientific literature." [19].

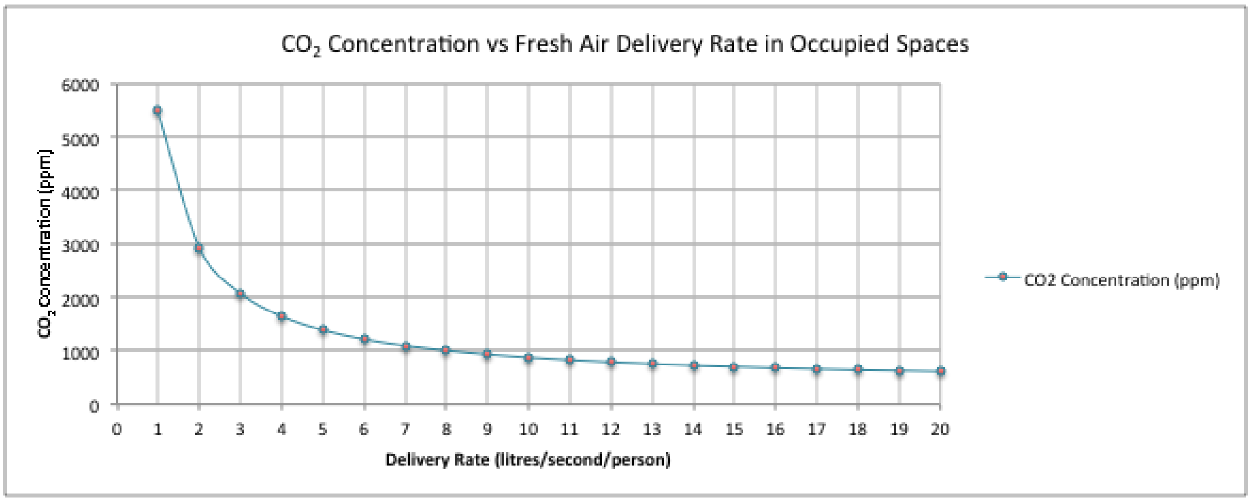

Figure 1: CO_2 vs. delivery rate.

Both the CIBSE [20] and ASHRAE [21] recommendations for ventilation rates are based on or around this level that equates to a minimum air supply rate of 8 litres per second per

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14 Porteous, CDA (2011). *Sensing a Historic Low- CO_2 Future*, Chemistry, Emission Control, Radioactive Pollution and Indoor Air Quality, Dr. Nicolas Mazzeo (Ed.), ISBN: 978-953-307-316-3, pp 213-246 InTech, DOI: 10.5772/16918

15 Appleby A. Ch. (1990) C1 *Indoor Air Quality and Ventilation Requirements. In Buildings and Health, the Rosehaugh Guide to the Design, Construction, Use and Management of Buildings*, London: RIBA Publications Ltd., 176 in pp.167-193.

16 Seppänen, OA Fisk W. J., Mendell M. J.. (1999) *Association of ventilation rates and CO_2 - concentrations with health and other responses in commercial and institutional buildings*. In Indoor Air 1999; 9: 226-252

17 Erdmann, CA; Steiner, KC; Apte, MG. (2002) *Indoor Carbon Dioxide Concentrations And Sick Building Syndrome Symptoms In The Base Study Revisited: Analyses Of The 100 Building Dataset*. In: Indoor Air 2002- 9th International Conference on Indoor Air Quality and Climate p.443-448 ISBN: 978-0-9721832-0-8; 0-9721832-0-5

18 Batterman, S., Peng, C.,(1995). *TVOC and CO_2 concentrations as indicators in indoor air quality studies*. American Industrial Hygiene Association Journal 56, 55–65.

19 P. Wargocki (2013) ibid

20 CIBSE, (2011) KS17, Indoor Air Quality and Ventilation., ISBN 9781906846190

person (circa 29 m^3/hour). In practice there appears to be a general consensus that concentrations up to 1000ppm represent no measurable threat to occupant health as no physiological effects are evident other than perhaps minor changes to respiration rates.

A paper addressing this issue was published by ASHRAE in 2001 [22]. This paper points out that CO_2 has long been used as a basis for ventilation design and control. CO_2 is a natural product of human respiration whose rate can be predicted based on an occupant's age and activity level. The key point made by the authors, is that the CO_2 level is a good surrogate for human emitted bio-effluents (i.e. odours) that are considered undesirable for overall human comfort. CO_2 is thus a proxy for levels of other bio-effluents that cause odours and are likely to be viewed as unacceptable in an olfactory sense, not because their presence is necessarily a direct health hazard. In an environment that does not contain other toxic compounds that may have off-gassed from furniture and fittings (formaldehyde etc.) the main objection is thus one of 'stuffiness'. Where this 'stuffiness' is also indicative of high relative humidity it is likely to stimulate the growth of bacteria and facilitate disease transmission.

Where non-people and people related emissions are consistent, then CO_2 concentrations can be used as a good indicator of indoor air quality. Where there are sources of other pollutants, such as gaseous pollutants, volatile organic compounds and particulate matter, these are also likely to be found in concentrations that increase linearly with CO_2 and/or temperature. A study in Korea [23] using multivariate analysis found that increases of indoor CO_2 concentrations as low as 564 ppm (mean value) were associated with wheezing attacks in children with a history of asthma. The study did not claim that CO_2 was the cause, simply that raised CO_2 levels may be considered a good surrogate for concentrations of other indoor pollutants. Increased respiration rates will result in the inhalation of greater volumes of airborne allergen burdens. A study of an office building in Beijing by Wang [24] where 98.7% of occupants reported one or more physiological symptoms considered to be signifiers for sick building syndrome (SBS), found that CO_2 concentrations between 700 and 1000ppm were associated with the build-up of a range of volatile organic compounds now commonly found in indoor environments across the developed world.

While CO_2 has been primarily identified as an indicator for human generated pollutant levels and per person ventilation rates, at high enough concentrations CO_2 can be a serious health hazard and can lead to death. Much work on this has been carried out with the aim of setting safe exposure levels over short or long timeframes driven by the need to maintain healthy and safe atmospheres in aircraft, submarines, and spacecraft

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[21] ASHRAE, Standard 62.1 (2013) Ventilation for acceptable indoor air quality

[22] Schell, M., Dan Int-Hout, (2001) *Demand Control Ventilation Using* CO_2 *.* ASHRAE Journal,. February (2001): 18-29

[23] Kim CS, Lim YW, Yang JY, Hong CS and Shin DC, (2002) Effects of Indoor CO_2 Concentrations on Wheezing Attacks in Children, Indoor Air, The International Academy of Indoor Air Sciences, Monterey, July 2002, Vol I, pp492-497

[24] Wang Li JI and Zhao CY, (2002) A case of sick building syndrome caused by incorrect ventilation design of the tight building, Conference Proceedings, Indoor Air, The International Academy of Indoor Air Sciences, Monterey, July 2002, Vol IV, pp490493

where the scrubbing of air to control CO_2 levels comes at a significant cost [25]. The 1000 days exposure limit set for both submarines and space station is 5000ppm. This level is stated to have been set based on a precautionary principle and because of "anecdotal reports that some ISS crew members exhibit behavioural changes when concentrations exceed 0.5%". More recently there has been work exploring the impact of CO_2 on public health driven by the possibility of CO_2 escapes from carbon capture and storage schemes in the UK and elsewhere. The UK Health and Safety Executive published a carbon capture related report in 2011 stating that severe health problems will occur for 60 minutes exposure to 63,000ppm, and 50% fatality would be observed at 84,000ppm [26]. A US review carried out by Rice into long term exposures highlighted reported issues at 8,500 to 15,000ppm including reduced lung capacity and increased blood pressure [27]. The same review highlighted reported increase in renal calcification in animals at 3000ppm.

These findings are at odds with more recent studies, which have reported some change in mental test performance at significantly lower CO_2 levels. Several studies in schools have reported poorer performance by pupils in cognitive tests at CO_2 levels above 1000ppm[28] [29]. These studies don't explicitly identify CO_2 as the cause of this change in mental performance but rather identify low ventilation rates as a potential problem.

A recent study reported by both Satish et al [30], and Fisk et al [31] does however identify CO_2 directly as the cause of changes in mental state leading to a change in decision making ability at levels as low as 1000ppm. This study performed 9 mental ability tests on the same subjects in controlled CO_2 concentrations of 600, 1000 and 2500 ppm and found that at the elevated CO_2 levels performance on 6 of the tests was significantly degraded. The change in mental state observed with increased CO_2 above outdoor levels is not yet well understood with the authors stating further study is required. The results of this particular study appear to re-enforce the 1000 ppm limit set for indoor air quality in school or office environments and possibly suggest even lower limits. Whether

[25] James J. T et al. (2009). Carbon Dioxide – Our Common "Enemy". NASA Technical Reports. http://ntrs.nasa.gov/search.jsp?R=20090029352 (accessed 15apr14)

[26] *HSE (2011)* Assessment of the major hazard potential of carbon dioxide (CO2) http://www.hse.gov.uk/carboncapture/assets/docs/major-hazard-potential-carbon-dioxide.pdf (accessed 15 apr 14)

[27] Rice S. A, (2003). Human health risk assessment of CO2: Survivors of acute high-level exposure and populations sensitive to prolonged low level exposure. Third Annual Conference on Carbon Sequestration 7 May 3-6, 2004, Alexandria, Virginia, USA.
www.netl.doe.gov/publications/proceedings/04/carbon-seq/169.pdf (accessed 15 apr 14)

[28] Chatzidiakou L et al. (2012). What do we know about indoor air quality in school classrooms? A critical review of the literature. Intelligent Buildings International Vol. 4, No. 4, October 2012, 228–259

[29] *Coley et al. (2004). The Effect Of Low Ventilation Rates On The Cognitive Function Of A Primary School Class. IJV Volume 6 No 2 Sept*

[30] *Satish U et al. (2012). Is* CO_2 *an Indoor Pollutant? Direct Effects of Low-to-Moderate* CO_2 *Concentrations on Human Decision-Making Performance. Environmental Health Perspectives - Volume 120, number 12, December 2012*

[31] *Fisk W J, Satish U et al (2013) Is* CO_2 *an Indoor Pollutant? Higher Levels of* CO_2 *May Diminish Decision Making Performance. LBNL 6148E*

elevated CO_2 alters brain physiology or is acting as a social cue for sleep or relaxation / reduced alertness is unclear.

The latest guidance from ASHRAE member organisations supports the translation of the 1000 ppm limits to housing both for living areas and for master bedrooms [32] thus 1000 ppm levels would appear to be justified.

CO_2 levels and airtightness of construction

The airtightness of the UK building stock has been characterised by various researchers, notably BRE [33] [34] [35] and Leeds Metropolitan University [36].

In terms of the airtightness the historical trend has been characterised by age of construction up to 1994 in BRE report BR 359 [37], UCL have characterised the effect of replacement windows [38] [39], Hubbard reported on the performance of heritage buildings [40], and LeedsMet have reported on post 2002 and post 2006 dwellings [41]. The airtightness is characterised in values of air change rate measured by blower door test at 50 Pa.

In summary the pre-2002 stock has a mean value of 12 $m^2/m^3.h$ @ 50 Pa with a wide spread between 2 and 22, post-2002 has a mean value of 10 with a spread between 4 and 14, post 2006 has a mean of 6 with a spread between 1 and 12. Post 2010 results would be expected to be tighter than the post 2006 stock. A subset of the data summarised here is shown in figure 2.

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[32] *ASHRAE 62.2 FAQs (2014) http://waptac.org/Additional-Pages/FAQ-ASHRAE-62002E2.aspx (accessed 23/02/2014)*

[33] Stephen, R. K. (1998) Airtightness in UK Dwellings: BRE's Test Results and Their Significance. BRE Report 359. Garston, Watford, Building Research Establishment.

[34] Stephen, R. K. (2000) Airtightness in UK Dwellings. BRE Information Paper IP 1/00. Garston, Watford, Building Research Establishment.

[35] Grigg, P. (2004) Assessment of Energy Efficiency Impact of Building Regulation Compliance. A Report Prepared for the Energy Savings Trust/Energy Efficiency Partnership for Homes. Client Report Number 219683, Garston, Watford, Building Research Establishment.

[36] Wingfield, J. Bell, M. Bell, J. & Lowe, R. (2006) Evaluating the Impact of an Enhanced Energy Performance Standard on Load-Bearing Masonry Construction – Report Number 5 – Post-Construction Testing and Envelope Performancet – Lessons from Stamford Brook: Understanding the Gap between Designed and Real Performance, PII Project CI 39/3/663, Leeds, Leeds Metropolitan University.

[37] Stephen, R. K. (1998) Airtightness in UK Dwellings: BRE's Test Results and Their Significance. BRE Report BR 359. Garston, Watford, Building Research Establishment.

[38] T Oreszczyn, D Mumovic, I Ridley and M Davies. The Reduction in Air Infiltration due to Window Replacement in UK Dwellings: Results of a Field Study and Telephone Survey

International Journal of Ventilation ISSN 1473-3315 Volume 4 No 1.

[39] I Ridley, J Fox, T Oreszczyn and S H Hong. The Impact of Replacement Windows on Air Infiltration and Indoor Air Quality in Dwellings. International Journal of Ventilation Volume 1 No 3.

[40] Diane Hubbard. (2011). Ventilation, infiltration and air permeability of traditional dwellings. Journal of Architectural Conservation. Volume 17, Number 3

November 2011

[41] http://www.leedsmet.ac.uk/teaching/vsite/low_carbon_housing/airtightness/housing/housing.pdf

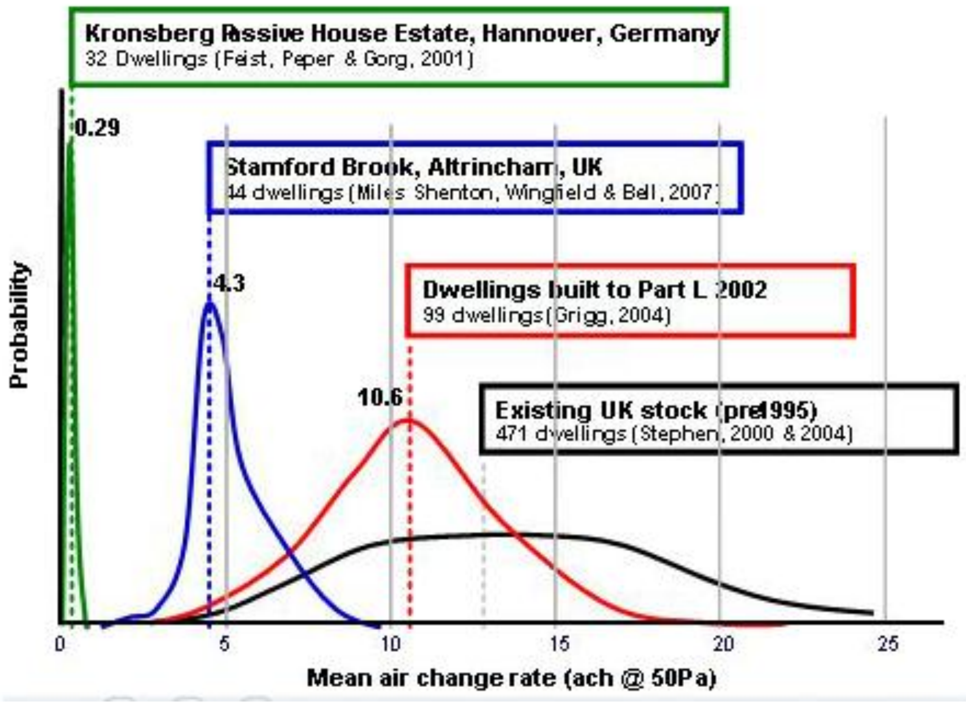

Figure 2: A sample of airtightness measurements for UK stock (after Leeds Met).

A CO_2 and infiltration rate calculator developed for this project can be used to investigate the impact of different airtightness of construction on CO_2 levels where some standard assumptions are made on occupancy and building geometry. Figure 3 shows the derived relationship between bedroom CO_2 making simplifying assumptions i.e. assuming a typical geometry, 2 person occupancy, doors and window vents closed tight. In this case the CO_2 levels are dependent on the infiltration which is in turn measured by the 50Pa blower door test. The calculations are simplified and based on a standard set of specific assumptions but clearly illustrate the non-linear effect leading to higher CO_2 levels with increased levels of airtightness and associated reduction in air infiltration.

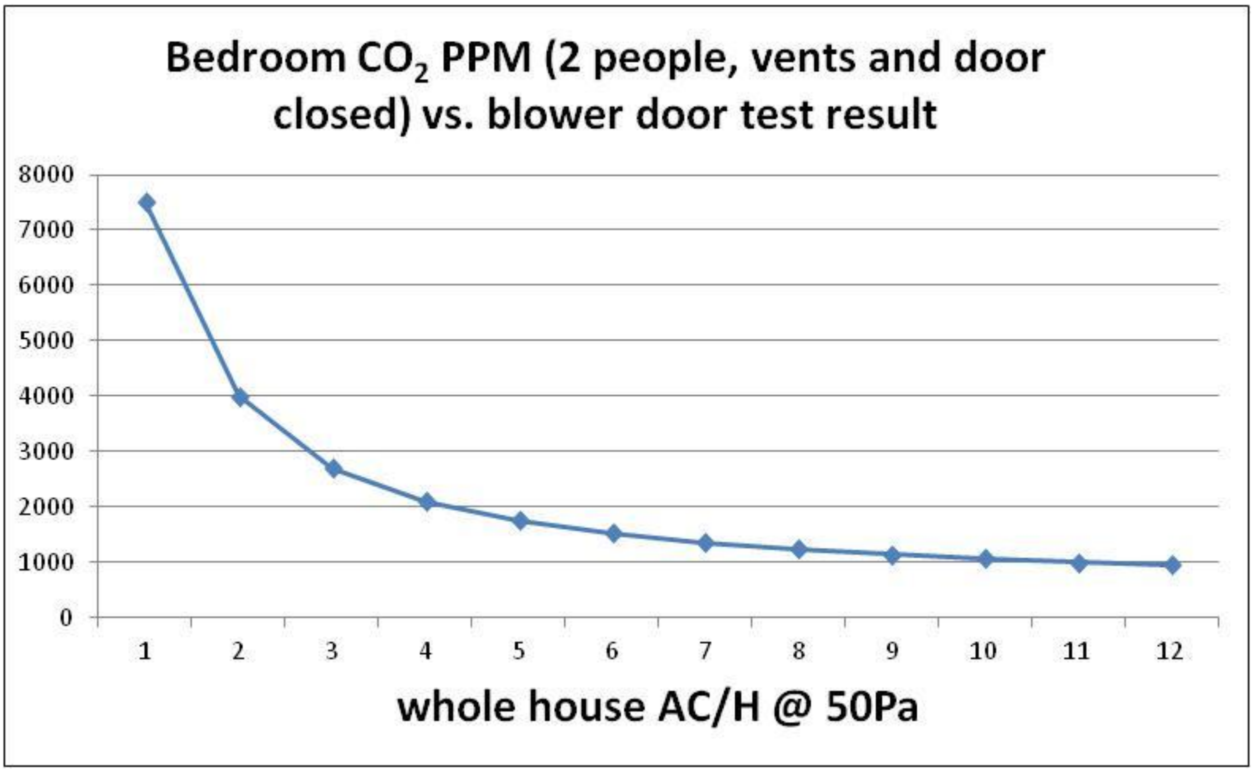

Figure 3: CO_2 vs. airtightness.

In this case the CO_2 ppm levels are dependent on the infiltration rate which is in turn measured by the whole house AC/H @ 50Pa as determined by a blower door test.

Non CO_2 pollutants and Indoor Air Quality

Indoor air in the modern dwelling house can contain a complex array of both naturally occurring and synthetic compounds, particulates and gases, as well as microbes and endotoxins. Reducing ventilation rates will increase the concentrations of such pollutants, whether they are off-gassing from building components, fittings or fixtures, being generated by biological sources, or are a result of occupant behaviour. The trend to make dwellings 'tighter', driven by energy efficiency concerns, could be producing a more toxic indoor environment with potential long term, insidious impacts on occupant health.

At the outset of the 20th century there were approximately 50 materials used to construct buildings. By the end of the century Raw [42] claimed that this list had grown to around 55000, with half of them being synthetic. Compounds found in indoor air may have off-gassed from the building materials, furnishings and fittings, internal processes, cleaning products, with - somewhat ironically - even 'air fresheners' being implicated as sources of indoor pollution. Domestic pollutants can be grouped under the following alphabetical classifications: ammonia, asbestos, benzenes, biocides, carbon dioxide, carbon monoxide, detergent, dust, ethanol, fibreglass, formaldehyde, hydrocarbons, hydrogen chloride, methanol, micro-organisms, motor vehicle exhaust, nitrogen oxides,

[42] Raw GJ. Sick Building Syndrome: A review of the evidence on causes and solutions. HSE contract research report no.42, British Research Establishment (BRE), Garston, Watford, 1992)

ozone, paint, poly chlorinated bi-phenols, pesticides, photochemical smog, radon, solvents, sterilant gases, sulphur oxides, tobacco smoke and vinyl chloride.

Gases that may be found in the indoor environment are carbon dioxide/monoxide, nitrogen and sulphur dioxide, volatile organic compounds, radon, formaldehyde and ozone. Suspended particulate matter that may occur includes asbestos fibres, fibrous particulates, bacteria and fungi, tobacco smoke, HDM allergens, pollen and dust.

This is important in western society where most of our time is spent indoors. In developing countries there are still communities where only a small part of the day is spent indoors, the prevalence of wheezing among children remains low. By contrast, in urban communities in developing countries, the population is increasingly indoors and asthma has become an epidemic disease that disrupts many families and causes large numbers of hospital admissions. This move indoors has inevitably involved major changes in the air we inhale, including effects of protein allergens, bacterial endotoxins, hydrocarbons and gases such as ozone and NO_2.

The respiratory tract is a major entry route and end organ for the effects of indoor pollutants. To understand the effects of various irritants is complicated, not only by complex mixing but, additionally by host response variability. Inhaling a wide range of diverse materials even at very low concentrations at a respiration volume between 10000 and 20000 litres per day can produce both immediate and delayed respiratory complaints. Bascom [43] classified indoor pollutants by their effects on human tissue; corrosives are so termed because they cause direct destruction of structural tissue; irritants are compounds the cause symptoms and inflammation (i.e. trigger an influx of cells and mediators); sensitisers are materials that induce a specific immunologic response (HDM allergens triggering IgE) with the well known properties of specificity, diversity and amplification.

Sick Building Syndrome

The health effects caused by exposures to specific airborne compounds such as ozone, carbon monoxide, oxides of nitrogen and sulphur, lead and various particulate matter are routinely addressed by the US Environmental Protection Agency in setting national air quality standards. Possible correlations between exposures to numerous compounds, categorised as air toxics and the exacerbation of asthma, remains seriously under researched. Pollutants such as diesel particulates, environmental tobacco smoke, volatile organic compounds, metals, pesticides and endotoxins have all been implicated in respiratory disease, at least as symptom triggers, if not primary sensitisers.

A study by the World Wide Fund for Nature [44] that tested for 77 synthetic chemicals in the blood of 150 volunteers, identified a median of 27 per person. Many of these chemicals are routinely found in the domestic environment (PCB’s in PVCu windows

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[43] Bascom R, Kesavanathon J and Swift DL. Indoor Air pollution: Understanding the Mechanisms of the Effects, in Gammage RB, Berven AB., Indoor Air and Human Health, ISBN 1-56670-144-9, 1996

[44] World Wide Fund for Nature (2003) Enough to make the blood boil, Initial results summary reported in the Scotsman, Science and Technology section, 14th November, Edinburgh, p13

and PBD's used as flame retardants in furniture) and are considered to be persistent bio-accumulative endocrine disrupters. With over 100000 synthetics available for inhalation or ingestion these tests clearly represent the tip of a toxic chemical iceberg. As most bio-medical studies, at best attempt to quantify the risks of exposure to a single compound or group, any study that attempts to control for synergistic, additive or antagonistic chemical and biological reactions, faces an unmanageable number of variables.

In the early 1980's, the WHO [45] attempted to define Sick Building Syndrome (SBS) on the basis of a group of frequently reported symptoms (sensory irritation in the eyes, nose and throat; neurotoxic or general health problems; skin irritation; non-specific hypersensitivity such as pneumonitis, humidifier fever, asthma and rhinitis and noxious odour and taste sensations), without a specific aetiological causal factor being identified. Although there is undoubtedly a psychosocial element to workplace satisfaction/ dissatisfaction, when similar groups have been compared, those working in buildings diagnosed as 'sick' invariably have physical, biological or chemical components in the mix.

The effects of exposure to hazardous indoor air pollutants, is not restricted to the respiratory tract. At the psychosocial level a study by Morrow [46] on 22 workers in Minnesota who were regularly exposed to organic solvents revealed a high level of somatic disturbance, anxiety, depression, poor concentration, social isolation and fear of losing control. This investigation is of course significant, in that it discovered that exposure to certain chemicals caused changes in neurological behaviour, which would normally be diagnosed as psychosomatic in nature. SBS thus appears to be applied to instances where there is a diagnostic failure to isolate the main compounds responsible, individually or in synergistic combination.

Carbon Monoxide (CO) and Nitrogen Dioxide (NO_2)

Although the prevalence of asthma in the UK is fairly equally distributed geographically, there are more asthmatic attacks in urban areas particularly when pollution levels rise. There are three main sources of CO that can be found in the internal environment - traffic fumes, carbon based fuel combustion appliances and cigarette smoking. Carbon monoxide is a toxic gas that mixes with the haemoglobin in the blood stream and at high concentrations will result in death. The WHO [47] set a guideline value of 10 mgm^{-3} for any eight hour period in the home. A study by Raw [48] measured carbon monoxide levels in 876 randomly identified English dwellings, over a period of one year. It found that carbon monoxide concentrations in kitchens and bedrooms almost doubled during autumn and winter, possibly due to increased heating system use and a reduction in natural ventilation rates. The report claimed that indoor exposures mainly arise from indoor sources and will vary seasonally, largely due to ventilation rates and occupant

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[45] World Health Organisation, (1983) Indoor Air Pollutants, Exposure and Health Effects Assessment, Euro-reports and Studies no. 78, Copenhagen

[46] Morrow LA, et al A (1989) Distinct pattern of Personality Disorder Following Exposure to Mixtures of Organic Solvents, Journal of Occupational Medicine, Vol 31, 1989, pp743-746

[47] World Health Organisation, (2000) Guidelines for Air Quality, WHO, Geneva,

[48] Raw GJ, Coward SKD, Llewellyn JW, Brown VM, Crump DR and Ross DI, (2002) Proceedings, Indoor Air 2002, The International Academy of Indoor Air Sciences, Monterey, July 2002, Vol IV, pp461 – 466

behaviour. Although CO levels in homes were found to be low - particularly over short time-spans when gas ovens are in use – NO_2 levels are above the WHO recommendations and could therefore have significant health implications.

Environmental Tobacco Smoke (ETS)

Rates of smoking are in decline, but in Scotland approximately 23% of the population smoke [49]. ETS produces airway inflammation and bronchial hyper-responsiveness. A significant relationship between household environmental tobacco smoke (ETS) exposure and childhood asthma has been reported by Morgan [50]. Furthermore a meta-analysis of 73 studies by Vork [51] claimed that the results indicated a strong and consistent association between exposure to ETS and the incidence of childhood asthmatic symptoms.

Although ETS and its constituent chemicals are found in various concentration densities per square metre in outdoor air, the close proximity between smokers and non-smokers and the persistence of pollutants in indoor spaces - due to absorption by indoor surfaces - produces an ETS inhalation intake by passive smokers, circa 100 times greater than for typical outdoor concentrations [52] [53]. Layton [54] calculated that the average person breathes approximately $12m^3$ of air per day. Nazaroff and Singer [55] using the concept of reference exposure levels (REL) - the background exposure level of the non smoking population - calculated that passive smokers will inhale $1.9ugm^{-3}$ of acrolein in a smoke filled environment, which corresponds to 30 times the REL of the non-smoking population. Relatively high-risk levels were also found for formaldehyde and acetaldehyde of approximately double the REL.

Although the short and long term effects of such high exposure levels are still to be assessed, it is clear that ventilation rates in dwellings play a major role in diluting or exacerbating indoor Hazardous Air Pollutants (HAP) concentrations and their associated toxic or pulmonary health outcomes. CIBSE [56] recommend an air supply

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[49] http://www.scotland.gov.uk/Topics/Statistics/Browse/Health/TrendSmoking

[50] Morgan WJ, Martinez FD, (1992) Risk factors for developing wheezing and asthma in childhood. Pediatric Clinician of North America, Vol. 39(6), 1992, pp1185-1203

[51] Vork KL. Broadwin RL and Lipsett MJ, (2002) Household Environmental Tobacco Smoke (ETS) - Exposure and risk of childhood asthma - Techniques to reduce between study hetrogeneity in a meta-analysis, Indoor Air, The International Academy of Indoor Air Sciences, Monterey, July 2002, Vol II, pp483-488

[52] Smith KR, (1993) Fuel combustion, air pollution exposure and health: the situation in the developing countries, Annual Review of Energy and the Environment, 1993, Vol 18, pp529-566

[53] Lai Ack, Thatcher TL, and Nazaroff WW (1996) Inhalation transfer factors for air pollution health risk assessment. Journal of Air and Waste Management Assoc. 1996, Vol 50, pp1688-16990

[54] Layton DW. (1993) Metabolically consistent breathing rates for use in dose assessments. Health Physics, 1993,Vol 64, pp 23-36

[55] Nazaroff WW and Singer BC, (2002) Inhalation of hazardous air pollutants from environmental tobacco smoke in US residences, Indoor Air 2002, The International Academy of Indoor Air Sciences, Monterey, July 2002, Vol II, pp477-482

[56] CIBSE Guide Section A2 (1986) Chartered Institution of Building Service Engineers, London, 1986, Table 1.10

rate for 'smokey' environments of between 16 and 36 litres per second, per person. In an average four person family living room with a volume of $50m^3$, this would represent an air change rate of between 4.6 and 10.3 ach^{-1}. Any intervention that increases ventilation rates is however likely to reduce ETS exposure in passive smokers.

Bioaerosols, mould and mycotoxins

Except for specific chemical and toxic gas exposures, building related illnesses are usually associated with exposure to bioaerosols [57]. Mould fungal spores have been implicated in many studies [58 59 60 61] as a causal factor in lung disease. Although the type and species will vary depending on location, hygro-thermal environment, construction techniques and internal finishes, there are 4 main types of mould in northern temperate latitudes that are highly prevalent: *penicillium*, *aspergillus*, *cladosporium* and yeasts.

A major meta-analysis by Fung [62] of 416 published articles concluded that the current published human studies demonstrate a clear association of allergy and respiratory symptoms with exposure to moisture and mould. Mould normally requires a humidity of over 70% to germinate. Microclimates provided by carpets, bedding and soft furnishings are likely to be significantly damper than the surrounding air. Maintaining the internal RH below 60%, should therefore, limit the likelihood of microbe viability.

Infectious aerosols are known to contribute substantially to the transmission of such diseases as the common cold, influenza, adenovirus, measles, tuberculosis and other common respiratory illnesses. Building design, construction and system operation, can also impact on rates of infectivity. A study undertaken by the US army [63] revealed 50% higher rates of clinically confirmed acute respiratory illness with fever, among recruits in newer barracks with closed windows, low rates of outside air supply, and extensive air recirculation than among recruits in older barracks with frequently opened windows, more outside air and less recirculation. Mendell [64] claimed that there were seven parameters which could significantly influence infection rates:

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[57] Andrae S, Axelson O, Bjorksten B, Fredriksson M, and Kjellman N, (1988) Symptoms of bronchial hyper-reactivity and asthma in relation to environmental factors. Archives of Disease in Childhood, 1988, Vol 64, pp473-478

[58] Dekker C, Dales R, Bartlett S, Brunekeef B, Zwanenburg H. (1991) Childhood asthma and the indoor environment. *Chest*, , Vol 100, pp922-926

[59] Jaakkola J, Jaakkola N, Ruotsalainen R, (1993) Home dampness and moulds as determinants of respiratory symptoms and asthma in pre-school children. Journal of Exposure Analyses of Environmental Epidemiology 1993, Vol 3, pp129-142

[60] Maier WC, Arrighi HM, Morray B et al. (1997) Indoor risk factors for asthma and wheezing among Seattle school children. Environmental Helath Perspectives, 1997, Vol 105, pp208-214

[61] Macher JM (1987) Inquiries received by the Californian Indoor Air Quality programme on Biological contaminants in buildings. EXS Advances in Aerobiology, 1987, Vol45, pp 275-279

[62] Fung F, and Hughson WG. (2002) Health effects of indoor fungal bioaerosol exposure, Indoor Air 2002, The International Academy of Indoor Air Sciences, Monterey, July 2002, Vol III, pp46-51

[63] Brundage JF, Scott RM, Lednar WM, Smith DW, Miller RN. (1988) Building associated risk of febrile acute respiratory diseases in army trainees, JAMA,, Vol 259, pp2108-2112

[64] Mendell MJ, Fisk WJ, Kreiss K, Levin H, Alexander D Cain WS, Gimam JR, Hines CJ, Jensen PA, Milton DK, Rexroat LP and Wallingford KM. (2002) Improving the health of Workers in Indoor

- rate and effectiveness of outdoor air ventilation which dilutes concentrations of indoor aerosols
- rate and efficiency of air filtration
- disinfection by ultraviolet light which may deactivate infectious organisms
- rate of air recirculation, which influences transport between regions of the building
- density of occupancy which influences the distance between individuals
- temperature and humidity of air which affects the viability of infectious aerosols and human susceptibility
- indoor toxic fungal exposures which may alter human susceptibility to infection.

The paper goes on to claim that providing 'healthful' air quality in buildings has the potential to prevent five to seven million communicable respiratory infections per annum, saving the US economy between five and seventy five billion dollars.

Ozone (O3)

Studies by Peden [65] and McConnell [66] have implicated ozone as both a sensitiser and a trigger for asthmatic incidents. Monn [67] has claimed that bio-allergens, suspended particles and ozone are the most important pollutants of indoor air. Devlin [68] demonstrated that ozone plays a significant role in the exacerbation of respiratory disease, by priming the airway mucosa enhancing the cellular responses to allergens, or by exerting an intrinsic effect on airway inflammation. A study by Bayer [69] monitoring indoor/outdoor ozone levels every 45 minutes demonstrated that, in general, indoor levels remain well below ambient.

Toxic chemicals

A meta-analysis of the literature by Barry [70] attempted to evaluate and categorise over 5000 separate papers published since the early 1960's. From this quarry they

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Environments: Priority Research Needs for a National Occupational Research Agenda, American Journal of Public Health, September 2002, Vol 92, No 9, pp1430-1440

[65] Peden DB, Setzer RW, Jr, and Devlin RB.. (1995) Ozone exposure has both a priming effect on allergen induced responses as well as an intrinsic inflammatory action in the nasal airways of perennially allergic asthmatics. American Journal of Respiratory Critical Care Medicine 1995, Vol. 151, pp. 1336-1345

[66] McConnell R, Berhane K, Gilliland F, London SJ, Islam T, and Gauderman WJ. (2002) Asthma in exercising children exposed to ozone: a cohort study. Lancet, 2002. Vol. 359, pp. 386-91

[67] Monn C, (2001) Exposure assessment of air pollutants: a review on spatial hetrogeneity and indoor/outdoor/personal exposure to suspended particulate matter, nitrogen dioxide and ozone. Atmospheric Environment, 2001, Vol 35, pp1-32

[68] Devlin RB, McDonnell WF, Mann R, Becker S, House DE, Schreinemachers D. Koren HS. (1991) Exposure of humans to ambient levels of ozone for 6.6 hours causes cellulal and biochemical changes in the lung. American Journal of Respiratory cell molecular Biology, 1991, Vol4 pp72-81

[69] Bayer CW, Cook AL, Roberts D, Via PD, Teague WG. (2002) Airs system: A real time monitor to measure indoor air pollutants and lung function in children with asthma, Conference Proceedings, Indoor Air, The International Academy of Indoor Air Sciences, Monterey, July 2002, pp498 -502

[70] Barry BE, Chang MP, Bloom SB, Moss NE and Bates CB, (2002) Assessment of exposures to airborne toxic chemicals and the development or exacerbation of asthma in the general population, Conference

developed a protocol to extract the most significant components using a five point (poor to excellent) scale. The result was a distillation of 752 papers separated into 19 categories. These were, in decreasing incidence: ETS (150), overview (148), non-halogented hydrocarbons (90), aldehydes (86), metals (85), diesel exhaust particulates (73), nitrogen containing compounds (43), miscellaneous (33), pesticides and herbicides (30), esters and phalates (27), fibres (16), halogenated hydrocarbons (14), acids (9), amines (9), glycol ethers (3), ketones (2) and nitrosoamines (2). Most of the papers concentrated their efforts on studying one specific variable. A study by Brugge [71] concluded that, due to the complexity of variables and confounders, a multi-factorial approach has to be adopted and that no single variable or component appears to have a dominant influence.

Volatile Organic Compounds (VOCs)

Studies by the BRE [72] into indoor VOC sources and personal exposure to VOCs concluded that of 24 identified sources, indoor exposure was far more significant than outdoor levels for six of the most common air pollutants. Further studies by Coward [73] looking at VOCs in a range of dwellings categorised by date of construction, concluded that VOC levels had risen by a factor of three over the 20th century due to the reduction in ventilation rates, combined with the type of construction materials now prevalent e.g. chipboard flooring, pvc tiles, paint finishes etc. VOC levels reduce through time as the components release their embodied compounds. The paper also demonstrated that off-gassing rates are affected by humidity and temperature, with rates peaking in Autumn. The study into VOCs in 876 dwellings in England had 8 significant conclusions:

- Indoor TVOC concentrations vary with season. Off-gassing appears to be affected by a combination of activities, temperature and ventilation.
- Benzene and toluene were positively correlated with smoking (as they are both constituents of tobacco smoke this is somewhat unsurprising).
- A built-in garage significantly increased TVOCs with a range of compounds found in paints, petrol and solvents migrating directly into the dwelling.
- Benzene and m/p-xylene were found in higher concentration in metropolitan areas. As they are constituents of petrol fumes this is not surprising. M/p xylene was also correlated with dwellings containing air freshners.
- Undecane was significantly increased by frequency of indoor painting.
- The main sources of VOCs were stored materials and/or car/fuel, frequency of decoration and type and age of fittings and furnishings, combustion of methane, and environmental tobacco smoke.
- There appeared to be no overall factor representing ventilation rates.

Proceedings, Indoor Air, The International Academy of Indoor Air Sciences, Monterey, July 2002, Vol I, pp125-130

[71] Brugge D, Vallaaarino J, Ascolillo L, Osgood ND, Steinbach S, Spengler J, (2002) Environmental factors for asthmatic children in public housing, Indoor Air, The International Academy of Indoor Air Sciences, Monterey, July 2002, Vol II, pp428-431

[72] Crump D, (1999) Minimising the impact on the indoor environment of chemical emissions from building products, Indoor Air 99, International Academy of Indoor Air Sciences, Edinburgh 1999, Vol 5, p288-293

[73] Coward SKD, Brown VM, Crump DR, Raw GJ, and Llewellyn JW, (2002) Indoor air quality in homes in England, Volatile organic compounds, BRE, Watford,.

- Most homes had VOC levels well below existing guidelines apart from benzene which was found in over 50% of dwellings to be above the National Air Quality Guidelines (NAQS) target for 2010.

Pesticides

Pesticides are toxic substances deliberately introduced into the domestic environment to control such as moths, fleas, cockroaches, flies, ants, rodents mould and bacteria. Godish [74] has identified the most commonly used indoor pesticides as hypochlorites, ethanol, isopropanol, pine oil, glycolic acid, 2-phenylphenol and 2-benzyl-4-chlorophenol. There is also a variety of volatile organic insecticides which are used to treat building materials such as diazinon, chlordane, lindane, malathion, chlorpyrifos, aldrin and boric acid. These are introduced either as emulsion sprays, fogging devices (mothballs), impregnated into pest or bait strips or incorporated in flea/tick collars. Those pesticides with high vapour pressures (around $1.2x10^{-2}$ mm Hg), off-gas more easily and can be found in greater concentrations, particularly immediately after application. Implications for occupant health are as short-term respiratory tract or skin irritants and long-term carcinogens. Compounds such as chlordane, heptachlor, lindane, dieldrin and PCP are known to accumulate in fatty tissue and are suspected human carcinogens. The widespread use of fungicidal washes associated with inhibiting and/or treating mould growth in a large number of Scottish dwellings suffering from winter condensation, undoubtedly constitutes a significant exposure hazard.

Toxic chemical particulates

Godish has also maintained that there is increasing epidemiological evidence that particulate phase matter (typically referred to as ‘dust’) is a major risk factor in occupant health. The generic term ‘dust’, refers to a large range of particle sizes, types, sources and chemical compositions. It can be measured using a number of techniques that count total suspended particles (TSP), respirable suspended particles (RSP), UV particulate matter (UVPM), particle numbers or specific particle fractions. Particles less than 3 microns are the most biologically significant as they can penetrate much deeper into the lungs. Particulates from engine exhausts that will be found in significantly increased concentrations near main roads are of a size that can accumulate in the lung, as the macrophages are not sensitive to such tiny diameters. There is thus a concern that increasing ventilation rates in areas where external ambient pollution is high, due either to high traffic densities and low traffic speed, or where smoke stacks from incinerators regularly ground in certain weather conditions, will trigger respiratory symptoms.

Endotoxins

Among the indoor pollutants that may be implicated in the aetiology of asthma are bacterial endotoxins. These are lipopolysaccharides that are found in the cell wall of gram-negative bacteria. In contrast to other indoor related agents the methodology for

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[74] Godish T. (1995) Sick Buildings: Definition, Diagnosis and Mitigation, Lewis Publishers, , ISBN 0-87371-346-X

measuring endotoxin exposure levels is not well defined. Simpson [75] claimed that they have pro-inflammatory effects and have causative associations with a range of occupational lung diseases. In the homes of adult asthmatics Michel [76] found a clear correlation between higher levels of indoor endotoxins and disease severity and Park [77] suggested that even exposure to relatively low levels of endotoxins in the first year of life may cause airway inflammation and wheeze in some infants.

A study by Tavernier [78] in Manchester UK, found high endotoxin levels in living room carpets at ten fold higher concentrations than bedroom carpets or mattresses. The mean value for asthmatic cases was almost double that of the healthy controls. The higher levels found in living room carpets were put down to heavier contamination by footwear, usage, food and drink spillage, and pet occupation. The study hesitated to make any claims as to causality as endotoxin levels may simply be correlated with some other environmental factor that was not measured. There is however an implication that floor surface coverings and soft furnishings should be made easier to clean, possibly inhibiting endotoxin deposition and growth.

Guidelines for Indoor Air Quality

In contrast to the domestic sector there are both guidelines and regulations issued annually by the Health and Safety Executive [79] for air quality in the workplace which are based on the concept of occupational exposure limits (OEL), maximum exposure limits (MEL) and time weighted averages (TWA). These lists have legal status but are not exclusive. Absence from the list does not imply that a substance has no ill effects on health, nor that it is safe to use without control. Where a substance does not have an OEL the employer must carry out a risk assessment to determine an ‘in-house’ OEL.

The World Health Organisation [80] has published guidelines for air quality targeted at ambient air pollutants. They are based on inhaled exposure to a single airborne chemical. They do not take account additive, synergistic or antagonistic effects or exposure through routes other than the lungs. The guidelines provide information on sources, concentrations, proven and suspected health effects and health risks.

[75] Simpson JCG, Niven RML, Pickering CAC et al. (1998) Prevalence and predictors of work related symptoms in workers exposed to organic dusts, Occupational Environmental Medecine, 1998, Vol55, pp668-672

[76] Michel O, Kips J, Duchateau J, Vertongen F, Robert L, Collet H, Pauwels R & Sergysels R. (1996) Severity of asthma is related to endotoxin in house dust. American Journal of Respiratory and Critical. Care Medecine,1996; Vol154(6 Pt 1), pp1641-1646

[77] Park JH, Gold Dr, Spiegelman DL, Burge HA & Milton DK.. (2001) House dust endotoxin and wheeze in the first year of life. American Journal of Respiratory and Critical Care Medicine. Vol. 163(2), 2001 pp322-328

[78] Tavernier G, Fletcher GD, Francis HC, Oldham LA, Fletcher AM, Stewart L, Gee I, Watson A, Frank TL. FrankP, Pickering CAC, and Niven RML, (2002) Endotoxin exposure in asthmatic children and matched healthy controls: results of IPEADAM study, Indoor Air, The International Academy of Indoor Air Sciences, Monterey, July 2002, Vol I pp488-491

[79] Health and Safety Executive (2003), Occupational exposure limits EH40, HSE Books, PO Box 1999, Sudbury

[80] WHO (2000) - Air Quality Guidelines for Europe, (European Series No. 91), 2000, Copenhagen, Denmark

The building regulations in the UK are geared to prescriptive measures to ensure 'adequate ventilation' on the basis that the outdoor air is unpolluted, but there are currently no standards covering the quality of indoor air with respect to specific toxic pollutants known to derive from indoor sources. Harrison [81] has reviewed the guideline values now emerging in Canada, Finland, Germany and Norway.

In general these are based on exposure levels (ppm or ug/m^3) over a given time-span (5/30 minutes, 1-8 hours and annual means.

Harrison gives five main reasons why guidelines need to be developed:

- To inform the design and management of buildings
- To elicit action to reduce exposure to potentially harmful substances
- To indicate the need, if any, for the development of control or mitigation policies or regulations
- To facilitate the setting of appliance emission standards to help control pollution at source
- To underpin the development of information and advice

Finnish Building regulations have specific requirements for Air Quality, setting maximum CO_2 levels at 1200 ppm and setting, maximum permissible levels of for other pollutants such as sulphur dioxide, nitrogen dioxide, particulates, lead, carbon monoxide and benzene [82].

The question of what pollutants should be monitored remains problematic. Of the studies that have attempted a multi-factorial approach, they have been unable to differentiate the influence, or even produce a rank order of the variables, likely to be the most significant in the aetiology or exacerbation of respiratory disease. It is clearly difficult - if not prohibitively expensive - to attempt to monitor everything. The best approach may be to develop a large enough evidence base where algorithms or stochastic modeling can be developed linking key known indoor pollutants with easily identified markers such as CO_2, NO_2, formaldehyde, allergens and moulds. Measuring temperature and humidity is also likely to be useful, not just in predicting the incidence of HDM allergens, mould and dampness, but the rate of VOC off-gassing from indoor sources. Appropriate and standardised measurement techniques will also have to be established, as will health risks from pollutants both in isolation and in combination.

In 1998 a Department of Health committee published a report [83] on the medical effects of air pollution on health. It concluded that there was no known safe threshold value for PM_{10} particulates, with each rise of $10ug/m^3$ responsible for a 3% increase in asthmatic

[81] Harrison PTC, (2003) Guidelines for Indoor Air Quality in the Home, Unhealthy Housing: Promoting Good Health, Conference, Warwick University, March 2003, p8

[82] Ministry of the Environment Housing and Building Department, (2003) D2, Indoor Climate and Ventilation of Buildings Regulations and Guidelines 2003 accessed at www.buildup.eu/sites/default/files/D2eng%20-ventilation%20guidelines%20in%20Finalnd%20%20in%20English_p.pdf 4/6/14

[83] COMEAP (1998). The Quantification of the Effects of Air Pollutants on health in the United Kingdom, Department of Health,

attacks, broncho-dilator use and lower respiratory tract problems and a 1.9% increase in acute hospital admissions.

The challenge of designing and implementing ventilation systems in buildings to take into account air change rates achieved from different configurations is not addressed in detail in current guidance to the Scottish regulations.

Studies examining occupant interaction

With regard to the specific question addressed in this study there are relatively few studies that have investigated indoor air quality with a focus on the role of the occupant interacting with the ventilation equipment such as trickle vent settings and frequency of window opening. This section references recent studies that have attempted to investigate the contaminants found in indoor air for a broad range of conditions. Most of these studies also usefully reported on occupant perceptions, interactions with the ventilation equipment, settings applied to trickle vents and windows, and the quality of installation and specification of the ventilation equipment. The protocols used for the indoor air quality measurements in the main relied on tracer gas decrement methods to assess air change rates.

There have been several studies which measured CO_2 levels in buildings, in dwellings, and in living rooms and bedrooms. CO_2 levels in bedrooms while sleeping have historically been reported as exceeding 1000 ppm. Laussmann and Helm reported levels of 4000 to 5000 ppm in the bedroom of a building constructed in 1908 [84], Hasselaar and Van Ginkel reported on a 1995 Netherlands study with 2300 to 4800 ppm in bedrooms [4], a 1994 Canadian study reported that levels often exceeded 4500 ppm in bedrooms with 2 people and doors closed, 3500 ppm with 1 person and door closed and around 1200 to 1900 ppm with doors open [85]. The Canadian study noted that most people slept with the door open, investigated potential ventilation options, and a follow on study into physiological effects of CO_2 levels while sleeping was done [86]. A 1994 study found concentrations of 20-30,000 ppm in inspired air during sleep when blankets obscure children's faces[87], follow up studies into CO2 levels were carried out in the context of sudden infant death syndrome and bed sharing infants[88]. These studies illustrate that CO_2 levels in bedrooms during sleeping have historically been high under certain circumstances, in all cases however the researchers suggest that elevated CO_2 levels are undesirable.

[84] Laussmann D , Helm D (2011). Air Change Measurements Using Tracer Gases. Chemistry, Emission Control, Radioactive Pollution and Indoor Air Quality, Dr. Nicolas Mazzeo (Ed.), ISBN: 978-953-307-316-3, InTech, DOI: 10.5772/16918

[85] Parent D, Stricker S, Fugler D. (1994) Ventilation and Air Quality Testing in Electrically Heated Housing. CMHC Rep, Nov 1994. https://www.cmhc-schl.gc.ca/publications/en/rh-pr/tech/95-201.pdf (accessed 15apr14).

[86] Stricker et al. (1997) Physiological Responses to Elevated Carbon Dioxide Levels in Buildings. Indoor Built Environment. 6 301-308.

[87] Malcolm et al. (1994). Carbon dioxide concentrations in the environment of sleeping infants. J. Paediatr. Child Health (1994) 30, 45-49

[88] Baddock et al. (2012). Hypoxic and Hypercapnic Events in Young Infants During Bed-sharing. Pediatrics 2012;130;237; originally published online July 16, 2012;

Some studies have been carried out to investigate indoor air quality in modern energy efficient buildings with natural ventilation strategies with and without intermittent extract fans. These include 3 UK Government funded studies carried out by BRE in 2001 [89], 2002 [90] and 2005 [91]. The first two found high levels of TVOCs and a third study found ventilation rates: 0.44ac/h winter with 68% of ventilation rates below 0.5 ach (BRE: condensation risk at <0.5). Flats seem to be less ventilated than the other types of houses and were found to be fully open in 4/37 homes and fully closed in 13/37 homes. Homes with the lowest ventilation rates in winter had the trickle vents fully closed.

The key sources are:

BD 2702 Ventilation and Indoor Air Quality in Part F 2006 Homes (2010) [92]

This is a particularly relevant study as the homes were built to the new air tightness standards of 5 $m^2/m^3.h$ @ 50 Pa. The study monitored 22 dwellings in England with protocols designed to assess if the 2006 edition of Approved Document F is effective at providing adequate ventilation and good indoor air quality in new dwellings. There was a specific focus on the use of trickle vents and intermittent mechanical wet zone extraction and testing was undertaken with all trickle vents open and fans operating at their highest settings when windows were in the closed position. The study monitored 5 parameters as a proxy for IAQ: temperature, relative humidity, formaldehyde, total volatile organic compounds and nitrogen dioxide.

Summary of Results

- 10 out of 22 dwellings achieved an air tightness level better than 5 $m^2/m^3.h$ @ 50 Pa.
- 72% of the dwellings were found to have insufficient trickle vent area.
- 60% of the trickle vents were closed at the first inspection.
- 52% of dwellings did not have the required 10mm gap under doors.
- Less than 50% of fans achieved the specified flow rate for mechanical extraction.
- 4 out of the 22 dwellings had high NO_2 levels associated with poor extraction in kitchen.
- 50% homes exceeded the TVOC levels set in the ADF.
- In some cases the fans had been replaced with smaller and quieter models.

Conclusions

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[89] S K D Coward, J W Llewellyn, G J Raw, V M Brown, D R Crump and D I Ross (2001). BR 433: Indoor air quality in homes in England.

[90] S K D Coward, J W Llewellyn, G J Raw, V M Brown, D R Crump and D I Ross.(2002). BR 446: Indoor air quality in homes in England – Volatile Organic Compounds

[91] C Dimitroulopoulou, D Crump, S K D Coward, V Brown, R Squire, H Mann, M White, B Pierce and D Ross.(2005). BR 477: Ventilation, air tightness and indoor air quality in new homes

[92] Simon McKay and David Ross (2010).. BD 2702 Ventilation and Indoor Air Quality in Part F 2006 Homes AECOM, Department for Communities and Local Government. ISBN: 978 1 4098 2375 9

- Installed trickle ventilator opening areas were non-compliant.
- There was a particular problem with trickle ventilation in flats where there was less opportunity for cross-flow ventilation.
- IAQ depended on the correct specification, good installation practices and occupant awareness and use.
- The current guidance is demonstrably inadequate for flats.

BR 477: Ventilation, air tightness and indoor air quality in new homes (2005) [93]

This study investigated naturally ventilated homes (n=37) built in England since 1995 with two, three month monitoring periods occurring during January-March and July – September 2002. The following seven parameters were measured: temperature, relative humidity, carbon monoxide, nitrogen dioxide, formaldehyde, total volatile organic compounds and PM10 particulates.

Ventilation rates were measured using tracer gas methods and the dwellings were also assessed using blow door techniques to 50 Pa. Five of the homes, found to have particularly poor IAQ were subsequently revisited in 2003 and underwent further test regimes.

Results.

- Average ventilation rates were found to be 0.44 ach-1 in winter rising to 0.62 ach-1 in summer.
- 68% of households fell below the recommended rate of 0.5ach-1 during winter tests.
- Flats had lower air change rates than houses.
- Most occupants were not aware of trickle ventilator function or operating modes.
- All trickle vents were found to be fully open in only 4 of the 37 homes.
- All trickle vents were found to be fully closed in 13 of the 37 homes.
- Homes with the lowest ventilation rates in winter had the trickle vents fully closed.
- The average air leakage rate at 50 Pa was found to be 12.9 ac/h similar to the overall housing stock at 13.1 ac/h at 50 Pa in a sample of 471 dwellings.
- Gas cooking was associated with higher NO_2 and CO concentrations.
- Indoor sources, such as toiletries and cleaning fluids when combined with lower ventilation rates (~0.30 ac/h) were associated with increased VOC levels that exceeded existing IAQ guidelines.
- The average temperature and RH in winter was 20.8°C (range 16.4–25.5°C) and 43% (range 26–62%).

Ventilation and indoor air quality in new homes, California Energy Commission[94]

[93]). C Dimitroulopoulou, D Crump, S K D Coward, V Brown, R Squire, H Mann, M White, B Pierce and D Ross (2005. BR 477: Ventilation, air tightness and indoor air quality in new homes

[94] Offermann, F. J. (2009). California Energy Commission: VENTILATION AND INDOOR AIR QUALITY IN NEW HOMES (2009

This study investigated window use, ventilation rates and contaminants in a 108 new homes in California. The dwellings had a range of ventilation systems and air change rates were assessed using tracer gas techniques. Measurements made included formaldehyde, total volatile organic compounds, PM2.5 particulates, nitrogen dioxide, carbon monoxide, carbon dioxide, temperature and relative humidity.

The Californian study did measure CO_2 but found levels to be below 1000ppm even though ventilation rates and formaldehyde levels were found to be well above acceptable levels. This appears to be a reflection on the relatively large volume per person in typical US dwellings, combined with the extensive use of synthetics that are likely to off-gas VOC's due to the relatively high ambient air temperatures.

Summary of results

- The median ventilation rate was 0.26 ach-1 with 67% of homes not meeting the local building code requirement of greater than 0.35 ac/h.
- 32% of occupants did not open their windows in winter.
- Nearly all homes exceeded the formaldehyde concentrations for cancer and chronic irritation and 59% exceeded guidelines for acute irritation.
- Dwellings had a CO_2 mean of 564 ppm (range up to 1108 ppm).
- 64% of mechanical systems were assessed as being poorly installed and/or operated.

Ageing and air tightness – how dwelling air permeability changes over time 2011 [95]

Routine air leakage testing (n=5500) has demonstrated that some new homes designed to achieve high standards of air permeability are actually achieving very high 'as- built' standards – standards at which additional ventilation provision would normally be advisable. NHBC have some concerns about the potential consequences of living in highly airtight homes that do not have provision of additional ventilation, although there is limited research into these effects.

The research found that, whilst two-thirds of homes did become leakier, the remaining third actually became more airtight. The re-tests demonstrated that most of the dwellings (83%) remained airtight, achieving a re-test result tighter than 5 $m^2/m^3.h$ @ 50 Pa. Results from these tests indicated that air permeability results far better than 10 $m^2/m^3.h$ @ 50 Pa were being achieved on a regular basis and that there is an improving trend.

The NHBC believes there is an urgent need for research into the performance of highly energy efficient homes with respect to the quality of the internal environment, ventilation systems and the impact on the health and wellbeing of occupants. Furthermore they have called for research into both the performance of products and systems specifically in respect to:

[95] Philips T, Rogers P and Smith N (2011). Ageing and air tightness – how dwelling air permeability changes over time, NHBC, Publication NF24,

- Noise generated.
- Ability to clean fans and ductwork.
- Achievement of the required air supply.
- Air filter efficiency.
- Use of demand control ventilation.
- Impact of chemical emissions from materials on indoor air quality.
- Performance of systems at installation, during one year of use, and beyond.
- Evaluation of indoor air quality and ventilation in a representative sample of homes (temperature, relative humidity, volatile organic compounds, formaldehyde, carbon monoxide, nitrogen dioxide, particles, mites, bacteria, fungi, radon, ozone, semi-volatile organic compounds in dust, carbon dioxide and air exchange rates).

These studies investigated the contaminants found in indoor air for a broad range of conditions, the studies also reported on occupant perceptions, interactions with the ventilation equipment, settings applied to trickle vents and windows, and the quality of implementation of the ventilation equipment.

Summary

A general conclusion that could be drawn from these studies is that where, trickle ventilation, plus intermittent extract are well specified and implemented and trickle vents are left fully open and unblocked by the occupants then adequate indoor air quality is achievable as long as there are no unusual pollution sources. A second conclusion is however, that these circumstances often do not occur in practice resulting in poorer than desired indoor air quality.

In summary, People exhale carbon dioxide—the average adult's breath contains about 35,000 to 50,000 ppm of CO_2 (100 times higher than outdoor air). Without adequate ventilation to dilute and remove the CO_2 being continuously generated by the occupants, CO_2 can accumulate [96]. CIBSE (AM10) [97] identifies that the rate of release of carbon dioxide from building occupants is 5.56x10-6 m3/s for occupants with sedentary type activity. For the purpose of this review we have assumed this CO_2 release rate. Historically C CO_2 has been used as an indicator of per person ventilation rate and air quality due to human generated sources. A more recent study has directly associated CO_2 levels in air with a change in mental function in the 1000 to 2500 ppm range. Levels in bedrooms have been historically reported as having peak values up to 4800 ppm. Increasing airtightness standards in buildings may reduce ventilation rates evidenced by increasing CO_2 levels. No limit has yet been established in international standards for CO_2 levels in bedrooms while sleeping. Current guidance of air change rates are predicated on moisture control rather than indoor air quality, but there is a general acceptance that 1000 ppm remains a valid threshold, and corresponds well with a delivery of 8 l.s/person identified in CIBSE Guide A [98], which also sets down classifications for IAQ (Table 1) and CO_2 concentrations associated with these. Whilst

[96] Prill, R. (2000). Why measure carbon dioxide inside buildings. Published by Washington State University Extension Energy Program. WSUEEP07-003.

[97] AM10, C. A. M. (1997). Natural ventilation in non-domestic buildings. The Chartered Institution of Building Services Engineers London.

[98] CIBSE. Guide A: Environmental design. 7th Edition, London: CIBSE, 2006

these tables are based on ‘BS EN 13779 Ventilation for non-residential buildings. Performance requirements for ventilation and room-conditioning systems’, they do provide a useful characterisation of IAQ quality.

Table 4.1 Ventilation and indoor air quality classification (BS EN 13779)(19)

Classification	Indoor air quality standard	Ventilation range / ($L \cdot s^{-1}$/person)	Default value / ($L \cdot s^{-1}$/person)
IDA1	High	>15	20
IDA2	Medium	10–15	12.5
IDA3	Moderate	6–10	8
IDA4	Low	<6	5

Table 1: Ventilation and air quality classifications (CIBSE Guide A)

Table 4.2 Approximate maximum sedentary CO_2 concentrations associated with CEN indoor air quality standards (BS EN 13779)(19)

Classification	Rise in indoor CO_2 concentration / ppm	Default value / ppm	Range in outdoor concentration / ppm	Total indoor value* / ppm
IDA1	<400	350	350–400	700–750
IDA2	400–600	500	350–400	850–900
IDA3	600–1000	800	350–400	1150–1200
IDA4	>1000	1200	350–400	1550–1600

* i.e. concentration rise plus outdoor value

Table 2: Maximum CO_2 concentrations associated with CEN air quality standards

ASHRAE member guidance is moving towards the application of the 1000 ppm limit in dwellings both for living rooms and bedrooms, although a potential conflict of interest exists where building service providers are concerned. A reasonable argument could be made for the 1000ppm limit in dwellings where rooms are increasingly used for home office and studying purposes, although the translation of results between contexts (multi-occupancy to single occupancy) should be viewed with some caution.

The placement of ventilation openings and other factors (height, obstructions, opportunity for crossflow, opportunity for buoyancy, door undercuts, orientation, exposure to weather, ceiling height, number of storeys, security of ventilation openings etc.) could potentially be included in a calculation that will estimate the ventilation rate for a particular configuration. This type of methodology already exists in very simplified form for summer overheating calculations in SAP (appendix P) and in PHPP. For schools a more comprehensive method is encapsulated in the BB101 ClassCool and ClassVent design and compliance tools [99].

[99] UK Education Funding Agency (2006) Building Bulletin 101Ventilation of School Buildings. https://www.gov.uk/government/publications/building-bulletin-101-ventilation-for-school-buildings (accessed 28apr14).

3. Overview Survey

The overview survey addressed research questions about occupant use of ventilation strategies, particularly trickle vents. These include: what are the predominant ventilation strategies adopted by occupants; what determines occupant ventilation habits, what are the barriers and opportunities for use?

The approach agreed with BSD was to undertake a reasonably large sample survey (n=200), of occupants of modern houses built to contemporary standard. This would be through a short (15 minute) interview conducted face-to-face. For logistical reasons a commercial research company Research Resource was used to conduct these surveys, based on a survey design and brief developed by the team and approved by BSD. The survey was conducted between 1st – 28th February 2014.

Determination of Sample Size

The brief required 200 returned surveys. Based on the experience of Research Resource it was estimated that a likely success rate would be around one in four. This determined the need for a database of around 800 addresses.

Generation of Addresses

Addresses were sought from a number of sources. These included:

- Existing clients and contacts from the research team.
- Contacts provided by Building Standards Division.
- A call for support issued by Homes for Scotland.
- A request disseminated through NHBC Scotland.

Those contacted were provided with an explanation of the process and a request for information. The key information to be provided were the full address and postcode, a Building Warrant reference number and date registered, and finally the type of ventilation system. This information is important to determine eligibility as discussed in the next section. This information was collated in a central database held by Anderson Bell + Christie Architects.

Eligibility Criteria

Some contacts were unaware of the cut-off dates for building warrants and did not appreciate that warrant reference numbers commencing with 10/ were not necessarily under 2010 regulations. For clarity the database records the edition of regulations to which addresses are designed. It is understood that 2009 Regulations came into force 1st May 2009. 2010 Regulations came into force 1st October 2010. 2011 Regulations came into force 3 October 2011. 2013 Regulations came into force 1st October 2013.

The initial brief was to investigate houses built to the 2010 regulations. Following initial queries it became clear that there would be a limited number of addresses available to the study from 2010 regulations onwards.

A number of factors may have influenced this.

- The impact of the 2008 recession, reducing the number of completed and occupied dwellings.

- The widespread use of whole house Mechanical Heat Recovery Ventilation within Housing Association stock.

- The widespread use of Decentralised Mechanical Extract Ventilation (24 hour fans in kitchens and bathrooms running at low voltage) by volume house builders.

- Developments which were constructed post 2010, but to previous regulations.

It was determined that in order to achieve the number of dwellings for the database some concessions could be made. It was agreed that the following properties could be eligible for the study.

1) 2009 Revision of Regulations

The 2009 update of the regulations referenced Accredited Details. The use of the Accredited Details allowed designers to apply a default value of 10 $m^2/m^3.h$ @ 50 Pa and negated the need for air tightness testing.

This sets a back stop figure, however independent testing on some of the 2009 projects by Anderson Bell + Christie demonstrated that Contractors were achieving values well in excess of the default value. Testing determined values between 4 $m^2/m^3.h$ @ 50 Pa and 2 $m^2/m^3.h$ @ 50 Pa. It was also felt that construction detailing between the 2009 and 2010 editions of the regulations was largely unchanged. Given the default air tightness figure and standardised detailing it was agreed to incorporate dwellings built to the 2009 update of the regulations.

2) Demand Mechanical Extract Ventilation (DMEV)

Addresses for approximately 400 dwellings built to 2010 regulations were provided by a single volume housebuilder, all of which feature DMEV.

Whilst DMEV is not considered natural ventilation this system does demand the use of trickle vents. As the primary research question for the study concerned trickle ventilator use these properties were deemed suitable for the study as they require occupant interaction with the trickle vent.

Confirmation With Housing Providers
Authorisation was sought from each housing provider prior to issuing letters to occupants. This gave the housing provider opportunity to comment on the letter. Written authorisation by email was required from housing providers before any letters could be issued to occupants. This checking procedure was recorded in the address database. A template letter with an information sheet was issued to all homes on the database. This provided information on the nature and purpose of the study and provided an option to opt out of the study.

Questionnaire Development
The questionnaire was developed with the involvement of a number of parties, including the research team, Building Standards Division and Research Resource.

The research team generated an initial questionnaire and this was reviewed with Research Resource, who carried out the surveys. This consultation led to a change in approach to the questionnaire. The initial intention had been to have the surveyors make some observations about trickle vent use. However Research Resource noted significant problems with gaining access to homes on a large scale which would generate a significantly lower response rate and would double the amount of resource that would be required. This would therefore make the data collection phase of the research unachievable. Consequently the questionnaire was revised to reflect a doorstep style survey that could be carried out by a single researcher.

This revised questionnaire was presented to BSD. A number of comments were made which led to some amendments. In addition to the main questionnaire, the survey also asked respondents if they were willing to participate in the follow-up study that would undertake monitoring in the houses. This methodology facilitated collection of the required number of survey responses while satisfying the brief requirements set by BSD.

Briefing Researchers
Research Resource provided the opportunity to brief their team of social researchers prior to working in the field. Anderson Bell + Christie provided a training session. This included background on the study and its aims and objectives.

A full size aluminium clad timber window was provided for the briefing. This allowed researchers to get hands on training on the use and physical appearance of the trickle vent. Part of the survey included show cards that illustrated common types of window we expected to see within the database of addresses, a timber window and a PVCu window. The show card was double sided and also demonstrated the function and operation of a trickle vent.

A pilot study of the survey was undertaken which indicated a positive response to the questionnaire. One issue arising was that in the pilot the return rate for those willing to participate in the follow-on study was limited, to around 1 in 10. From 200 surveys this would have yielded insufficient numbers to achieve the 40 houses targeted. It was agreed to remove the restrictions on eligibility and ask all respondents if they would be willing to participate. Contact details were taken so that the team could later decide on suitable criteria and make contact as appropriate.

The Survey

During the course of the survey a number of access issues were identified. In some cases dwellings were occupied by residents with special needs. Contact was made with the housing provider to assist with access and to accompany researchers as required. Advance notice and close communication with the housing provider was maintained. As there were a number of dwellings in remote locations, it was agreed that the accessible properties be attempted first, however if the numbers were not being achieved then the more remote properties should be targeted.

Private dwellings presented two key issues. Firstly, the majority of available addresses were from a single volume house builder. To combat this the researchers were asked to first target all other private dwellings in the database, before approaching these dwellings. Secondly the success rate at private dwellings was significantly lower than at any other tenure type.

Results

A total of 200 surveys were obtained. A complete set of responses is provided in Appendix A, and copies of the survey form are included in Appendix B. As noted, access to privately owned properties was restricted, due to lack of data about locations provided by developers, and response rates to the surveyors tended to be lower in these houses. Since 2010 approximately 66% of new houses are privately owned, but of the survey only 21% were privately owned. This was raised at an interim project meeting with BSD, but given that a reasonable proportion of the responses were from private homes and analysis of the differences between private and tenanted properties showed that in general there were no significant differences in responses, further surveys were not pursued. Construction types and space standards are generally very similar in the volume market and there is confidence that the results provide a statistically significant insight into ventilation habits in Scottish Housing.

Ventilation awareness

Prior to the study there was some presumption that householders are not especially aware of trickle vents, but this was found not to be the case, with 84% of respondents being able to identify them from the show cards and 82% of respondents identifying that they were for ventilation, with only 15% not knowing what they were.

It would appear that this knowledge is not necessarily based on advice at handover, with 82% of respondents indicating that they had not received advice on how to best ventilate their house, but there is clearly reasonable awareness in occupants about the nature and purpose of trickle vents.

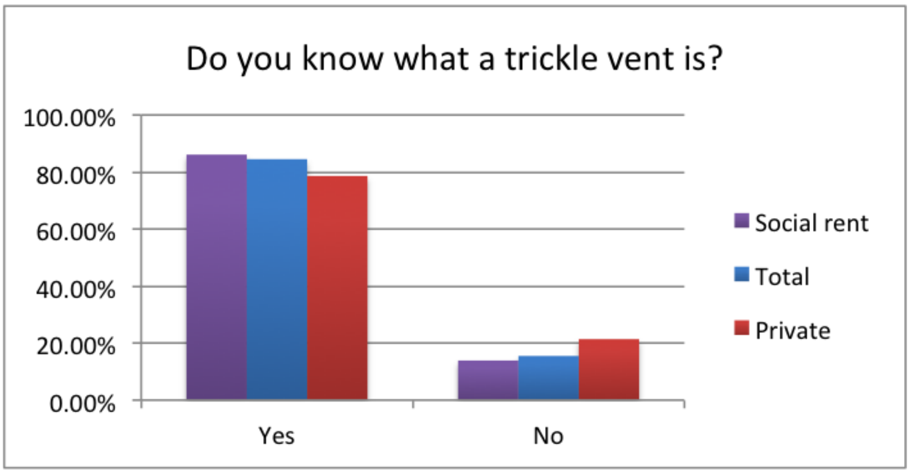


Figure 4: do you know what a trickle vent is?

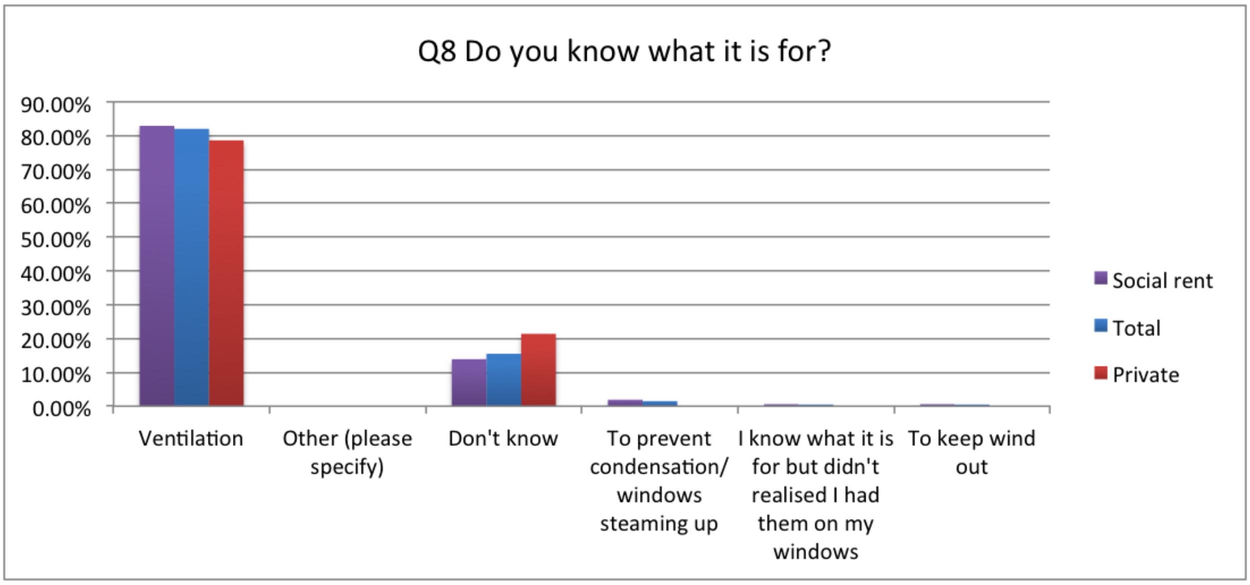


Figure 5: Do you know what it is for?

Trickle ventilation habits

Occupants were asked how frequently they used the trickle vents in the bedrooms and living rooms. A clear and consistent picture emerges from this, with the majority never opening trickle vents in living rooms (62%) or bedrooms (63%). A significant group does leave them open all the time in living rooms (24%) and bedrooms (28%). The smallest group is those that take advantage of their controllability and open and close them at some point during the week in the living rooms (13%) or bedrooms (9%).

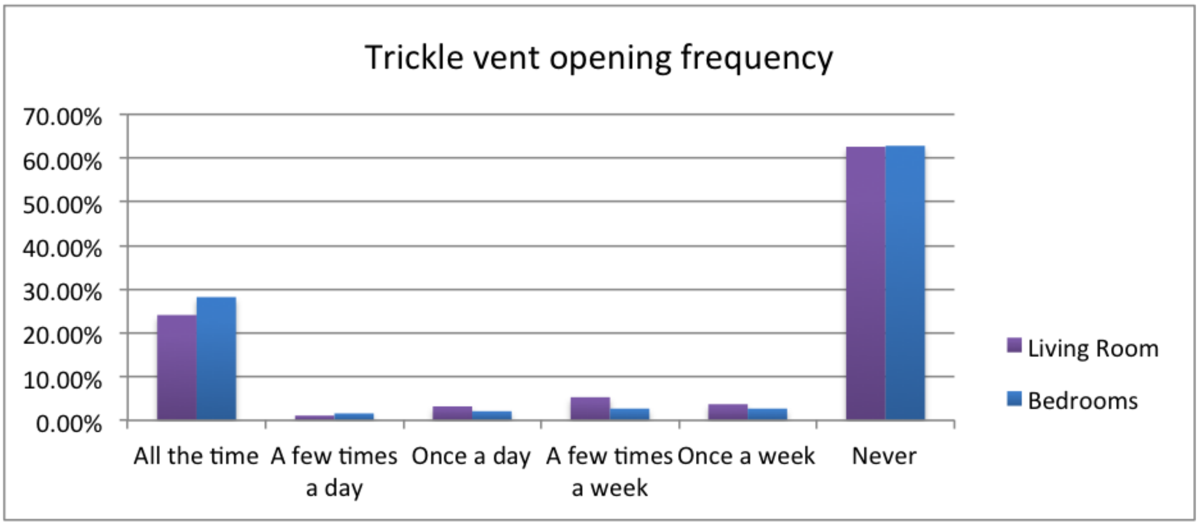


Figure 6: Trickle vent opening frequency.

Occupants were asked why they did not use the trickle vents (Figure 7). The reasons were varied, but were consistent between living rooms and bedrooms. These include lack of awareness of the purpose or location, nuisances such as draughts and noise, but in comparison to window opening (see Figure 12), concerns over heat loss were very small.

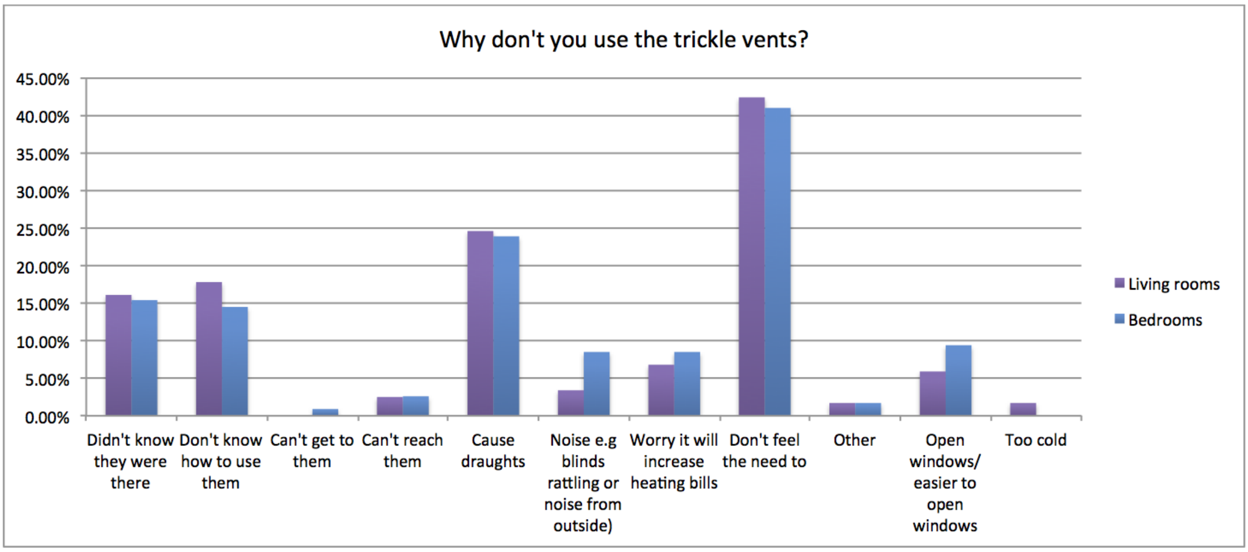


Figure 7: Reasons for not using trickle vents

Of interest however is the fact that the largest response was from occupants who didn't feel the need to (41%). This is backed up by responses to questions about air quality, with 92% of respondents describing the air quality in the living room as good or very good. This is an important finding in this debate, particularly in the light of measured levels of ventilation discussed in the following sections, which illustrates that in some rooms very poor air quality is observed.

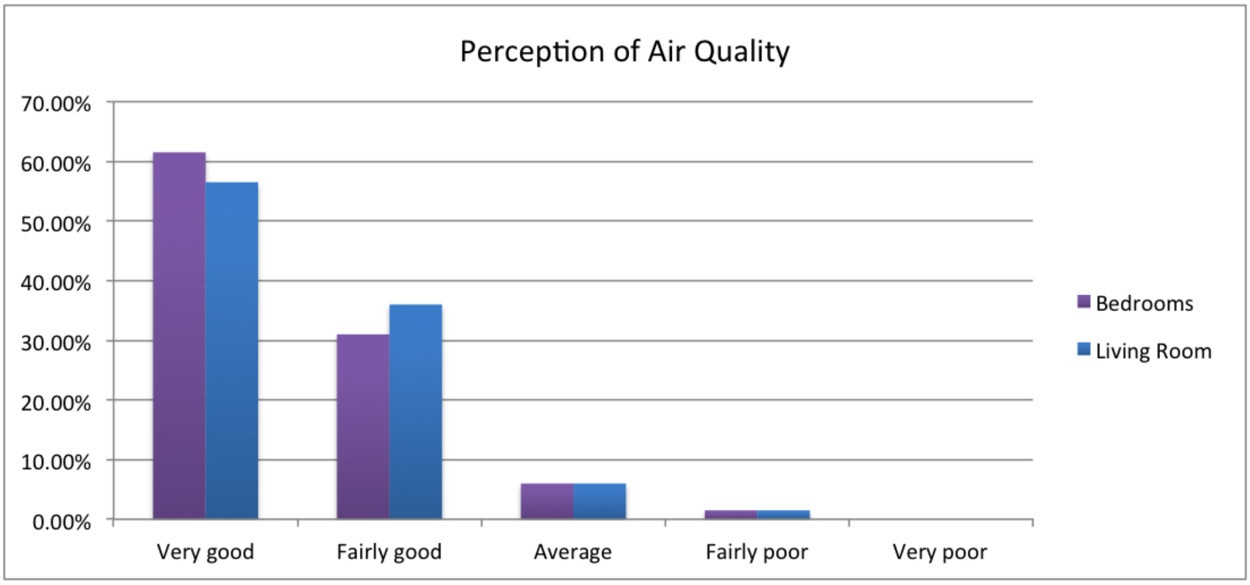


Figure 8: Perception of Air Quality

A lack of awareness of their presence (15%) or how to use them (15%) presented a relatively significant group. The former corresponds with the overall question about knowledge of what the trickle vent is, and the latter must be influenced by the general lack of advice – of the 18% of occupants who had received advice only 37% had received specific instruction on the use of the vents (about 6% of the total). Of those that had received advice, the information provide was generally relevant.

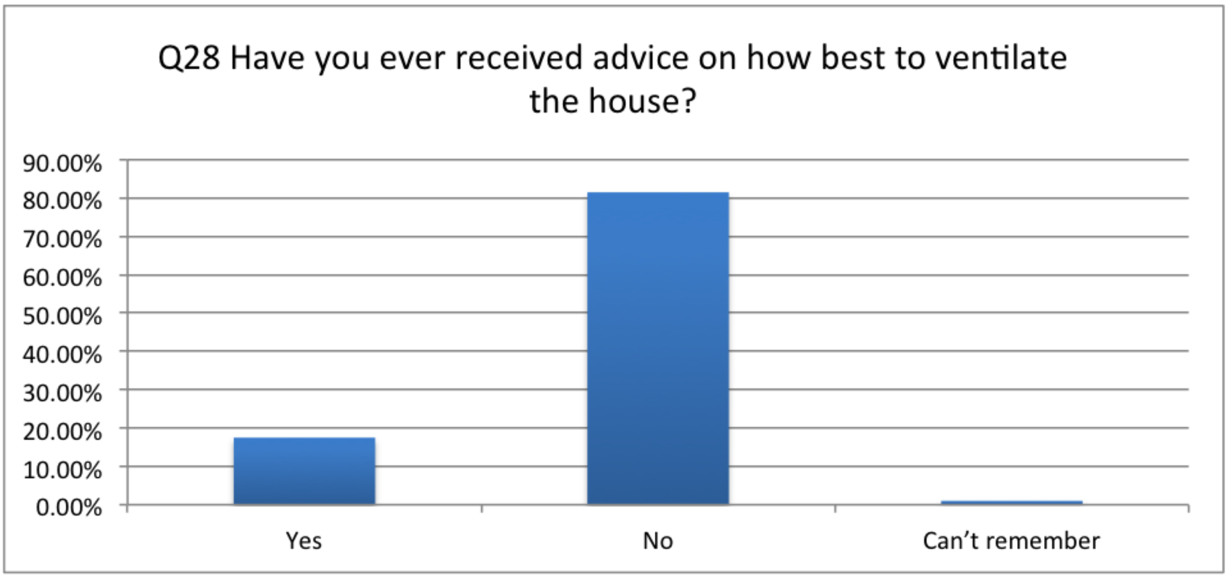


Figure 9: have you received advice on how best to ventilate the house?

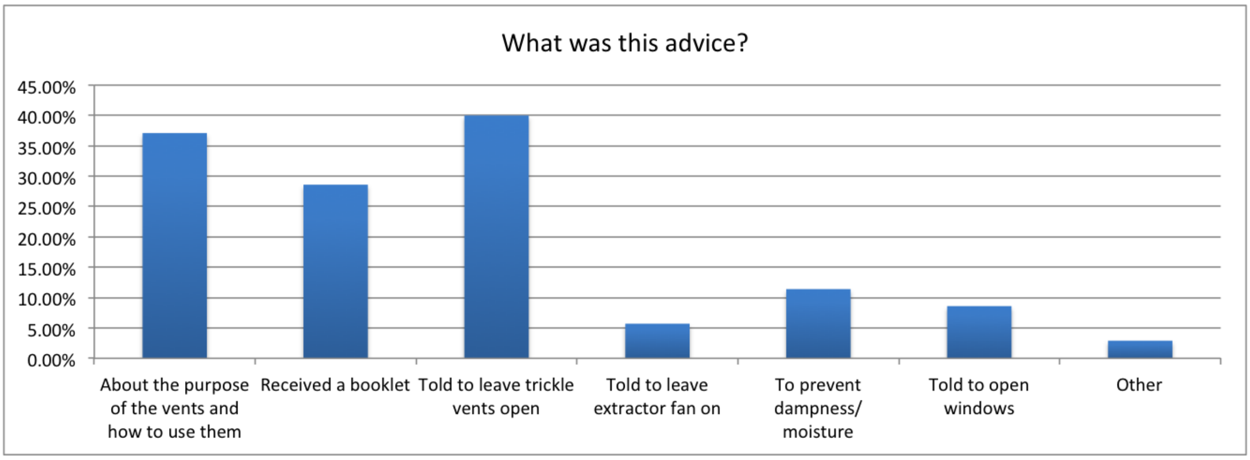


Figure 10: What was this advice?

Window opening behaviours.

Occupants were asked about the window opening use in the living room and bedroom. The presumption in regulations is that window opening provides the facility for purge ventilation and is under the control of the occupants. The survey showed that patterns of window opening were more diverse than trickle vent use, nevertheless the majority of occupants (45%) never open the living room windows or only open them a few times a week, in contrast to 12% opening them all the time. Bedrooms showed a similar response with 41% never opening them or opening them occasionally, but interestingly a higher proportion (20%) have them open all the time.

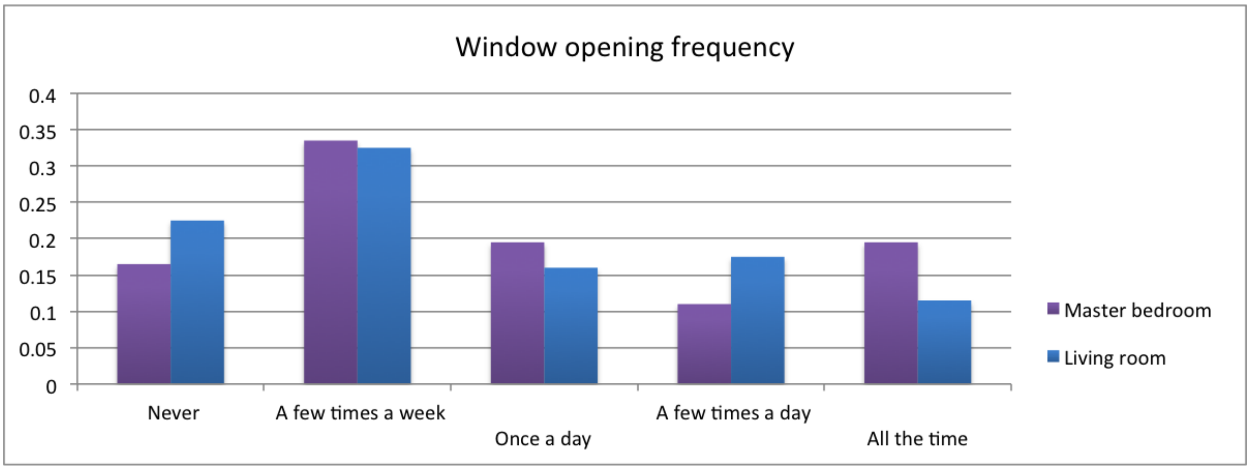


Figure 11: Window opening frequency

Occupants were also asked about the drivers and barriers for opening windows. It is clear that control of temperature is the predominant factor, with ‘too warm’ being the main reason (75% living rooms, 72% bedrooms) for opening windows and ‘heat loss’ being the main reason for keeping them closed (60% living rooms, 59% bedrooms).

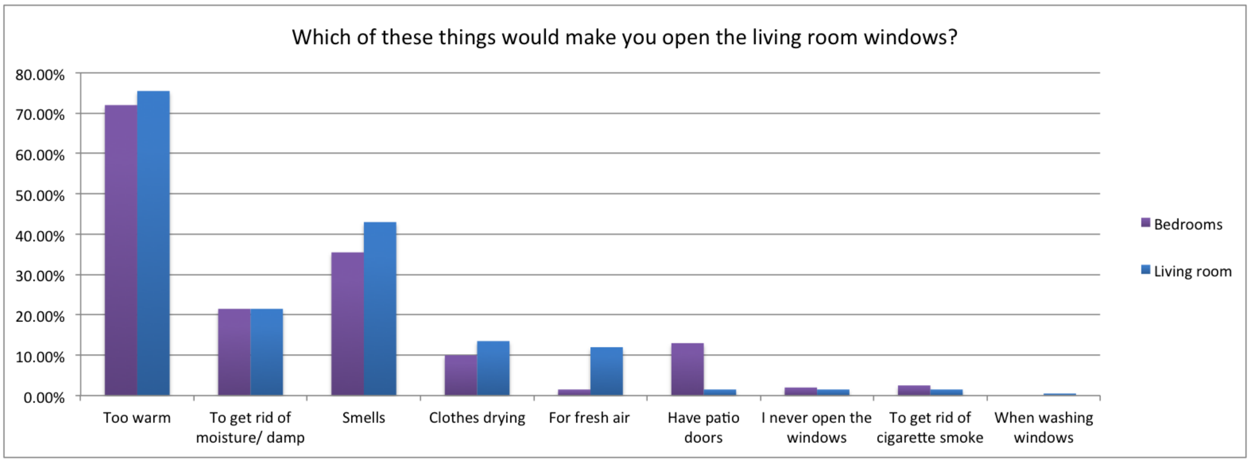


Figure 12: Window opening drivers

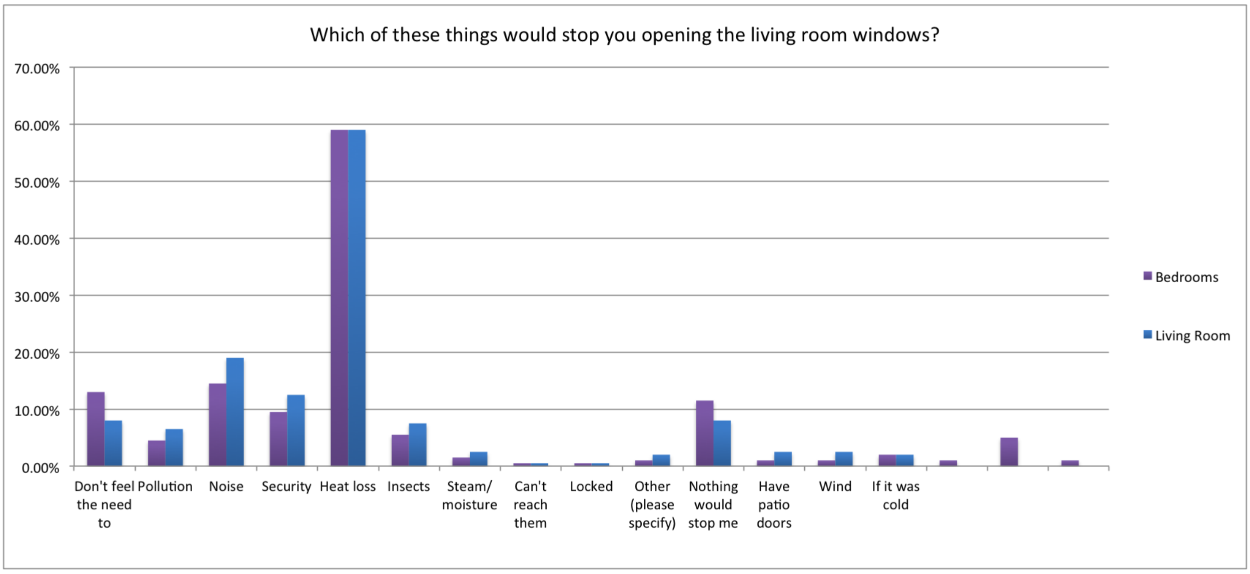


Figure 13: Window opening barriers

A number of incident triggers were cited, for example smells (43% living rooms, 35% bedrooms). Use of window opening to deal specifically with clothes drying was very low (10%), despite almost all respondents reporting drying clothes in the house, with 31% drying every day and 57% drying every 2-3 days.

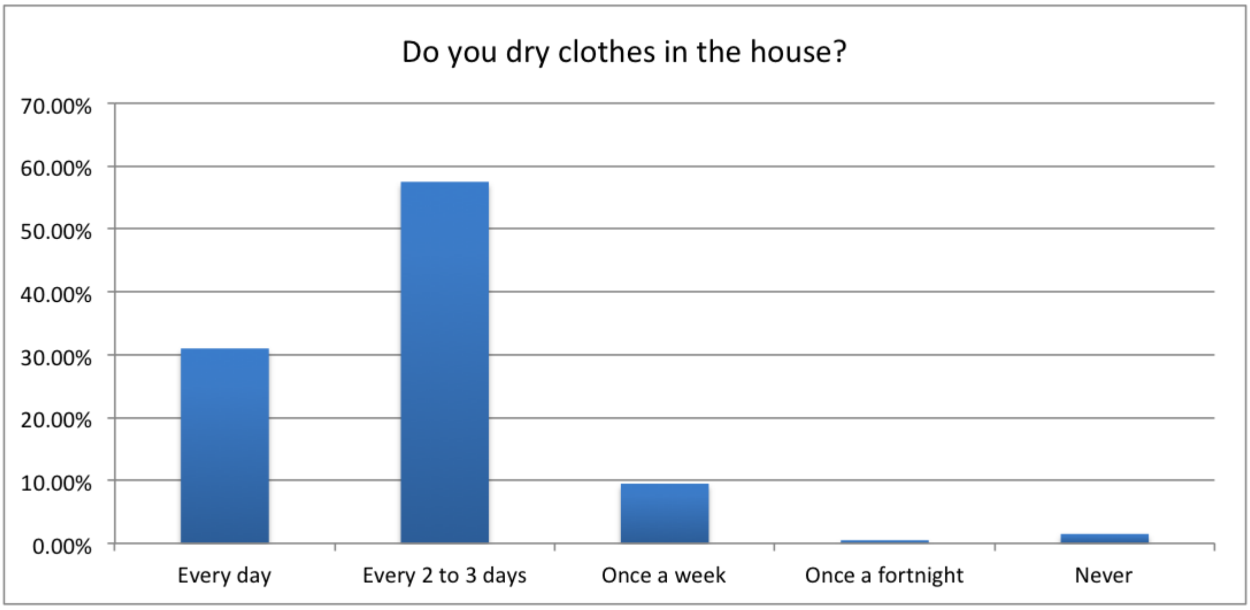


Figure 14: Internal clothes drying

Specific questions were asked about bedroom ventilation habits that could impact on the efficacy of the ventilation provision, for example occlusion of windows by blinds and curtains and door opening. Occupants were asked to indicate whether curtains or blinds were closed, and whether bedrooms doors were closed..

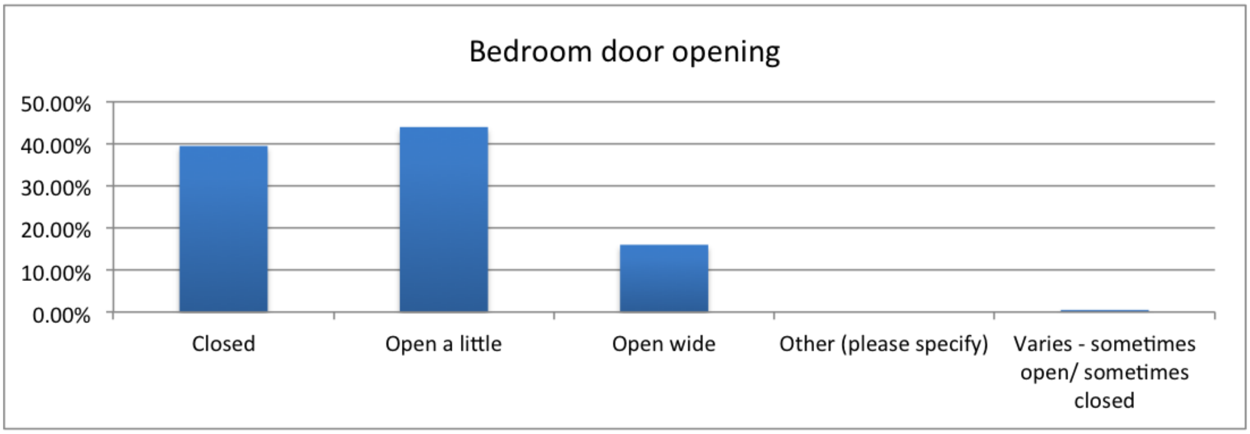


Figure 15: Bedroom door opening

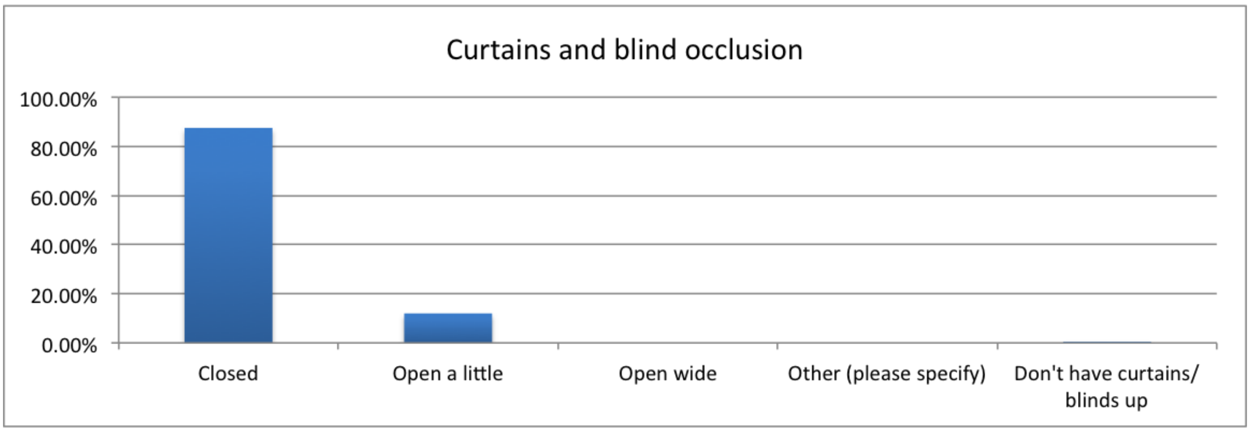


Figure 16: Bedroom curtain/blinds closed

Most occupants had blinds or curtains closed overnight (88%) and 40% had the door closed, with a further 44% having it open a little. Only 16% had the door open wide. Whilst this could be read that a larger proportion (60%) have doors open fully or partially, thus facilitating air movement across the house, this must be seen in the context of general responses about trickle vent use, with the large majority being closed. Closing of doors is not an unreasonable activity in homes, and many types of dwellings, for example flats, may have self-closers to meet fire regulations or lack of provision for cross ventilation due to their built form. Therefore relying on doors being open or the availability of cross ventilation may not be a robust strategy for natural ventilation.

Summary

The survey provided a very clear picture of window and trickle vent use in new housing in Scotland. Occupants are aware of the purpose of trickle vents, however the majority of trickle vents are closed. Windows are preferred as a method of ventilation, but this tends to be as a means to control temperature rather than air quality. The fact that a large proportion of occupants did not feel the need to open trickle vents may be due to the more immediate effects of window opening for controlling tangible environmental issues such as heat, whilst lack of ventilation is less easily detected or perceived. This is even more the case in bedroom spaces, wherein at the beginning of the night when occupants go to bed conditions are reasonable, but deteriorate overnight, and only improve due to window opening in the morning, or occupants leaving the bedroom.

The general picture from the survey illustrates the tensions that arise between energy and ventilation quite clearly, with concern about heat loss being the main reason for not opening windows.

4. Sample Monitoring

Two questions arise from this survey, the first being what environmental conditions are experienced as a result of these behaviours? The second is whether more frequent use of trickle vents results in improved ventilation and consequent air quality?

To investigate the actual conditions being experienced, three monitoring programmes were conducted as part of this study. The first took a sub-set of 40 houses from the overview survey and undertook sample monitoring for a 48 hour period, measuring temperature, relative humidity and CO_2 levels, as well as collecting contextual information on occupancy and observations of conditions and the findings from this are described in this section. The second collated data from the on-going TSB BPE studies and asked occupants to keep a detailed diary over a week long period, during which they were asked to keep trickle vents open. The third study undertook measurements of indoor pollutants in a sample of these properties. The findings from this are described in Section 5.

Data was gathered on environmental conditions in living rooms and bedrooms, but this analysis has concentrated on ventilation in bedroom spaces for several reasons. Firstly on-going monitoring suggests that CO_2 levels, and by implication ventilation rates, whilst exceeding the 1000 ppm level at key times, are reasonable in living rooms spaces. This was further identified in data gathered from the TSB studies. However, accurate assessment of ventilation provision is extremely difficult in these types of spaces. Occupancy, in terms of both time and number of occupants is highly variable, as are other confounding variables, such as window and door opening, cooking and clothes drying, and physical form. Thus high CO_2 levels may be the result of number of occupants rather than the ventilation measures. As a result is it very difficult to isolate specific incidences of occupant interaction with trickle ventilation and window opening from this data. Whilst peaks of CO_2 levels were apparent and in some instances effects of window opening can be identified, as numbers of occupants, times of occupancy, and other contributors to CO_2 are unknown variables, the effects of user interaction with ventilation, in particular trickle vents is harder to identify.

In comparison bedrooms are the spaces in which occupants spend the most uninterrupted time, typically 7–8 hours, and children may also use bedrooms for socialising and schoolwork in which case they could spend almost all their time at home in the bedroom. Furthermore, bedrooms over-night present steady-state conditions with occupants asleep, with little or no adaptive behaviour – ventilation regimes established at the time of going to bed remain in force overnight. Accordingly, environmental conditions in bedroom spaces have become the principal focus for the monitoring as this allows the effects of varying ventilation strategies to be identified.

The overview survey discussed in Section 3 clearly identified that occupant interaction with ventilation is generally infrequent. Accordingly the methodology adopted in this work package attempted to identify the effects of ventilation regimes.

Monitoring Setup
The WP3 stage required the monitoring of up to 40 representative properties for a 48 hour period, monitoring environmental conditions in the living room and bedroom. It was initially thought that this could be included as a further stage in the overview survey, however as this was a doorstep study a revised protocol for identifying and selecting sites for the follow up sample monitoring has been developed and implemented. As part of the overview sampling occupants were asked to indicate whether they would be willing to participate in the follow up study and information about this was provided to those who expressed an interest.

During the pilot study a 'trigger question' asking about window opening was used to control whether occupants were asked to participate, however this yielded low response rates. At the end of February, 69 addresses for sample monitoring were identified, of which 48 (79%) reported having bedroom and living room windows closed. Of these 48 houses, 14 (29%) reported having trickle vents open.

Monitoring Protocol
Whilst there was merit in asking occupants to set prescribed ventilation conditions, this introduced an experimental, rather than observational dimension, which would have been difficult to control so this was not undertaken. The agreed method was that the 48-hour monitoring periods would sample the houses 'as found', to observe effects of occupant interaction (if any) but would note possible window occlusion, number of occupants, overnight door conditions and external conditions. During installation some evidence of the Hawthorne effect [100] was noted, with occupants being more aware of ventilation issues (having participated in the original doorstep survey), and so care was taken to ensure that the monitoring did not influence behaviours.

It was also determined the monitoring should focus on bedrooms for two reasons. Firstly, the bedrooms are clearly more challenging spaces in terms of ventilation, in terms of their occupancy and adaptive behaviour, but also through the ability to observe effects of ventilation strategies. This is much more difficult in living rooms, where patterns of occupancy are highly variable and environmental conditions are affected by a wide range of variables, to the extent that that it would be difficult to isolate the effect of trickle vents. Secondly, the access rate for the monitoring was much slower than predicted, so more parallel monitoring could be undertaken for bedrooms only.

The equipment used in the study were sets of Gemini Tinytag TGE-0020 CO_2 loggers, and Tinytag TGU 400 temperature and relative humidity sensors. These were selected because of their accuracy, portability and lightweight. The loggers are set up to log at 5 minute intervals, which provides sufficient granularity for the study, but is within the capacity of the units. The CO_2 sensor (unlike the temp/RH unit) does require to be plugged in, which restricts its placement to a certain degree, but the locations are noted as part of the study. In each house there are two sets, one recording temperature,

[100] Schwartz, D, Baruch F, Tamar K, and Fallaw S. (2013). The Hawthorne effect and energy awareness. *Proceedings of the National Academy of Sciences of the United States of America* 110, no. 38: 15242-6. http://www.pnas.org/content/110/38/15242.short

humidity and CO_2 in the living room, and the other recording temperature, humidity and CO_2 in a bedroom.

A protocol for equipment deployment was agreed, which required a relatively short visit to install the loggers and collect additional data from the houses. This allows the collection of contextual information, including information on the house type, and also photographs of the location. See Appendix C, Survey Protocol for further information. In this this element of the study data is anonymised as part of the ethical requirements of the research.

Surveys of 61 houses identified through the questionnaire have been conducted from March through to May 2014 with access granted to 47 dwellings. Of these 40 provided usable data. Exclusions occur where residents have turned off CO_2 loggers, or did not occupy bedrooms. In only one circumstance results were excluded following the identification of potential construction defects.

Properties included were a mixture of timber frame, masonry and steel frame constructions all featuring intermittent ventilation to bathrooms and kitchens with trickle vents positioned in window frames of each apartment.

In addition to CO_2, temperature and relative humidity logging, monitoring included a measured survey of each living room and bedroom with dimensions, orientation, location of windows & doors, occlusion to vents, door undercut size and possibility of cross ventilation within the property recorded.

It was apparent that the questionnaire process had raised awareness about the purpose and use of trickle vents some months before the physical monitoring. Therefore the position of the trickle vent, open or closed, was recorded, and occupants were asked to maintain their trickle vent positions in the state they were reported in the initial survey, that is open or closed. It was apparent from the general survey that diurnal trickle vent interaction is very rare (only 4% used them once a day or more) and this statistic is reflected in the monitored properties in which only one property interacted with the vents during the period.

Finally, residents were asked to occupy the property as normal and to complete a diary, for the 48 hour monitoring period including the number of occupants and the opening of windows and doors in both the living room and bedroom.

Results – CO_2 Surveys

Physical Properties

Surveys were conducted across a mixture of flatted accommodation (62%), two storey detached, semi-detached, terraced, maisonette houses (34%) and single storey bungalow style dwellings (4%). A summary of monitoring data collected is given in Table 3 below.

	Code	Type	Number of Storeys	Bedroom Storey	External Elevations with Windows	Bedroom Window Orientation	Cross Ventilation within dwelling	Door Undercut (mm)	Cross Ventilation within room	En Suite	Vent Position	Window Position	Door Position	Occupancy (number of people)	Area (m2)	Volume (m3)	Design Air-Tightness Level (m3/hr/m2@50 Pa)	Air-Tightness Level (m3/hr/m2@50) Pa(not tested: BC sample test info)
1	T1	Semi-Detached	1	Grd	East & West	East	Yes	5	No	No	Closed	Closed	Closed	2	10.89	26.3	n/a	3.21
2	T2	Semi-Detached	1	Grd	North & South	North	Yes	5	No	No	Closed	Closed	Open Day 1, Closed Day 2	2	13.6	31.8	n/a	5.18
3	T3	Flat	1	1st	North & South	North	Yes	0	No	No	Closed	Closed	Open	2	10.95	28.9	n/a	6.75
4	T4	Flat	1	Grd	North & South	North	Yes	10	No	No	Open	Open Day 1, Closed Day 2	Open	2	11.56	27.5	n/a	2.37
5	T5	Flat	1	Grd	North & South	South	Yes	0	No	No	Open	Closed	Open	2	10.56	25.7	n/a	3.21
6	FG1	Flat	1	1st	East & South	East	Yes	0	No	No	Open	Closed	Open	2	11.12	26.7	n/a	5.389
7	FG2	Flat	1	3rd	West & North	West	Yes	0	No	No	Closed	Closed	Closed	2	11.77	28.6	n/a	5.389
8	FG3	Flat	1	Grd	East & South	East	Yes	0	No	No	Closed	Closed	Open	2	11.4	26.9	n/a	5.389
9	FG4	Flat	1	Grd	West & South	West	Yes	0	No	No	Closed	Closed	Open	1	12.58	30.2	n/a	5.389
10	FG5	Flat	1	Grd	East & North	East	Yes	0	No	No	Closed	Closed	Open	2	12.08	29	n/a	5.389
11	WG1	Flat	1	1st	North & South	South	Yes	20	No	No	Closed	Closed	Closed	2	12.89	31.8	7	3.94
12	WG2	End Terrace	2	1st	East & West	West	Yes	10	No	No	Closed	Closed	Closed	1	12.84	30.9	7	3.94
13	WG3	Flat	1	1st	East & West	West	Yes	5	No	No	Open	Closed	Closed	2	11.74	28.2	7	4.75
14	WG4	End Terrace	2	1st	East & West	West	Yes	25	No	No	Closed	Closed	Closed	1	11.44	28.1	5	2.38
15	WG5	End Terrace	2	1st	East, South & West	West	Yes	25	No	No	Open	Closed	Closed	2	12.55	30.1	5	2.38
16	WG6	Flat	1	1st	East & West	East	Yes	20	No	No	Open	Closed	Closed	1	12.98	31.3	5	2.38
17	WG7	Flat	1	1st	North & South	South	Yes	20	No	No	Closed	Closed	Open	0	11.74	28	7	3.94
18	WG8	Semi-Detached	2	1st	North, East & South	North	Yes	10	No	No	Open	Closed	Closed	2 to 6	12.69	30.5	7	3.94
19	WG9	Semi-Detached	2	1st	East & West	East	Yes	5	No	No	Closed	Closed	Closed	1	12.15	29.3	7	4.75
20	WG10	End Terrace	2	1st	East, North & West	West	Yes	10	No	No	Open	Closed	Closed	2	11.28	27.2	5	2.38
21	WG11	Mid Terrace	2	1st	East & West	East	Yes	20	No	No	Closed	Closed	Closed	1	12.55	30.1	5	2.38
22	E1	Flat	1	1st	SW, NW & NE	North-West	Yes	20	No	No	Closed	Closed	Open	3	10.96	26.3	10	n/a
23	E2	Flat	1	Grd	SE, SW & NW	South-West	Yes	0	No	No	Open	Closed	Closed	1	18.4	26.5	10	n/a
24	E3	Flat	1	2nd	SE, SW & NW	South-West	Yes	10	No	No	Closed	Closed	Closed	3	11.25	30.6	10	n/a
25	E4	Mid Terrace	2	1st	NE & SW	North-East	Yes	5	No	No	Closed	Open	Open	1	11.34	27	10	n/a
26	E5	Flat	1	Grd	SW, SE, NW & NE	SW & SE	Yes	15	Yes	No	Closed	Closed	Closed	1	12.38	29.7	10	n/a
27	E6	Flat	1	1st	SW, SE, NW & NE	SW & SE	Yes	0	Yes	No	Closed	Open	Open	2 (Day1); 1 (Day2)	12.54	30.1	10	n/a
28	E7	Flat	1	2nd	SW, SE & NE	South-East	Yes	0	No	No	Open	Closed	Open (Day1); Closed (Day2)	1	11.92	28.6	10	n/a
29	E8	End Terrace	2	1st	NE & SW	North-East	Yes	10	No	No	Closed	Closed	Closed	1	11.76	28.6	10	n/a
30	E9	Flat	1	Grd	NE & SW	South-West	Yes	15	No	No	Closed	Closed	Closed (Day1); Open (Day2)	2	10.88	25.3	10	n/a
31	E10	Flat	1	1st	NE & SW	South-West	Yes	0	No	No	Open	Closed	Closed	2	12.77	30.7	10	n/a
32	E11	Mid Terrace	2	1st	NE & SW	South-West	Yes	5	No	No	Open	Open	Open	1	11.51	27.5	10	n/a
33	E12	End Terrace	2	1st	NE & SW	South-West	Yes	20	No	No	Closed	Closed	Open	1	11.61	27.9	10	n/a
34	E13	Flat	1	Grd	SE, SW & NW	South-West	Yes	0	No	No	Closed	Closed	Closed	1	11.25	26.99	10	n/a
35	E14	Flat	1	2nd	SW, NW & NE	North-West	Yes	3	No	No	Closed	Closed (Day1); Open (Day2)	Closed	1	11.25	30.59	10	n/a
36	E15	Flat	1	1st	SE, SW & NW	South & Sout	Yes	10	Yes	No	Open	Closed (Day1); Open (Day2)	Closed	3	13.23	31.88	10	n/a
37	E16	Flat	1	1st	SW, NW & NE	North-West	Yes	10	No	No	Closed	Closed	Closed	2	11.28	27.07	10	n/a
38	E17	Flat	1	3rd	SW, NW & NE	North West	Yes	0	No	No	Open	Open	Closed	1	11.21	30.37	10	n/a
39	VG1	Flat	1	Grd	North & South	North	Yes	10	No	No	Closed	Open	Open	2	12.28	28.98	10	n/a
40	VG2	Flat	1	Grd	North & East	North	Yes	15	No	No	Closed	Open	Open	2	10.41	24.56	10	n/a
41	VG3	Flat	1	1st	North & East	North	Yes	0	No	No	Closed	Closed	Closed	1	10.49	24.85	10	n/a
42	VG4	Flat	1	1st	North & South	North	Yes	10	No	No	Closed	Open	Closed	2	10.15	23.95	10	n/a
43	VG5	Maisonette	2	Grd	North & South	South	Yes	10	No	No	Open	Open	Closed	2	8.03	20.15	10	n/a
44	EK1	Detached	2	1st	East & West	West	Yes	10	No	Yes	Open	Closed	Closed	1	16.64	38.94	6	3.53
45	EK2	Detached	2	1st	North & South	South	Yes	10	No	Yes	Closed	Closed	Open	2	14.32	33.5	6	3.53
46	S1	Detached	2	1st	North & South	South	Yes	10	No	Yes	50% Open	Closed	Closed	2	12.1	29.06	5	4.33
47	S2	Detached	2	1st	North & South	North	Yes	0	No	Yes	Open	Closed	Open	3	12	28.67	5	4.2

Table 3: Sample monitoring data summary

Window Orientation & Cross Ventilation
Surveys were undertaken at 7 locations with homes varied in orientation and storey height as recorded in Figure 17 above. All properties had at least two windowed elevations allowing the possibility of cross ventilation from front to back (62%) or front to side (38%) assuming internal doors and windows or vents are open. A minority of bedrooms (7%) have a possibility for cross ventilation within the rooms themselves.

All bedrooms monitored within private dwellings had en-suites which increased capacity for cross ventilation through both intermittent extract fans and windows with trickle vents. In three of the four dwellings returning usable data this resulted in CO_2 concentrations close to the recommended 1000 ppm.

While no direct correlation in the results between window orientation and CO_2 concentrations was apparent this is likely to be due to the relatively small number of surveys and other confounding factors. It is predicted that higher external wind speeds, greater exposure and planned air paths would result in increased ventilation rates thereby reducing CO_2 concentrations.

Dimensions
Bedrooms surveyed had an average area and volume of $12m^2$ and $28.6m^3$ respectively. Areas compare well to the Housing for Varying Needs standard which promotes an area of approximately $11.7m^2$ for double bedrooms. Where private housing was surveyed bedrooms areas averaged slightly greater at $13.8m^2$. Again there was no direct correlation between room size and CO_2 concentrations although data collected, and discussed later, does provide evidence that volume, particularly a larger volume created when an internal door is left open, benefits from lower average time weighted CO_2 levels.

Air – Tightness
Air-Tightness Testing was not undertaken as part of this study. However some investigation was conducted with BSD who were able to locate air-tightness test data as submitted to Local Authority Building Control Departments as part of the Completion Certificate process. It is notable that current Building Regulations require there developers to provide a test for 1 in 20 dwellings and none of the dwellings monitored during this study had been the subject of an actual test.

The sample data available does indicate that better than predicted values are regularly being achieved in the tested dwellings. Where this improved performance far exceeds the predicted value, as is the case in a number of these sample tests, there is a potential ventilation risk and in such circumstances consideration should be given to the possibility that the proposed trickle ventilation strategy may no longer be fit for purpose.

Window Position
As anticipated, due to the pre-exclusion of window openers during the initial questionnaire phase the number of households who opened windows was reasonably low at 23%. As indicated in the questionnaire it is generally considered that the number of window openers will rise at warmer times of the year. However no indication of this was noted during the survey period and it remains possible that opening and closing of windows is a habitual act and not solely temperature dependant. Further investigation

would be required across a longer period, which is outside the scope of this investigation.

Assuming the quality of external air is appropriate the opening of a window for either purge or continuous ventilation will greatly reduce the presence of CO_2 and other toxins. Figure 17 below was recorded in the same bedroom on consecutive nights with similar occupant behaviours and demonstrates a reduction in CO_2 due to continuous ventilation provided by leaving a window open overnight.

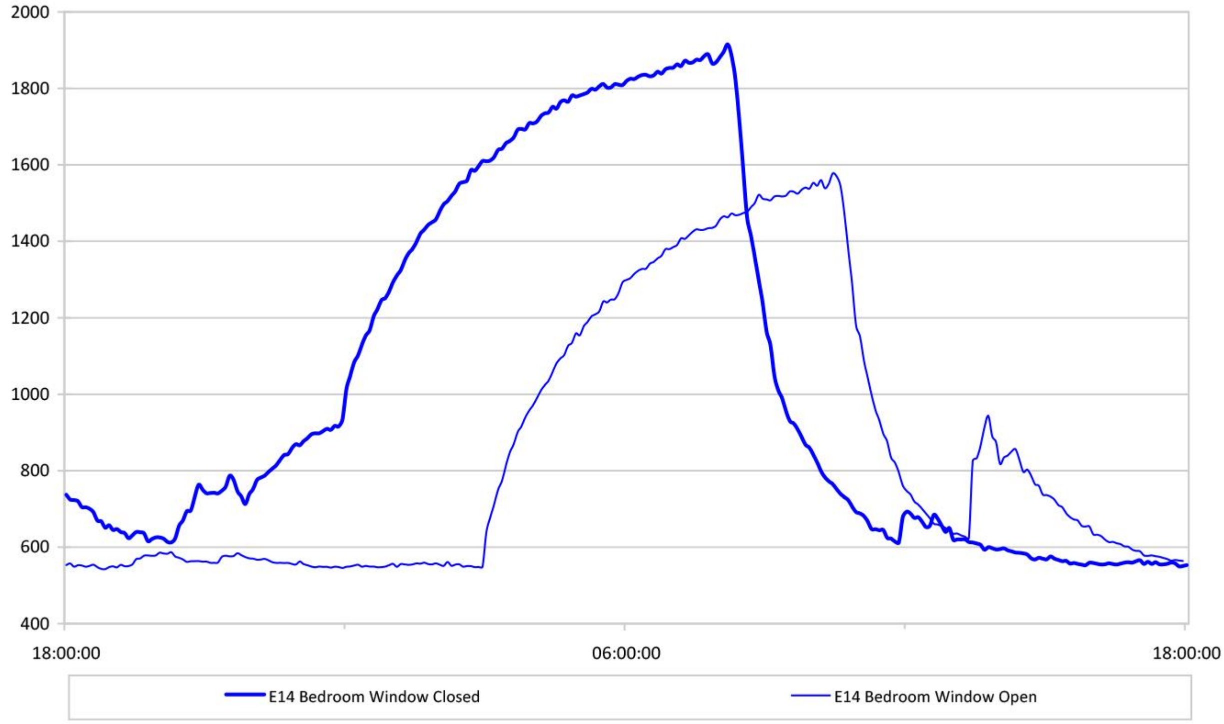


Figure 17: Difference in CO_2 levels when window is open vs window closed. Comparison using the same bedroom under similar conditions on consecutive nights

Despite differing window opening behaviours and regardless of vent position 97% of the rooms with windows closed presented with concentrations of CO_2 greater than 1000 ppm.

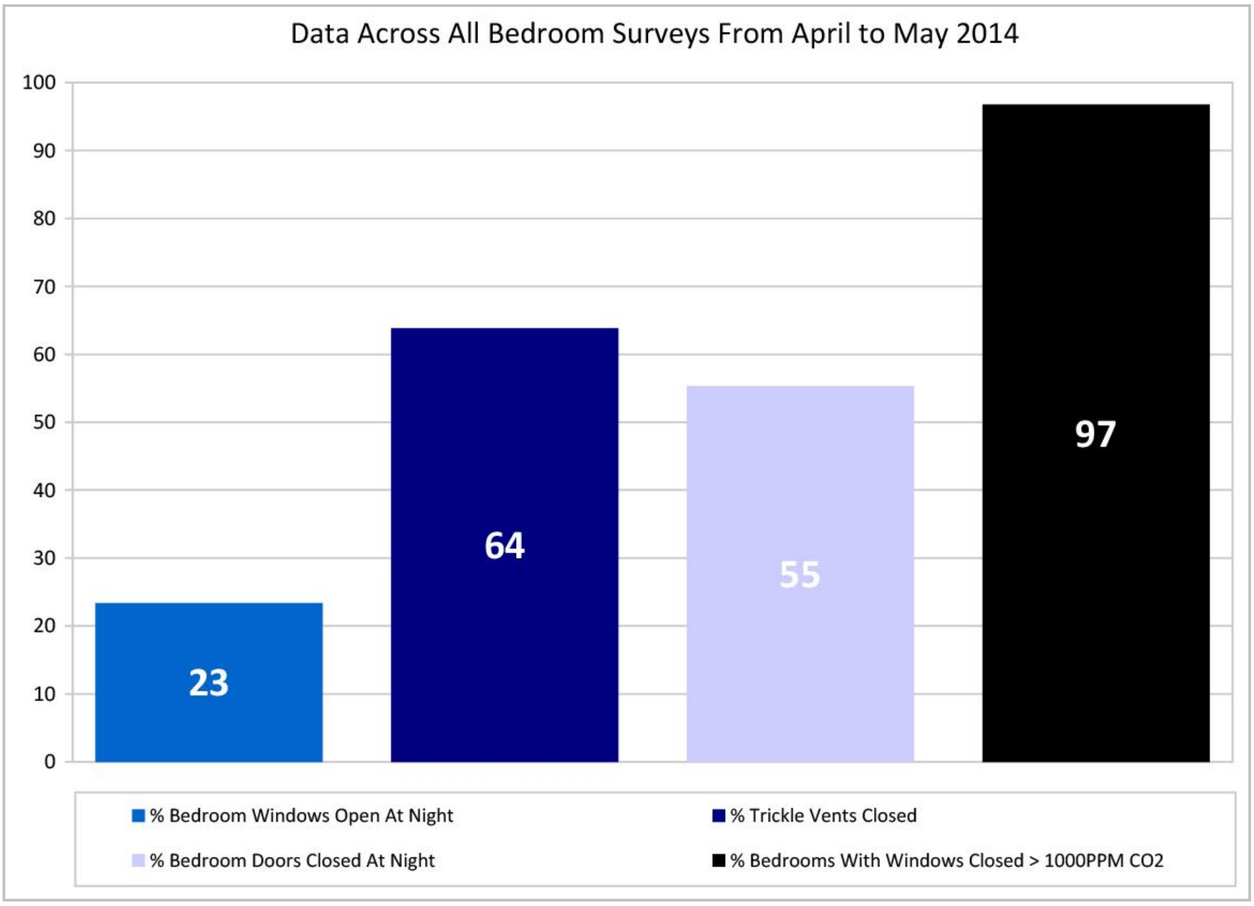


Figure 18: Conditions encountered across CO_2, temperature & relative humidity surveys

Trickle Vent Position

Slightly less than two thirds of properties, some 64%, were found to have trickle vents closed, a result within 1% of the number indicated by the original questionnaire. Coupled with anecdotal resident accounts during the monitoring set up, where only two residents suggested regular use of vents and one reported actual interaction, there is an indication that despite additional knowledge provided by participation in the original survey a majority of residents continue not to use trickle vents to amend their internal environment.

Open Trickle Vent

Closed Trickle Vent

Figure 19: Trickle Vent Positions Open & Closed

Occlusion To Vents

Nearly all dwellings surveyed had some form of obstruction to the vents. While no properties were found to have deliberate blockages to trickle vents it was common to find blinds, curtains or both blocking the ventilation route. It is also likely that use of such obstructions will occur when the room is occupied at night, the very time that higher ventilation rates are required to ensure reasonable indoor air quality is achieved.

Occlusion by Blinds

Occlusion by Curtains & Blinds

Figure 20: Trickle Vent Positions Open & Closed

The average CO_2 concentrations across bedrooms monitored in all 40 dwellings are recorded as 1520ppm. Where windows are open average CO_2 levels recorded were below 1000ppm. It is noteworthy that even with windows open the time weighted average CO_2 level of 972 ppm recorded is well above normal background levels around 400ppm. Where windows are closed, as occurred in 77% of dwellings across the study, time weighted average CO_2 levels were 1752ppm. In this circumstance, when trickle vents remain open the average CO_2 levels are marginally improved, but remain high at 1571ppm. However where windows and vents are closed, as per a third of all properties in the study, CO_2 concentrations are highest with the survey data reporting the average concentration of 1847ppm (Figure 21).

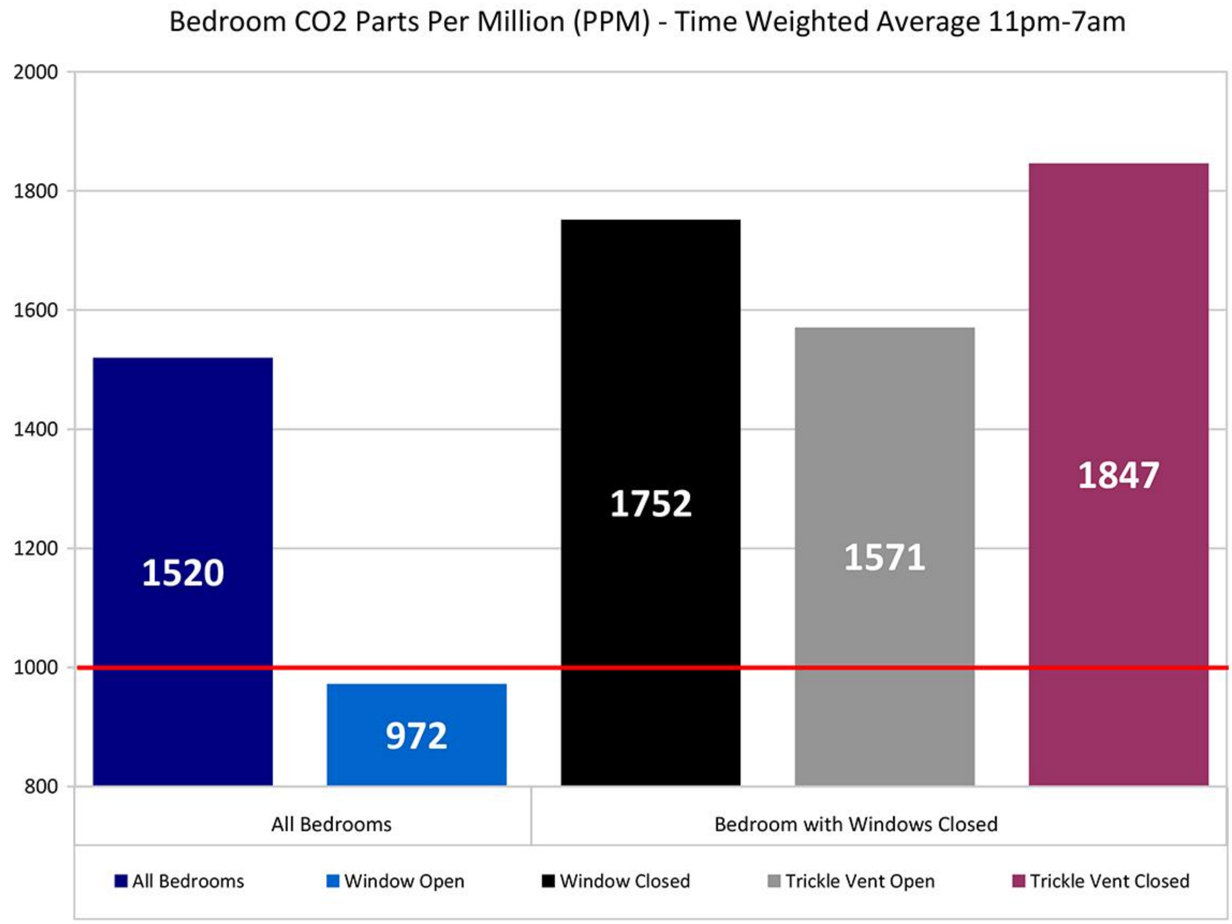


Figure 21: Average CO_2 concentrations in bedrooms with trickle vents open and closed, and windows open and closed.

Occupancy

All bedrooms monitored would be classified as double bedrooms with an average area of $12m^2$ and volume of $28.6m^3$. We encountered a number of different occupancies from a single person up to a maximum of 6 people. These can be considered in 3 categories; under occupancy, 1 person; prescribed occupancy, 2 persons; and over occupancy, 3+ persons. Figure 22 provides the percentage of time that bedrooms presented greater than 1000ppm CO_2, in all 40 monitored properties, divided into these categories and further separated to display rooms with trickle vents or open and windows open or closed.

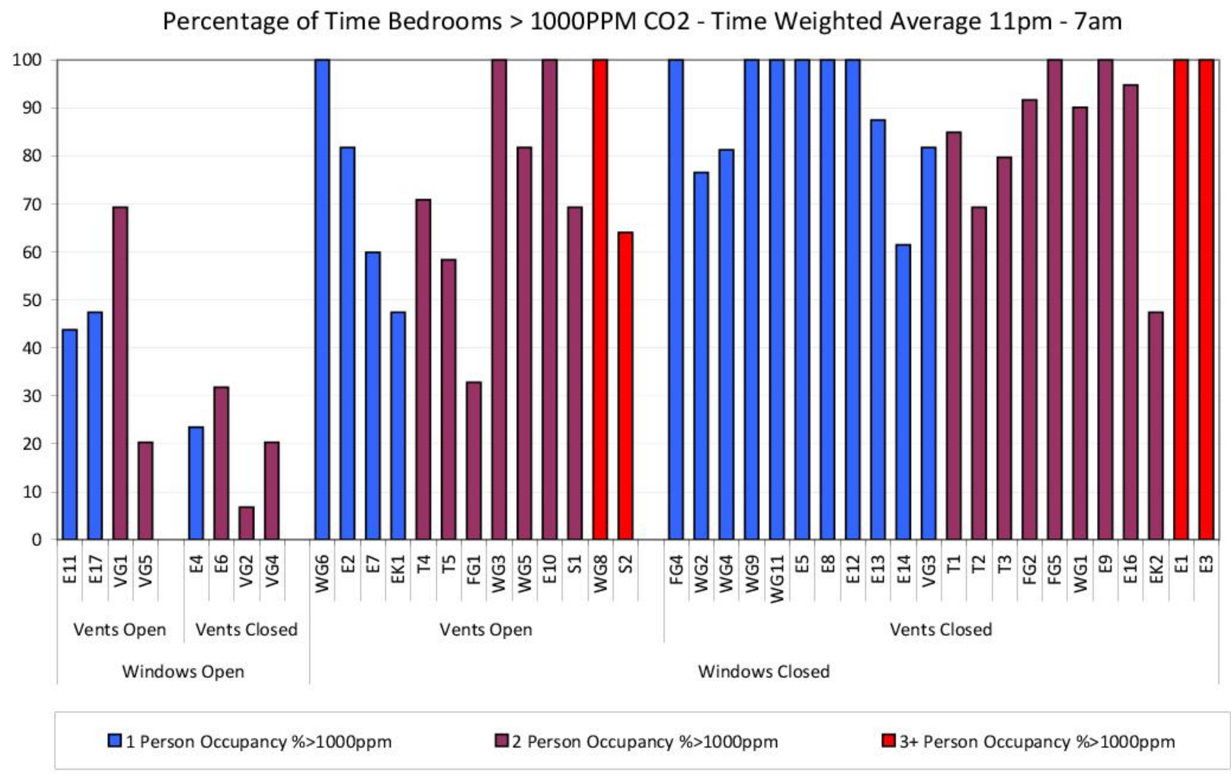


Figure 22: Percentage of time CO_2 levels were found to be above 1000ppm (11pm – 7am)

All properties, regardless of window position, present with levels of CO_2 in excess of 1000 ppm at some point through the night. Where windows are closed, CO_2 levels of 1000 ppm are exceeded for at least 33% of the time. While it is likely that CO_2 levels increase more rapidly in rooms of greater occupation the results do not indicate a definite difference between occupancy rates and CO_2 concentrations when rooms are under occupied or populated as prescribed. It is however noteworthy that of the four bedrooms that were over-occupied, three of them contain levels of CO_2 greater than 1000 ppm continuously between 11pm and 7am. Indeed over 30% of all bedrooms presented with CO_2 concentrations above 1000 ppm all night.

Door Position

Approximately half of households in this sample (57%), closed bedroom doors at night. While the closing of vents and doors create predictable barriers to free ventilation, observations suggest that door closing may be dependant on the number and age of occupants in the household. This appears to be related to different life stages for example, where a young child is present doors are almost always open while it is likely that a teenage or young adult will seek privacy by closing the door. In contrast the elderly tend to open doors especially when challenged by mobility or health issues.

The door undercut provides limited ventilation flow for closed doors. It appears that the introduction of carpets often causes the removal of this ventilation route with the average door undercut size recorded during the survey period being 10mm, while a third of bedrooms had no door undercut. Despite this disadvantage the average time weighted CO_2 for bedrooms with no door undercut was 1368 ppm, a slightly better than average performance overall.

Door Undercut

Door Undercut Blocked by Carpet

Figure 23. Door Undercuts

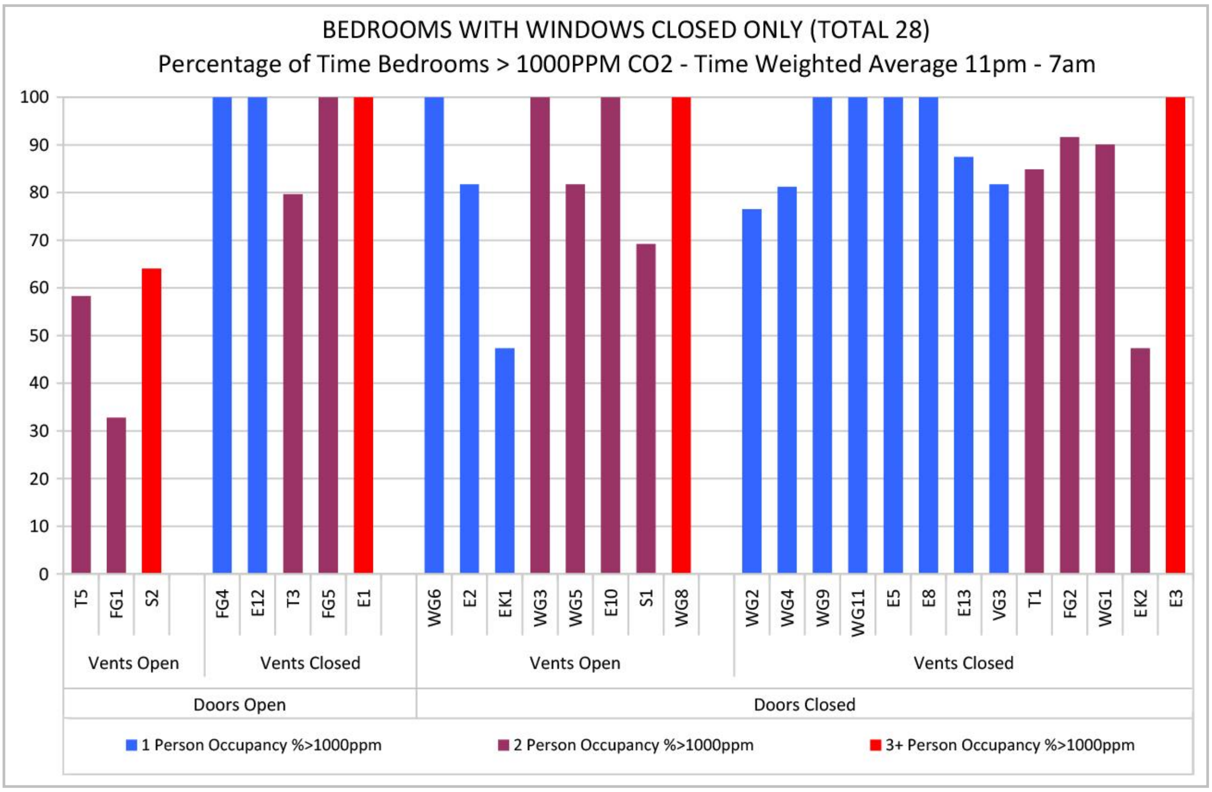


Figure 24: Percentage of time bedrooms have CO_2 concentrations greater than 1000 ppm between 11pm and 7am.

Figure 25: Difference in CO_2 levels when door is open vs door closed. Comparison using the same bedroom on consecutive nights under similar conditions with both window and trickle vents closed.

Where vents and doors are open the percentage of time that bedrooms surveyed had a CO_2 concentration greater than 1000 ppm is greatly reduced as demonstrated in figure 24. CO_2 concentration is slightly reduced when the door is left open but no cross ventilation is provided by a trickle vent or open window due to dilution in a greater volume as demonstrated in figure 25 below.

Figure 26 confirms the improvement with average CO_2 concentrations, where vents and doors are open, only slightly above the recommended 1000 ppm indicating improved ventilation rates. The significance is that where the opportunity for cross ventilation exists and no obstacles to air flow are present it may be possible, given correct weather and wind patterns, to achieve CO_2 concentrations close to the recommended level.

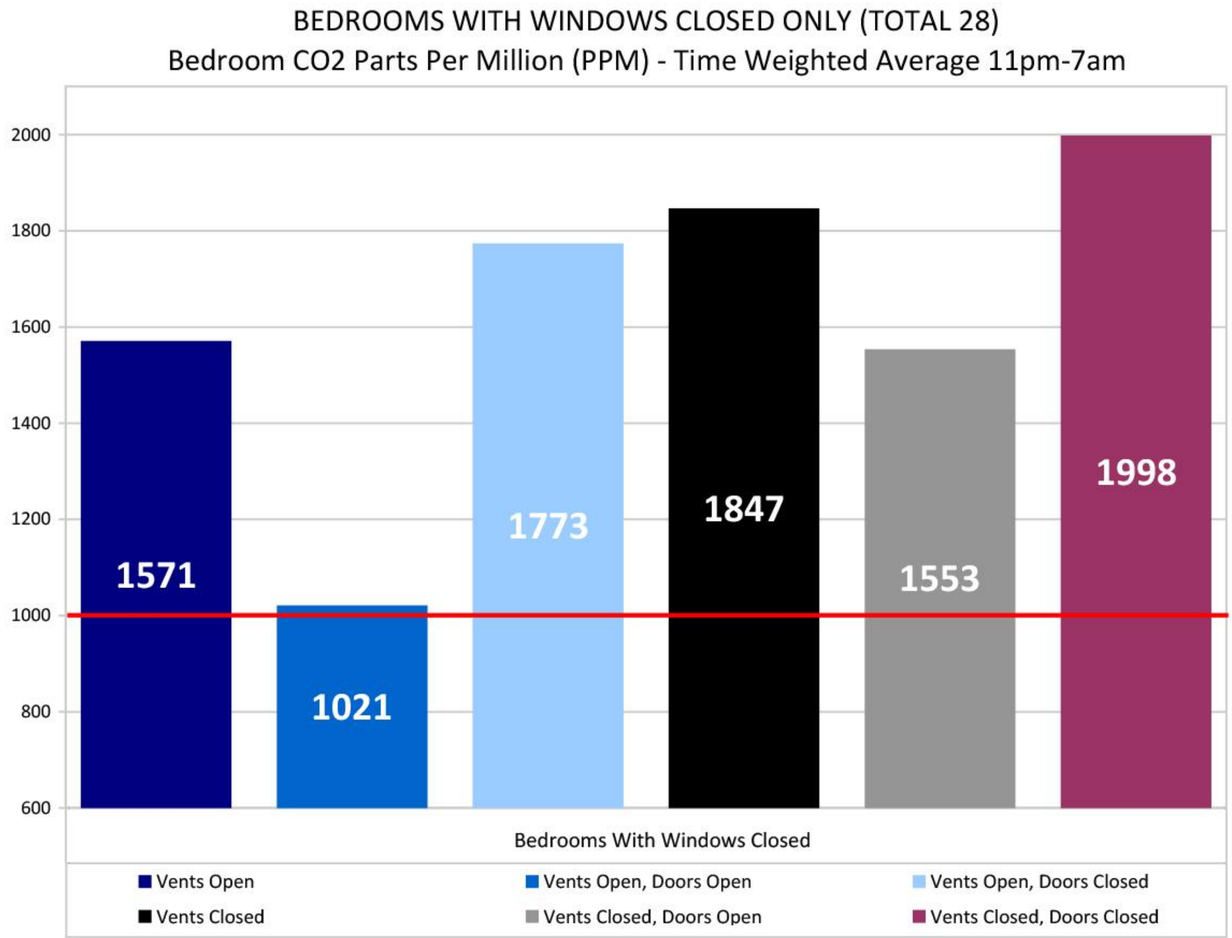


Figure 26: Condition dependant average CO_2 concentrations in bedrooms with trickle ventilation

When considering levels of CO_2 we must acknowledge predictable and necessary user interactions such as closing trickle vents or doors. It is therefore noteworthy that when vents are closed but doors open, concentrations of CO_2 recorded were slightly above average at 1553 ppm (Figure 26) suggesting that while a larger volume of air for dilution is beneficial, movement of air through an increased ventilation rate is key to greatly reducing CO_2 levels. When considered against the potential additional construction cost implications of building larger volumes without impacting on bedroom privacy, ventilation rate becomes even more important.

Importantly the difference between vents open and closed, where doors are closed, is significantly small with both data sets recording average CO_2 at 1773ppm and 1998ppm respectively, well above the recommended 1000ppm level. This is a strong indication that the internal ventilation is a more important effect than that of the trickle vents, whether open or closed.

Temperature and relative humidity

Bedrooms surveyed appear to be generally warm and dry. The overall tendency is for bedrooms to have higher temperatures and resulting lower RH. There was a considerable range across the set – lowest average temperature was 17 ^oC and the highest was 25 ^oC.

		night 1						night 2						total over 2 nights		
	Vent Position	Number of Occupants	Window Position	Door Position	Temp 'C	RH %	CO_2 ppm	Number of Occupants	Window Position	Door Position	Temp 'C	RH %	CO_2 ppm	Temp 'C	RH %	CO_2 ppm
T1	Closed	2	Closed	Closed	19	51	1962	2	Closed	Closed	20	53	2013	19	52	1988
T2	Closed	2	Closed	Open	18	57	968	2	Closed	Closed	18	61	1469	18	59	1219
T3	Closed	2	Closed	Open	17	54	1130	2	Closed	Open	18	59	1152	17	56	1141
T4	Open	2	Open	Open	17	51	959	2	Closed	Open	16	51	1064	16	51	1012
T5	Open	2	Closed	Open	20	47	945	2	Closed	Open	20	47	1253	20	47	1099
FG1	Open	2	Closed	Open	18	57	988	2	Closed	Open	17	55	862	18	56	925
FG2	Closed	2	Closed	Closed	22	56	2046	2	Closed	Closed	21	55	1748	21	56	1897
FG4	Closed	1	Closed	Open	21	65	1367	1	Open	Open	20	66	1413	20	66	1390
FG5	Closed	2	Closed	Open	19	70	1595	2	Open	Open	20	73	2043	19	72	1819
WG1	Closed	2	Closed	Closed	24	56	1926	2	Closed	Closed	21	45	1979	23	51	1953
WG2	Closed	1	Closed	Closed	21	52	1159	1	Closed	Closed	21	49	1012	21	50	1085
WG3	Open	2	Closed	Closed	20	68	2450	2	Closed	Closed	20	65	2618	20	67	2534
WG4	Closed	1	Closed	Closed	20	64	2342	1	Closed	Closed	18	57	1804	19	61	2073
WG5	Open	2	Closed	Closed	17	67	1302	2	Closed	Closed	17	60	1367	17	63	1334
WG8	Open	2 to 6	Closed	Closed	22	60	2155	2 to 6	Closed	Closed	21	66	2414	21	63	2285
WG9	Closed	1	Closed	Closed	21	55	2147	1	Closed	Closed	21	52	2060	21	54	2104
WG11	Closed	1	Closed	Closed	21	48	2306	1	Closed	Closed	25	42	1152	23	45	2294
E1	Closed	3	Closed	Open	20	69	1575	3	Open	Open	20	71	1658	20	70	1617
E2	Open	1	Closed	Closed	18	59	1398	1	Closed	Closed	19	55	1213	18	57	1306
E3	Closed	3	Closed	Closed	21	67	2352	3	Closed	Closed	21	65	2448	21	66	2400
E4	Closed	1	Open	Open	26	53	1005	1	Closed	Open	24	44	687	25	49	846
E5	Closed	1	Closed	Closed	19	71	3119	1	Closed	Closed	19	65	2809	19	68	2964
E6	Closed	2	Open	Open	20	55	1032	1	Open	Open	21	50	1413	20	53	881
E7	Open	1	Closed	Open	18	60	788	1	Closed	Closed	19	55	1345	19	58	1066
E8	Closed	1	Closed	Closed	23	60	2156	1	Closed	Closed	24	61	2328	23	61	2242
E9	Closed	2	Closed	Closed	22	55	2025	2	Open	Open	24	51	1614	23	53	1819
E10	Open	2	Closed	Closed	21	61	2210	2	Closed	Closed	19	61	2692	20	61	2451
E11	Open	1	Open	Open	21	53	1038	1	Open	Open	20	50	944	21	52	991
E12	Closed	1	Closed	Open	21	57	1983	1	Open	Open	20	56	1906	20	57	1945
E13	Closed	1	Closed	Closed	19	57	1592	1	Closed	Closed	19	59	2049	19	58	1821
E14	Closed	1	Closed	Closed	19	60	1504	1	Open	Closed	18	58	832	19	59	1168
E16	Closed	2	Closed	Closed	24	50	2691	2	Closed	Closed	24	53	2896	24	51	2793
E17	Open	1	Open	Closed	19	55	917	1	Closed	Closed	21	56	1279	20	55	1098
VG1	Open	2	Open	Open	22	64	1620	2	Open	Open	22	53	951	22	58	1285
VG2	Closed	2	Open	Open	21	61	801	2	Open	Open	20	54	613	21	57	707
VG3	Closed	1	Closed	Closed	23	71	1411	1	Closed	Closed	23	70	1026	23	70	1219
VG4	Closed	2	Open	Closed	21	61	1511	2	Closed	Closed	21	51	626	21	56	1069
VG5	Open	2	Open	Closed	21	60	900	2	Closed	Closed	20	53	901	20	56	901
EK1	Open	1	Closed	Closed	19	59	1099	1	Closed	Closed	20	58	959	20	59	1029
EK2	Closed	2	Closed	Open	18	63	900	2	Open	Open	17	65	1092	18	64	996
S1	50% Open	2	Closed	Closed	19	68	2412	2	Closed	Closed	19	64	2006	19	66	2209
S2	Open	3	Closed	Open	20	55	1025	3	Open	Open	20	53	1053	20	54	1039

Table 4. Average temperature, humidity and CO2 levels.

Overall 8 out of 42 (19%) rooms had averages over the recommended comfort level of 21. The RH levels were in general within accepted limits, but the range was great varying from 45 to 70. It should also be considered that the high temperatures may be masking moisture content and vapour pressure levels may be of greater concern.

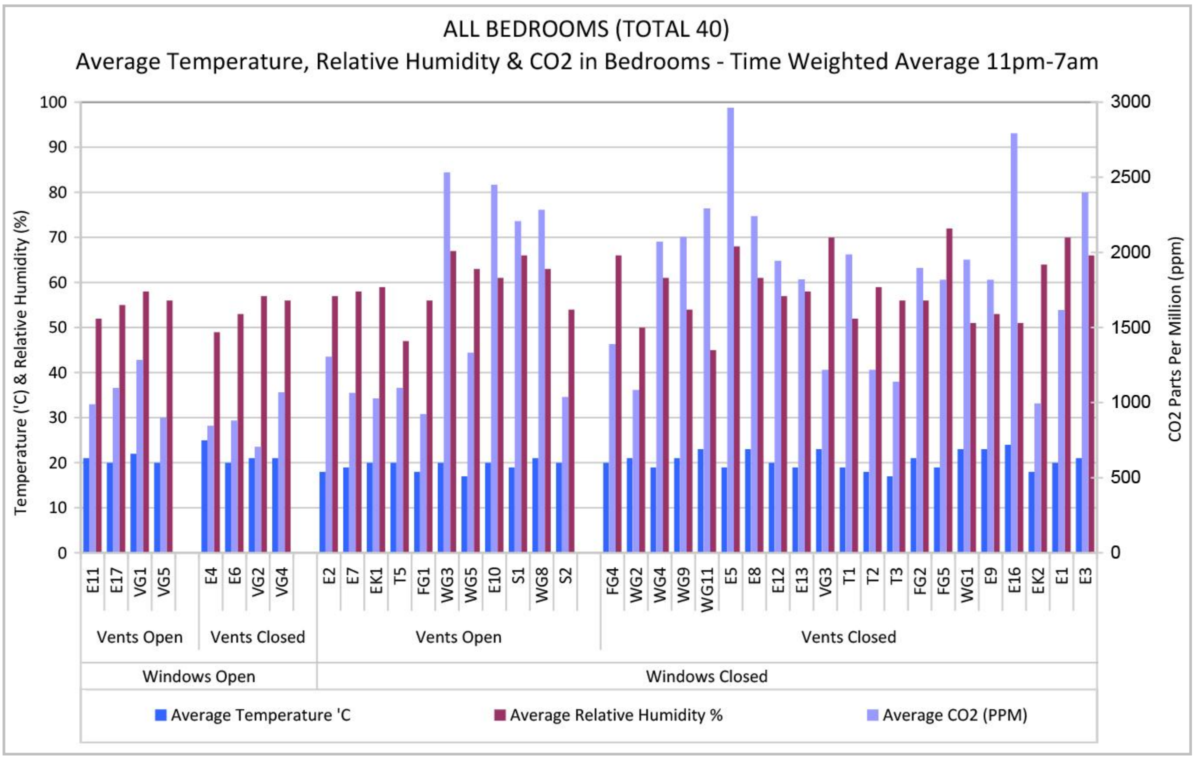


Figure 25. Average Temperature, Humidity and CO_2 levels recorded in bedrooms between 11pm and 7am with Trickle Vent and Window Position.

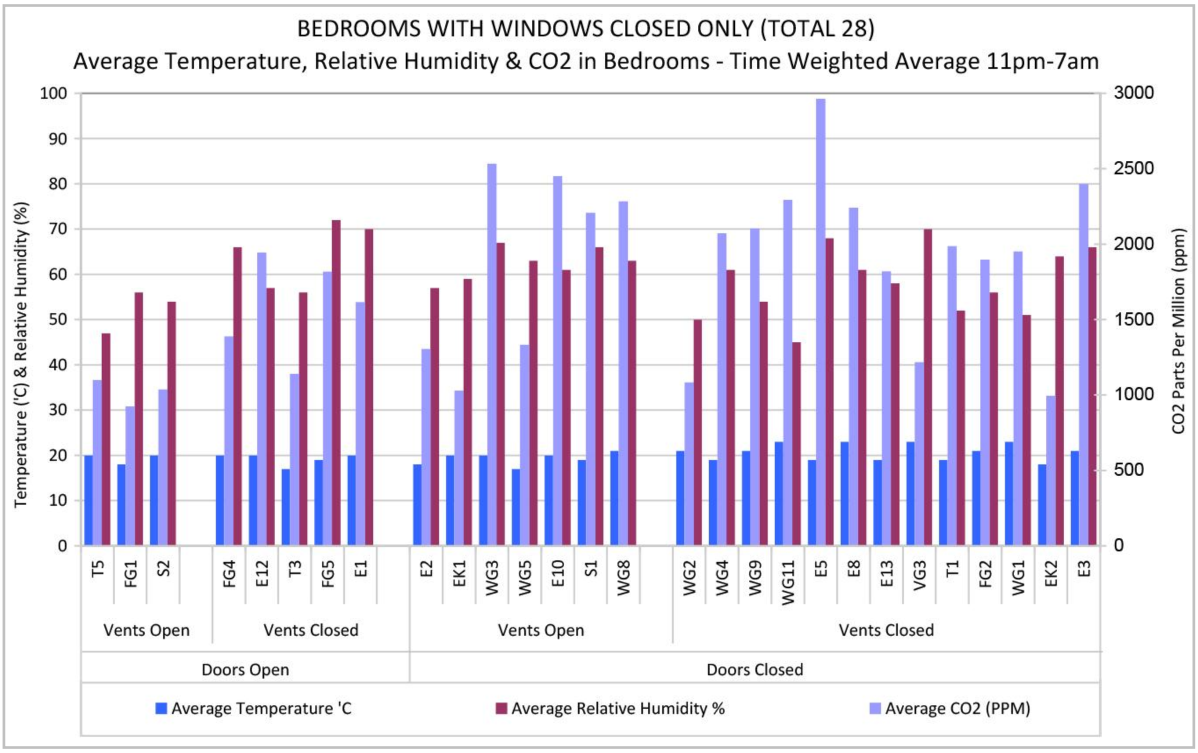


Figure 26. Average Temperature, Humidity and CO_2 levels recorded in bedrooms between 11pm and 7am with Trickle Vent and Door Position.

Figures 25 and 26 indicate that there is a general relationship between RH and CO_2 levels with higher levels of each often recorded when ventilation rates are reduced due to closed windows, doors and trickle vents. However this relationship is not clear in all circumstances and therefore temperature and relative humidity may not provide a definitive guide or indication suitable for occupants to determine indoor air quality.

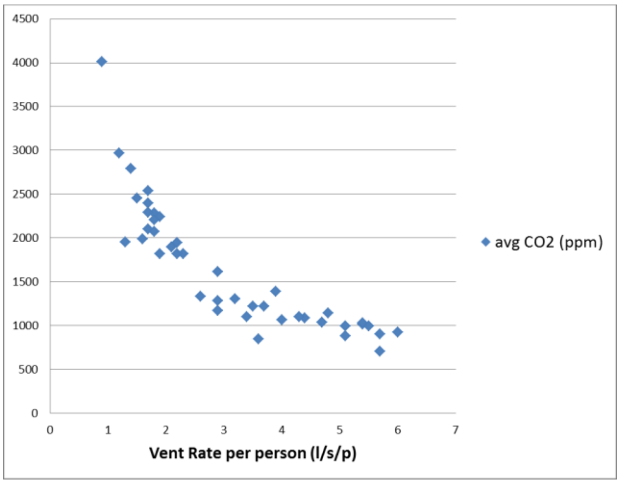
This data has been used to calculate ventilation rates for the bedrooms and these are shown in Table 5.

Property	Bedroom Occupancy (people)	Area (m2)	Volume (m3)	min CO2 (ppm)	max CO2 (ppm)	avg CO2 (ppm)	Vent rate per person (l/s/p)	AC/h for bedroom space (per h)
T1	2	10.89	26.3	578	3033	1988	1.6	0.44
T2	2	13.6	31.8	834	1594	1219	3.5	0.8
T3	2	10.95	28.9	890	1278	1141	4.8	1.19
T4	2	11.56	27.5	794	1172	1012	5.4	1.42
T5	2	10.56	25.7	761	1653	1099	3.4	0.95
FG1	2	11.12	26.7	770	1098	925	6	1.61
FG2	2	11.77	28.6	831	2447	1897	2.1	0.52
FG3	2	11.4	26.9					
FG4	1	12.58	30.2	1339	1489	1390	3.9	0.46
FG5	2	12.08	29	1370	2255	1819	2.3	0.57
WG1	2	12.89	31.8	484	3620	1953	1.3	0.3
WG2	1	12.84	30.9	653	1355	1085	4.4	0.51
WG3	2	11.74	28.2	2215	2916	2534	1.7	0.43
WG4	1	11.44	28.1	704	2721	2073	1.8	0.24
WG5	2	12.55	30.1	846	2040	1334	2.6	0.62
WG6	1	12.98	31.3	2696	4971	4008	0.9	0.11
WG7	0	11.74	28					
WG8	3	12.69	30.5	1540	2723	2285	1.8	0.65
WG9	1	12.15	29.3	1026	2958	2104	1.7	0.21
WG10	2	11.28	27.2					
WG11	1	12.55	30.1	1259	2910	2294	1.7	0.2
E1	3	10.96	26.3	1147	1867	1617	2.9	1.19
E2	1	18.4	26.5	660	1730	1306	3.2	0.44
E3	3	11.25	30.6	1259	2987	2400	1.7	0.58
E4	1	11.34	27	469	1583	846	3.6	0.48
E5	1	12.38	29.7	1632	3841	2964	1.2	0.15
E6	2	12.54	30.1	649	1215	881	5.1	1.23
E7	1	11.92	28.6	624	1462	1066	4	0.5
E8	1	11.76	28.6	1638	2663	2242	1.9	0.24
E9	2	10.88	25.3	1046	2362	1819	2.2	0.62
E10	2	12.77	30.7	1521	3232	2451	1.5	0.35
E11	1	11.51	27.5	798	1157	991	5.5	0.72
E12	1	11.61	27.9	1322	2298	1945	2.2	0.29
E13	1	11.25	26.99	736	2662	1821	1.9	0.25
E14	1	11.25	30.59	546	1854	1168	2.9	0.34
E15	3	13.23	31.88					
E16	2	11.28	27.07	615	3538	2793	1.4	0.36
E17	1	11.21	30.37	743	1389	1098	4.3	0.51
VG1	2	12.28	28.98	738	1885	1285	2.9	0.71
VG2	2	10.41	24.56	569	1128	707	5.7	1.69
VG3	1	10.49	24.85	926	1529	1219	3.7	0.55
VG4	2	10.15	23.95	514	3226	1069	1.5	0.45
VG5	2	8.03	20.15	656	1130	901	5.7	2.06
EK1	1	16.64	38.94	795	1182	1029	5.4	0.49
EK2	2	14.32	33.5	670	1214	996	5.1	1.11
S1	2	12.1	29.06	1062	2729	2209	1.8	0.46
S2	3	12	28.67	906	1304	1039	4.7	1.73

Table 5. Calculated bedroom ventilation rates based on Occupancy, Maximum CO_2 measurements and Bedroom volumes.

	Ventilation rate per person (l/s/p)	Air Changes per hour
Average	3.1	0.7
Maximum	6.0	2.1
Minimum	0.9	0.1

Table 6. Summary of calculated bedroom ventilation rates based on Occupancy, Maximum CO_2 measurements and Bedroom volumes.



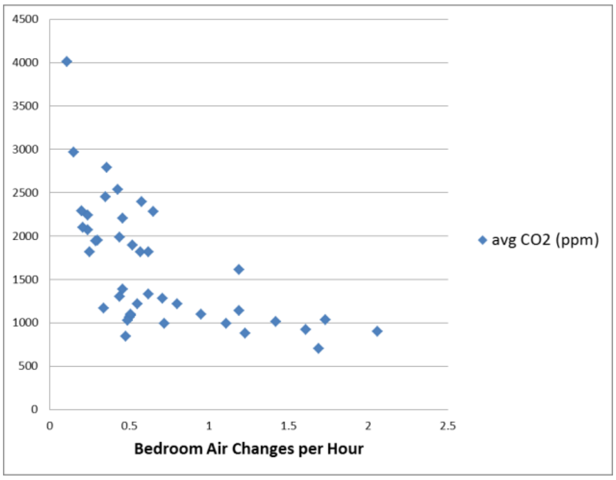


Figure 27. Average bedroom CO_2 level v. ventilation rate per person. Figure 28Average bedroom CO_2 level v. bedroom air change rate

Per person ventilation rates and overall bedroom air change rates were calculated from the maximum CO_2 level, the occupancy and the room volumes as recorded in the surveys. Average per person ventilation rates are 3.1 l/s/p and the average bedroom air change rate was calculated to be 0.7 ac/h. Whilst within the limits of ach/h designed to control moisture these levels seem reasonable, but are much lower than a desired rate of 8 l/s/p required to maintain good air quality.

The average CO_2 levels were then plotted against the per person ventilation rates and bedroom air change rates and very clear relationships are shown. The metabolic rates of individuals and constancy of occupancy at the reported levels are variables which will add some uncertainties into these relationships but overall trends are as would be expected.

These levels of ventilation are lower than would be desirable to achive good levels of air quality. Whilst incidences high levels of VOCs were not observed, the correlation with VOC's and CO_2 levels is apparent.

Observations
The surveys highlight that both physical obstruction and occupant behaviour are barriers to trickle vent efficiency.

Observations suggest that trickle vents are frequently out of immediate reach due to height, furniture and positioning of blinds and curtains. Certainly the placement of trickle vent controls differs from window handles, which are required to be in an accessible position.

The majority of bedroom windows surveyed have some form of blinds or curtains that would occlude the vents, especially at night when curtains and blinds are most used.

It is noted that the survey team found no instances where vents had been interfered with or blocked however the installation of floor coverings frequently obstructed door undercuts with residents comments including that they had to physically shorten doors to allow opening after fitting carpets.

The use of floor carpeting is popular throughout the UK for aesthetic and comfort purposes. Although not part of the survey or questionnaire, it is reasonable to assume that carpets and other devices used to prevent draughts at doorways are viewed as beneficial by many occupiers. If this assumption is correct it would indicate a lack of understanding about the need for adequate cross ventilation within the home.

During the physical survey several residents did offer opinions regarding keeping vents closed for comfort reasons, particularly to avoid potential for draughts and noise. It was also common for occupants to comment on lack of use indicating that regular or habitual interaction with trickle vents may not be the norm and is therefore even less likely to occur as frequently as may be needed to alter the internal environment to cope with the differing conditions that regularly present across any 24 hour period.

This is further complicated by residents’ inability to determine good air quality. The previous questionnaire indicated that a very high number, over 90% of respondents, describe the air quality in their master bedroom as very good or fairly good while results from the physical surveys suggest that 83% of properties present with time weighted average CO_2 concentrations (11pm – 7am) in bedrooms greater than 1000 ppm.

Further to this, where conditions are present that encourage residents to take action over their internal environment, potentially due to temperature, moisture, odour or seasonal habits, they are more likely to open windows for purge ventilation rather than use trickle vents. Again this is highlighted by the initial questionnaire based survey that found that while 63% of respondents never use bedroom trickle vents, 59% open windows regularly and is supported by the low number of vent users found during the physical surveys.

While purge ventilation can deal with the immediate condition it should also be considered that occupied internal environments will begin to degrade as soon as windows are closed as demonstrated in Figure 29.

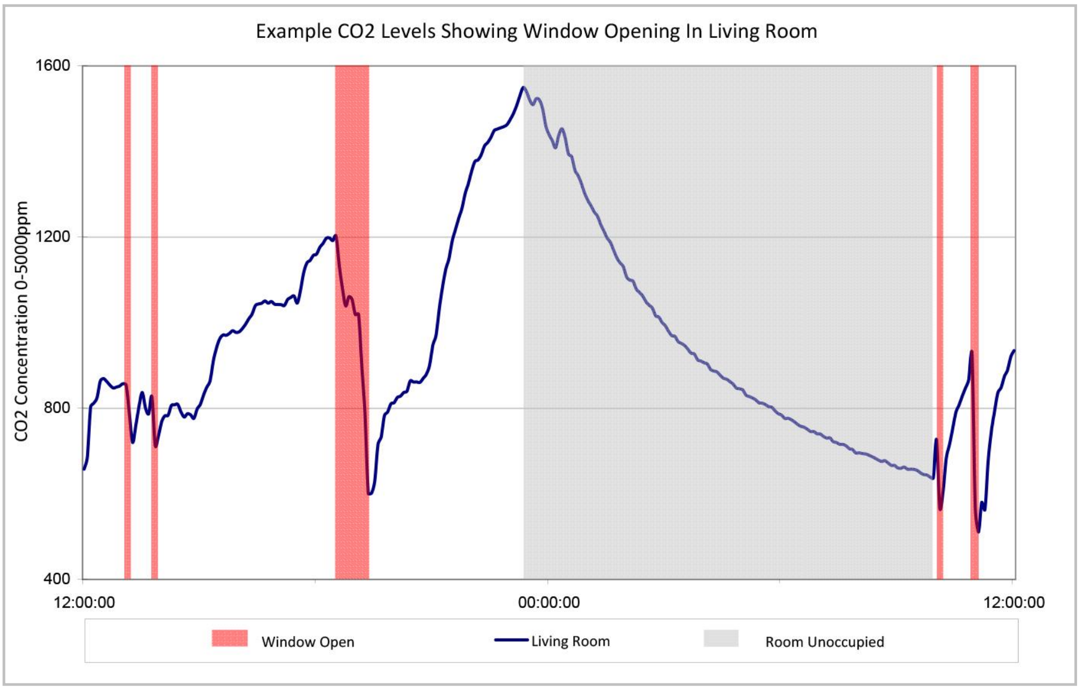


Figure 29: Example CO_2 concentrations in living room with 2 person occupancy showing recovery to baseline level when window opened and rate of increase when closed.

This monitoring primarily considers conditions specific to bedroom occupancy, which tends to occur overnight while the resident is asleep and therefore unable to interact and alter their environment. Figure 30 provides typical survey results over the entire 48 hour period under differing conditions including windows open, windows closed, vents open, vents closed, doors open, doors closed.

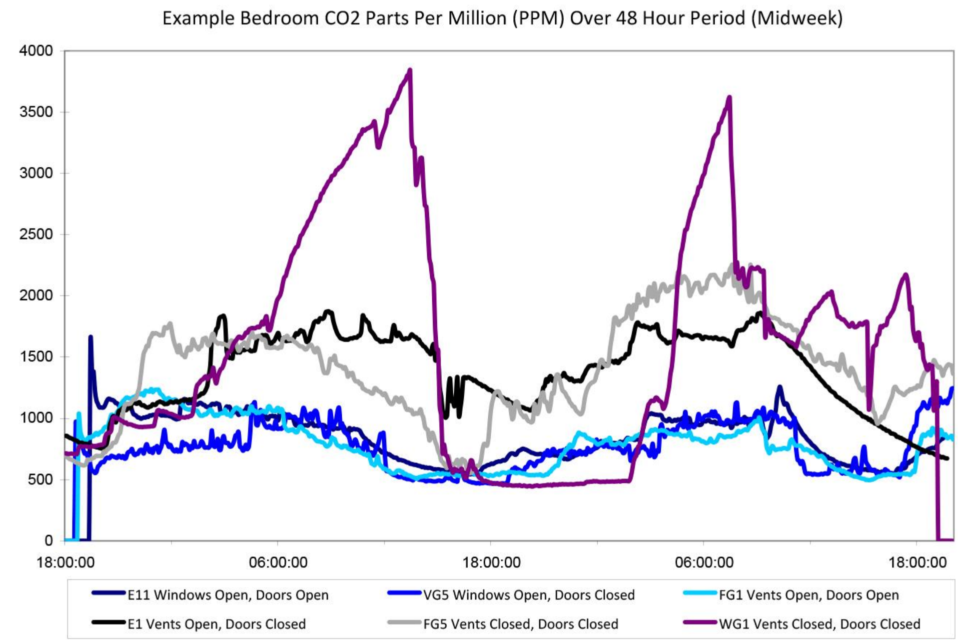


Figure 30: Example CO_2 concentrations in bedrooms over a 48 hour midweek monitoring period.

Summary

Out of this sample all but two presented with average CO_2 concentrations over 1000 ppm across two nights regardless of trickle vent or door position.

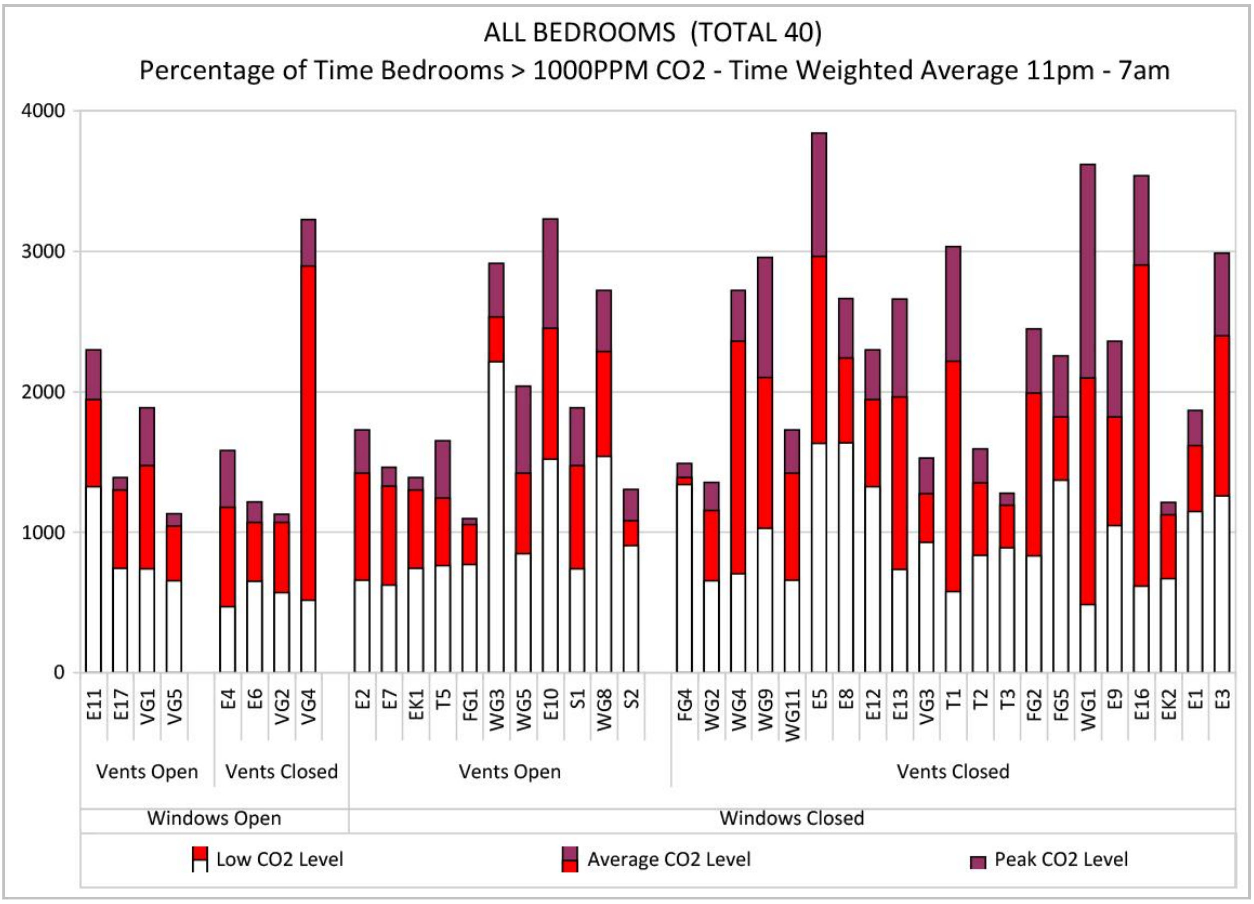


Figure 31: Low, Average and Peak CO_2 concentrations in bedrooms over a 48 hour midweek monitoring period.

The data collected also confirms that single occupancy does not exclude the likelihood of average CO_2 increasing above the 1000ppm threshold and highlights the probability of prolonged exposure with a third of all dwellings achieving levels of CO_2 greater than 1000 ppm all night.

The results also indicate that it is possible to achieve CO_2 concentrations close to 1000 ppm where particular conditions are in place, namely trickle vents and doors are left in the open position. However this must be understood within the context that resident behaviour patterns are predictable and will require either the trickle vents or doors to be closed for reasons of fire safety, noise or privacy. Where doors are closed, the data collected confirms that average concentrations of CO_2 in the bedroom between the hours of 11pm and 7am are almost double the recommended 1000ppm level whether the trickle vent is open or closed.

5. Detailed Monitoring

Project Information

Detailed monitoring is also being undertaken on 26 dwellings across Scotland funded by the UK Technology Strategy Board Building Performance Evaluation Programme (BPE).These studies undertake post-construction testing and monitoring of energy and environmental conditions for a 24-month period. The programme includes 32 domestic projects across the UK of which there are 7 domestic studies in Scotland with 6 multi-dwelling sites currently being evaluated by MEARU, (the seventh being a single privately owned house) and includes 26 houses in total. Of these houses 21 use trickle vents, the other 5 being Passivhaus projects that use MVHR systems.

A comprehensive set of criteria for BPE has been set out by the Technology Strategy Board (TSB) for projects funded by the Building Performance Evaluation programme[101]. These include a series of physical tests including air permeability testing at the both the start and the end of the project, U-value testing, and thermographic surveys. Information is gathered on the construction, design intention and occupant experiences through a design and construction audit; drawings & SAP calculation review; qualitative semi-structured interviews and walkthroughs with occupants and, separately, the design team; photographic survey; and an occupant survey using a domestic version of the Building Use Survey (BUS).

There is also a review of systems design and implementation, including installation and commissioning checks of all services and systems. Energy and environmental monitoring includes metered gas, electricity, water and if appropriate heat, into (and out of) dwelling; sub metering according to use e.g. space heating, water heating, cooker, lights and appliances. Monitoring of internal environmental conditions includes temperature humidity and CO_2, external temperature and relative humidity on site and external climate conditions. Monitoring is undertaken at 5-minute intervals.

For the projects being evaluated by MEARU some additional data is being collected. The TSB requirement only specifies CO_2 in one room, but this is being monitored in three rooms, including at least one, but in some cases, two bedrooms. Additionally, contact sensors have been placed on the principal opening to these rooms, which detect opening incidences (but not degree). The occupant surveys and interviews have been extended to gather specific data on patterns of occupancy and behaviour, with occupant diaries being used to gather detailed information.

There are six sites included in this study. These are in a diverse number of geographical locations across Scotland:

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101 Technology Strategy Board (2010) *Building Performance Evaluation, Domestic Buildings, Guidance for Project Execution*

Inverness ((Lat 57.4 Long -4.2). Submitted under 2007 regulations. This rural site has 52 properties in total and was constructed as a Housing Expo, which opened in 2010, showcasing designs of contemporary low energy architecture. Evaluation is being undertaken on n=8 houses (2 x 4 different house types). Occupants include social rented and owner-occupiers.

Lockerbie (Lat 55.2, -3.3 Long). 2010 regulation and Passivhaus certified. This is also a rural development of 8 x 2-story houses built to Passivhaus standards, of which n=4 are included in this study. These are privately rented, but subsidised for affordable rents.

Livingston (Lat 55.9, Long -3.5). 2010 Regulations. This is a development of 8 x 2-story terraced houses of which n=2, an end terraced and a mid terraced are being monitored. These are social rented for tenants with special needs.

Barrhead (Lat 55.1, Long -4.4). 2010 Regulations. This is a development of 16 amenity cottages, houses and flats for older people. There are n=3 houses being monitored, 1 cottage flat, 1 2-story mid-terrace house and 1 upper floor flat.

Queens Cross (Lat 55.8, Long 4.2). 2007 Regulations. The development is on two neighbouring inner city sites, providing 117 flats and houses. The flats include 34 supported 1 and 2-bedroom flats for the elderly in one block; and 54 1 and 2 bed mainstream flats block; of which n=3 sheltered flats and n=3 conventional flats are being monitored.

Dunoon (Lat 55.9, Long -4.9). 2010 Regulations and Passivhaus certified (one property). The development consists of 14 semi-detached affordable sector houses. One is a fully accredited Passivhaus Standard dwelling and the adjacent 13 dwellings meet the Code level 4 low-energy standard, but not the Passivhaus Standard. The Passivhaus dwelling (n=1) and n=2 low-energy houses are being monitored. The houses have shared equity between the housing association and part owner occupiers.

Loc	Ref	Const	Type	Beds	GIFA (m2)	Heating	Control	Hot Water	Air Air Perm	Vent	Occ
BA	BA1	TF, VP	2H MT	2	93.9	R GB	P T, TRVs	GB, ST	4.25	Trickle	2A
BA	BB1	TF, VP	1F GF	2	75.8	R GB	P T, TRVs	GB, ST	2.88	Trickle	2A
BA	BC1	TF, VP	2H ET	2	75.4	R GB	P T, TRVs	GB, ST	4.98	Trickle	2A
LI	LA1	TF, VP	2H MT	3	106	R GB	P T, TRVs	GCB	3.71	Trickle	3A
LI	LA2	TF, VP	2H ET	3	105.9	R GB	P T, TRVs	GCB	3.73	Trickle	3A
LO	**DD**	**TF**	**2H SD**	**2**	**87.3**	**MVHR HW**	**T**	**LBS/ST**	**2.42**	**MVHR**	**1A1C**
LO	**DA2**	**TF**	**2H SD**	**2**	**87.3**	**MVHR HW**	**T**	**LBS/ST**	**2.14**	**MVHR**	**1A**
LO	**DC**	**TF**	**2H SD**	**3**	**102.8**	**MVHR HW**	**T**	**LBS/ST**	**2.72**	**MVHR**	**3A2C**
LO	**DB**	**TF**	**2H SD**	**3**	**102.8**	**MVHR HW**	**T**	**LBS/ST**	**2.41**	**MVHR**	**2A2C**
DU	TA	CPTF	2H SD	3	113.6	EC	T	EB, ST	4.04	Trickle	2A3C
DU	P14	CPTF	2H SD	3	113.6	EC	T	EB, ST	4.29	Trickle	2A2C
DU	**PTB**	**CPTF**	**2H SD**	**2**	**103.4**	**MVHR, ASHP**	**T**	**ASHP, ST**	**0.96**	**MVHR**	**2A2C**
IN	IA1	TF	2H ET	3	109	R/UF GCB	P T, TRVs	GCB	3.82	Trickle	2A4C
IN	IB1	TF	2H MT	3	109	R/UF GCB	P T, TRVs	GCB	4.21	Trickle	1A5C
IN	ID1	TF	1F GF	2	76	R CBB	P T, TRVs	CBB	5.71	Trickle	2A
IN	ID2	TF	1F GF	2	76	R CBB	P T, TRVs	CBB	4.53	Trickle	2A
IN	IB1	TF	2H SD	3	90	R GB	P T, TRVs	GCB	5.82	Trickle	2A2C
IN	IB2	TF	2H SD	3	90	R GB	P T, TRVs	GCB	6.07	Trickle	2A1C
IN	IC1	TC	1F GF	1	52	EC, LBS	P, T	IH	5.93	Trickle	1A
IN	IC2	TC	1F TF	1	52	EC, LBS	P, T	IH	6	Trickle	2A
GL	GB1	M	1F GF	2	67.57	R, CB CHP	P T, TRVs	CBCHP	3.61	Trickle	2A1C
GL	GB3	M	1F GF	1	72.15	R, CB CHP	P T, TRVs	CBCHP	7.91	Trickle	1A
GL	GB2	TF	1F MF	1	67.57	R, CB CHP	P T, TRVs	CBCHP	4.59	Trickle	1A
GL	GA1	TF	1F TF	1	49.53	R, CB CHP	P T, TRVs	CBCHP	7.91	Trickle	1A
GL	GA2	M	1F GF	2	49.53	R, CB CHP	P T, TRVs	CBCHP	10.39	Trickle	1A
GL	GA3	TF	1F TF	2	75.5	R, CB CHP	P T, TRVs	CBCHP	7.59	Trickle	2A

Key: TF=Timber Frame, M=Masonry, CPTF=Closed panel Timber Frame, TC=Timber Cassette VP=Vapour permeable H=House, F=Flat: MT=Mid Terrace, ET=End Terrace, GF=Ground Floor, MF=Mid Floor, TF=Top Floor, SD=Semi-detached; R=Radiators, UF=Underfloor GB=Gas Boiler, CGB=Gas Combi Boiler, CB=Communal Boiler, CHP=Combined Heat and Power ST=Solar Thermal, EI=Electric Immersion. Italics=elderly/disabled occupants, Bold=Passivhaus

Table 7: Construction types and occupancy

The predominant form of construction is timber frame (84%). This is broadly representative of the construction industry in Scotland where 76% of new-build construction is timber [102], up from 70% in 2009 [103]. Four of the houses (15%) use a vapour permeable timber construction, however in two of these the bedrooms are in roof spaces and thus the enclosing structure is traditional timber frame. Only four of the dwellings (flats) (15%) use masonry construction.

The most common form of heating is some form of wet central heating, used in seventeen houses (65%). Of these, in eight houses (30% of the total) this is from some form of communal boiler (six are gas and two are biomass). The remaining nine (35% of the total) use gas central heating. All the wet systems use traditional programmers, thermostats and TRVs on radiators.

In the remaining houses two dwellings use electric storage heaters, supplemented by log stoves. In four of the Passivhaus dwellings (15%) heating provision is provided by a post heater supplied from the hot water cylinder and one Passivhaus project uses an air source heat pump.

All the houses have openable windows, and all have trickle vents, with the exception of the Passivhaus projects. In all but two of the bedrooms there is a single window, the others (9BB1 an 11BB1) have two windows on adjacent walls. The non passivhaus dwellings have mechanical extract ventilation in the kitchens and bathrooms, with the exception of two houses which have passive stack ventilation (IB1, IB2) and two flats have Dmev extract systems (IC1 and IC2). Trickle vents are on window frames at the top of the window.

All the houses apart from ID1 and ID2 have the possibility of cross ventilation through the dwellings if internal doors and windows or vents on both sides of the dwellings are open. Only IC1 and IC2 have a possibility of cross ventilation in the rooms themselves although in both these houses this is not used.

Air-tightness.
All the dwellings have had the first of two air permeability tests undertaken and the results of these are shown in Table 7. Air permeability figures are within design expectations, but results range from 0.955 $m^2/m^3.h$ @ 50 Pa to 10.39 $m^2/m^3.h$ @ 50 Pa. This latter figure is the only one that fails to meet the Building Standard recommendation in force at the time of construction (2010 Scottish Building Standards) of 10 $m^2/m^3.h$ @ 50 Pa. All but 5 meet the current recommendations of 7 $m^2/m^3.h$ @ 50 Pa and the average is 4.59 $m^2/m^3.h$ @ 50 Pa. The Passivhaus projects (noted in light blue) have the lowest air permeability and average at 2.45 $m^2/m^3.h$ @ 50 Pa. They remain within the recommended figure of 3-5 $m^2/m^3.h$ @ 50 Pa for MVHR systems [104].

[102] Structural Timber Association (2012). Market Report 2012, October 2013. Accessed at http://www.structuraltimber.co.uk/information-centre/downloads/187.html?view=download Jun 2014

[103] Davies, I, *Sustainable Construction Timber – Sourcing and Specifying local timber* (Forestry Commission Scotland, 2009) http://www.forestry.gov.uk/forestry/INFD-6B2JFB

104 Banfill, P,; Simpson, S; Gillott, M; White, J. (2011) *The potential for energy saving in existing solid wall dwellings through mechanical ventilation and heat recovery. Energy efficiency first: foundations of a*

Outwith these projects there is no obvious pattern associated with construction, for example flats in Glasgow having figures at opposite ends of the spectrum.

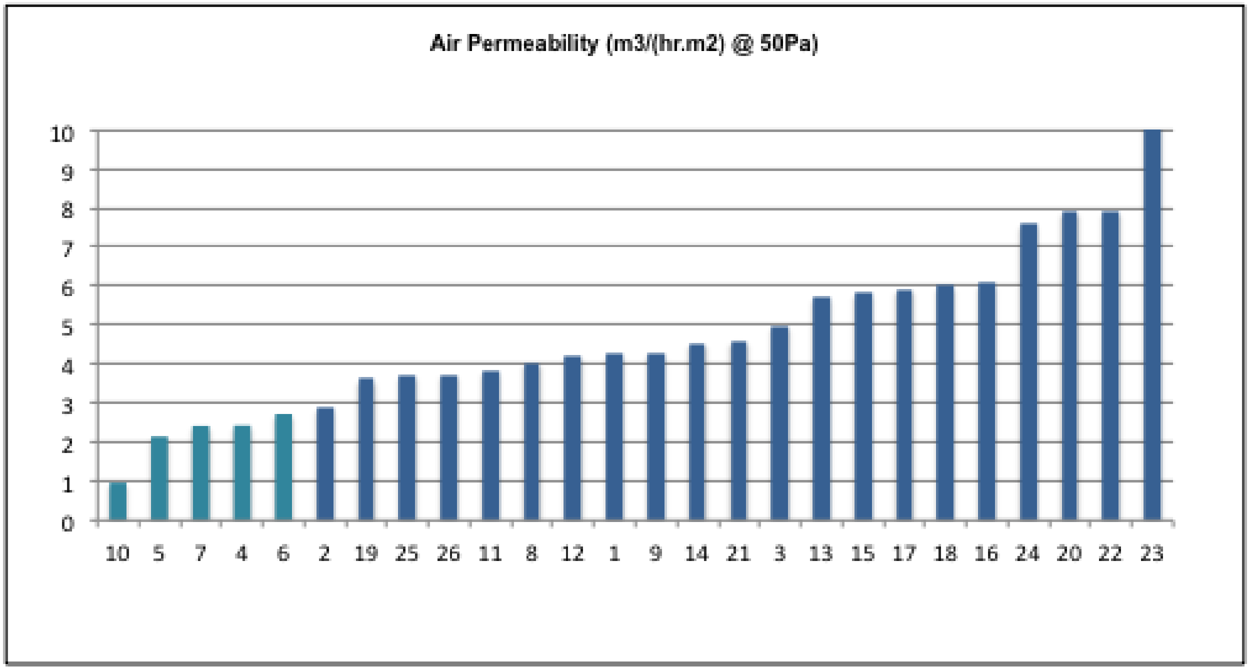


Figure 32: Air permeability tests

Nevertheless high levels of air-tightness are present across the sample and this suggests that standards of building or finishing in general are improving. Of significance to this study is the fact that, excluding the Passivhaus projects, twelve out of twenty-one dwellings (57%) have 'overshot' the figure of 5 $m^2/m^3.h$ @ 50 Pa, below which mechanical ventilation is recommended, but do not have this provision. It is a cause for concern that these high levels of air-tightness exist without the necessary planned ventilation strategy.

A further observation is that during the air permeability tests common causes of air leakage could be identified, including external doors, but also service penetrations in bathrooms from water and waste pipes. A reasonable assumption leading from this is that given the test figure applies to the whole house, some areas may experience much lower rates of air permeability. Thus bedrooms may (especially with closed doors) be considered as discrete spaces and rates of air permeability in these spaces may be much lower than the whole house value.

A related area of investigation in these dwellings concerned extract ventilation. One of the dwellings exhibited problems of dampness and mould growth in the bathroom and initial investigations suggested the extract provision may be deficient. This led to it being tested and as the results were of concern the testing regime was extended to all the dwellings in the project. Volume flow rates were measured in-situ using the volume flow meter and accessories detailed below and were undertaken in accordance with HM Government 'Domestic Ventilation Compliance Guide, 2010 edition with 2011

low-carbon society: Proceedings of ECEEE 2011 summer study on energy efficiency.. p. 1401-1412, 2011 amendments. Observator Instruments - Automatic volume flow meter with pressure compensation Type: Diff Automatic, Cert No: UK08111MN, Calibrated: 20th June 2013 and light extension hood, Type: AT-242, Cert No: UK08111MN, Calibrated: 20th June 2013.

The apparatus used allows values to be derived using the "Unconditional Method" of measurement. The powered flow hood eliminates back pressure and places no additional restrictions on fans under test, therefore results displayed on the equipment can be taken as the correct without any further need to apply pressure drop correction factors. The results of this are shown in Table 8.

The results show that 26 out of 31 fans tested were underperforming and that 71% were failing the design performance criteria.

Dwelling	Fan Location	Avg Measured extract rate (l/s)	Design extract rate (l/s)	Pass/Fail Measurement test
IA1	Kitchen	25.60	60	Fail
	Utility	29.40	30	Pass
	Shower	7.50	15	Fail
	Bathroom	7.50	15	Fail
IA2	Kitchen	34.50	60	Fail
	Utility	31.90	30	Pass
	Shower	3.70	15	Fail
	Bathroom	4.60	15	Fail
IB1	WC	3.20	7	n/a
	Bathroom	4.90	15	n/a
IB2	WC	5.20	7	n/a
	Bathroom	4.00	15	n/a
	Kitchen	62.60	30	Pass
IC1	Kitchen	5.80	60	n/a
	Bathroom	7.30	15	n/a
IC2	Kitchen	8.50	60	n/a
	Bathroom	5.90	15	n/a
ID2	Kitchen	26.10	60	Fail
	Bathroom	6.90	15	Fail
BC1	Bathroom	11.83	15	Fail
	Kitchen	64.27	60	Pass
BB1	Bathroom	17.30	15	Pass
	Kitchen	71.87	60	Pass
BA1	WC	12.40	15	Fail
	Bathroom	2.80	15	Fail
	Kitchen	0.00	60	Fail
GB3	Bathroom	9.20	15	Fail
	Kitchen	32.57	60	Fail
GB1	Bathroom	11.13	15	Fail
	Kitchen	41.43	60	Fail
GB2	Kitchen	30.10	60	Fail
	Bathroom	16.30	15	Pass

Table 8: Mechanical fan testing results

Whilst this study is focussed on the use of trickle vents, this data is clearly of relevance, particularly in those houses using DMEV ventilation systems.

Monitored data

The long term monitoring has indicated issues of poor ventilation, along with other concerns about environmental performance. For the purposes of this study a specific week of monitoring was established and occupants were asked to keep a detailed diary of their activities in the house during the period. The study period was between 3rd – 9th February 2014.

Data is collected in living rooms and bedrooms. As with the sample monitoring, it is difficult to isolate the effects of occupant interaction with ventilation in living rooms, particularly trickle vents. In this sample there is a wide variety of building forms, including open plan living rooms and kitchens, some double height spaces, a range of occupant numbers and occupancy patterns. Whilst data is recorded on window opening, other significant events that would raise CO_2 levels including the numbers of occupants, internal door opening or closing, cooking and other activities are much more variable. The summary data for the period is shown in Table 9.

Ref	Floor Area	No of Occupants	Temperature °C			Relative Humidity %					Window Open
	(m^2)	Pax	Min	Max	Mean	Min	Max	Mean	Max	Mean	%
BA1	93.1	2	19.68	24.93	21.96	34	46	39	1416	757	0
BB1	75.8	2	17.35	23.40	20.78	42	49	45	1344	898	0
BC1	75.4	2	19.70	27.20	23.50	29	37	33	1691	936	0
LA1	104.0	3	23.15	27.20	24.71	34	42	37	1303	831	n/a
LA2	104.0	3	21.43	26.40	23.15	23	35	26	1347	686	n/a
TA1	120.0	5	19.65	23.23	21.28	46	61	51	1341	845	1
TA2	120.0	4	21.58	24.38	22.87	30	37	33	1066	670	14
TB1	104.0	2	16.45	21.85	18.22	42	50	47	1709	1210	0
IA1	110.0	6	21.88	26.60	24.13	27	38	32	1369	856	9
IA2	110.0	6	21.83	24.43	22.95	30	37	34	1481	1088	14
ID1	76.0	2	21.23	25.95	24.14	25	34	28	1119	735	0
ID2	76.0	2	18.63	24.30	20.93	30	40	34	1169	698	0
IB1	90.0	2	19.03	23.78	21.48	31	41	36	938	678	0
IB2	90.0	4	18.48	24.78	21.47	29	44	35	1778	962	5
IC1	63.0	2	14.05	25.10	17.46	27	47	38	1356	759	0
GB3	73.3	3	20.38	23.90	21.97	48	57	52	2544	1635	100
GA2	51.0	1	25.20	27.13	25.87	32	36	34	1459	1115	0
GB1	66.0	1	15.93	22.25	17.92	42	49	46	1800	781	0
GB2	66.0	3	21.75	31.48	24.75	32	46	37	2791	875	2

Table 9: Living room average weekly temperature, RH and CO_2.

As can be seen, evidence of high CO_2 levels is apparent, although periods of high concentrations are shorter and levels are more variable. In some instances the effects of ventilation activities, particularly the use of window opening can be observed - see Figure 33 and 34 below. In general CO_2 levels remain below 1000 ppm when the windows are open. Toward the end of the week the windows are closed and CO_2 levels rise noticeably and remain above 1000 ppm for the majority of time. However looking more closely it can be seen that CO_2 levels drop prior to the window being closed, due to people leaving the room. Whilst this behaviour may result in good ventilation, it will have concomitant effects on energy use.

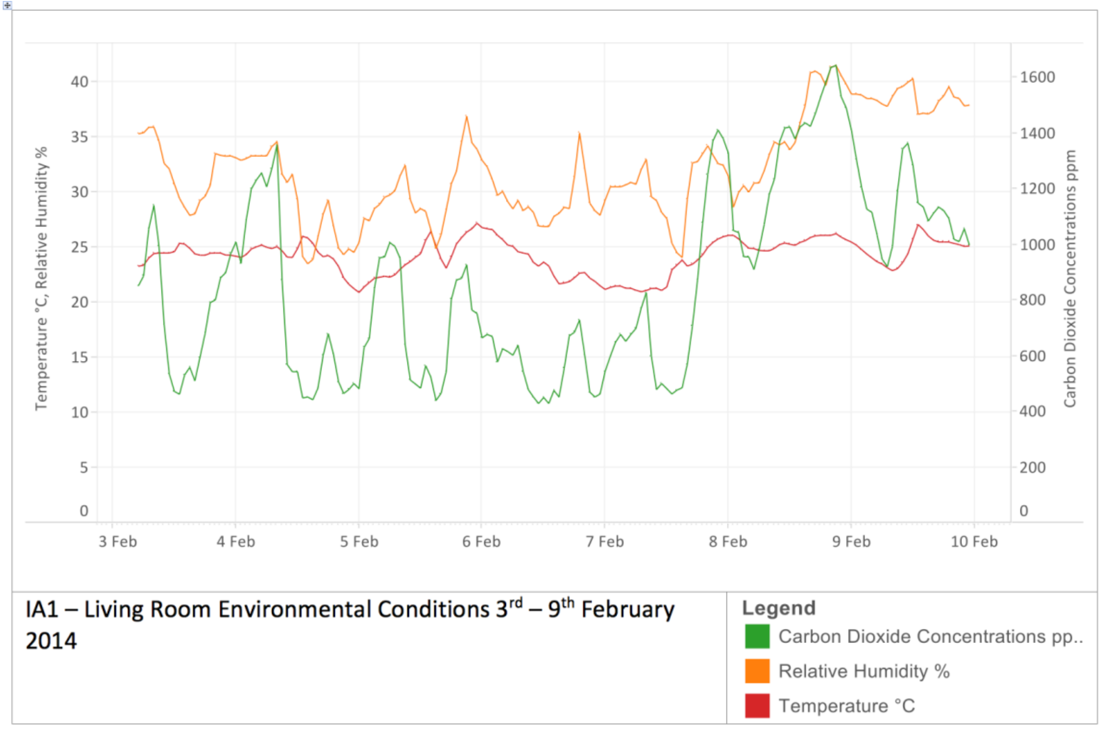


Figure 33: IA1 CO_2, temperature and relative humidity weekly conditions.

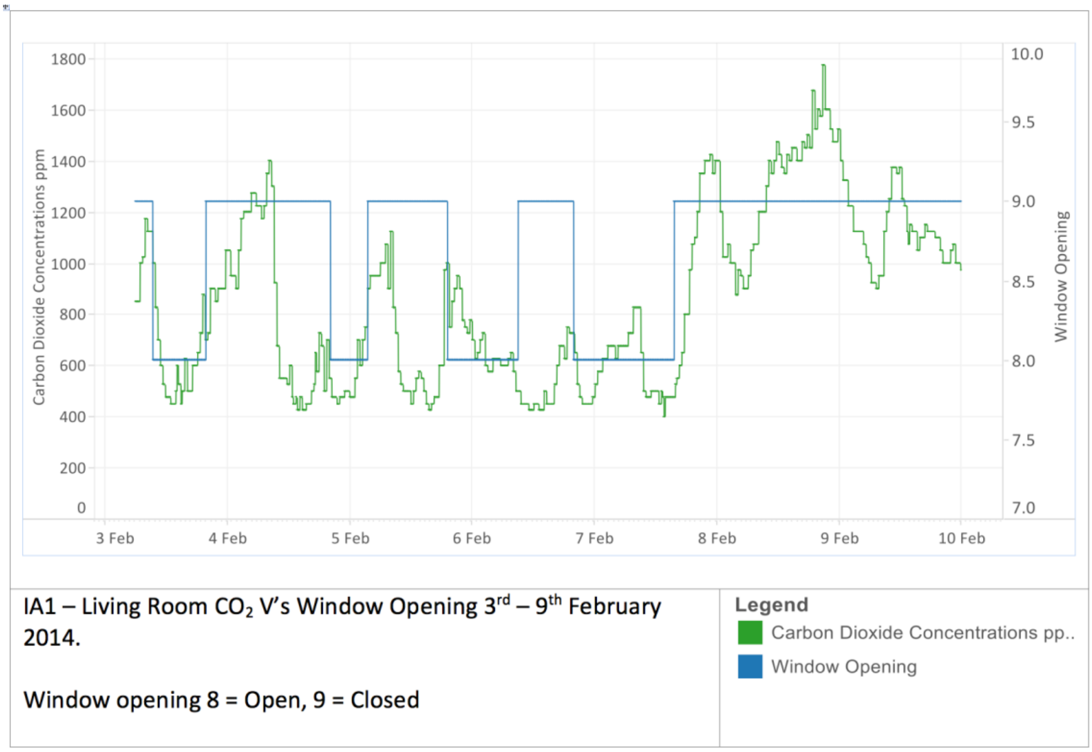


Figure 34: IA1 CO_2 and window opening patterns.

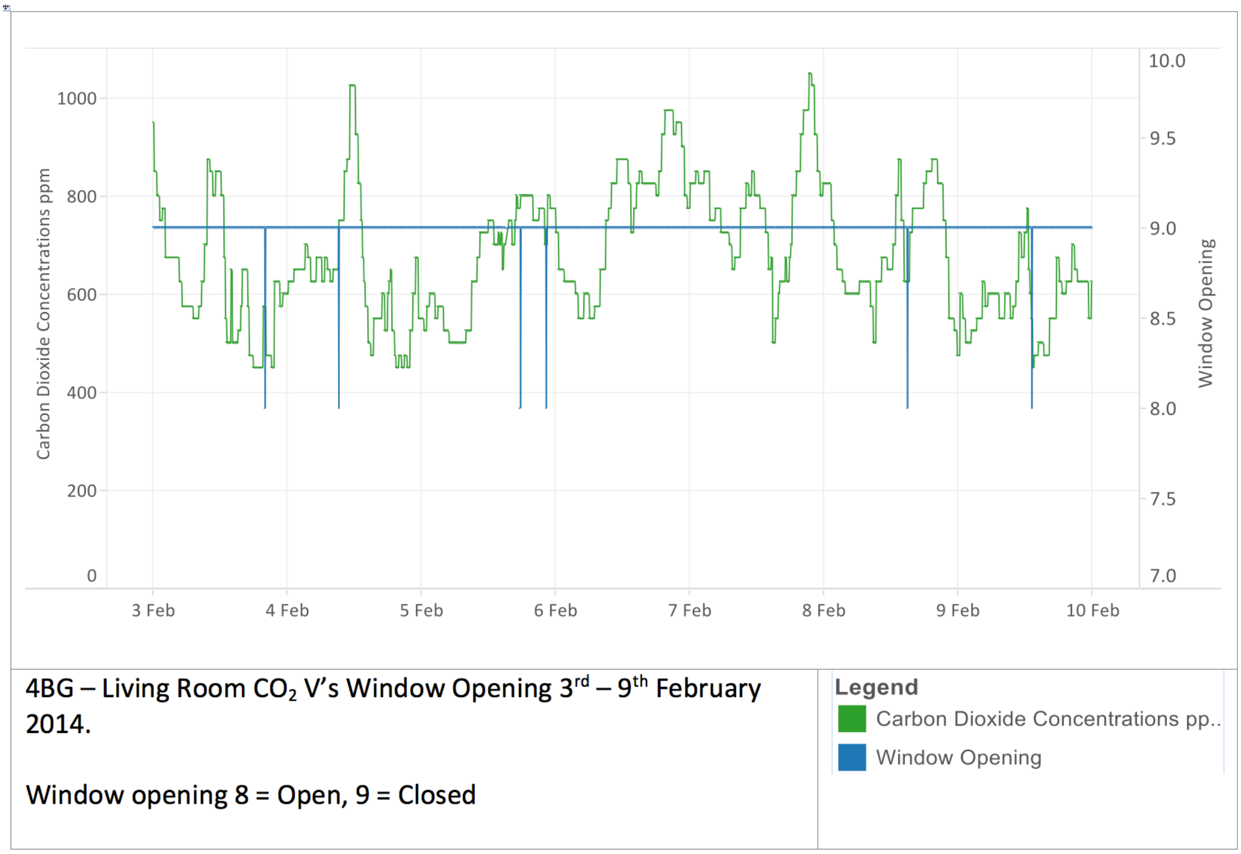


Figure 35: IB1 CO_2 levels and window opening frequency.

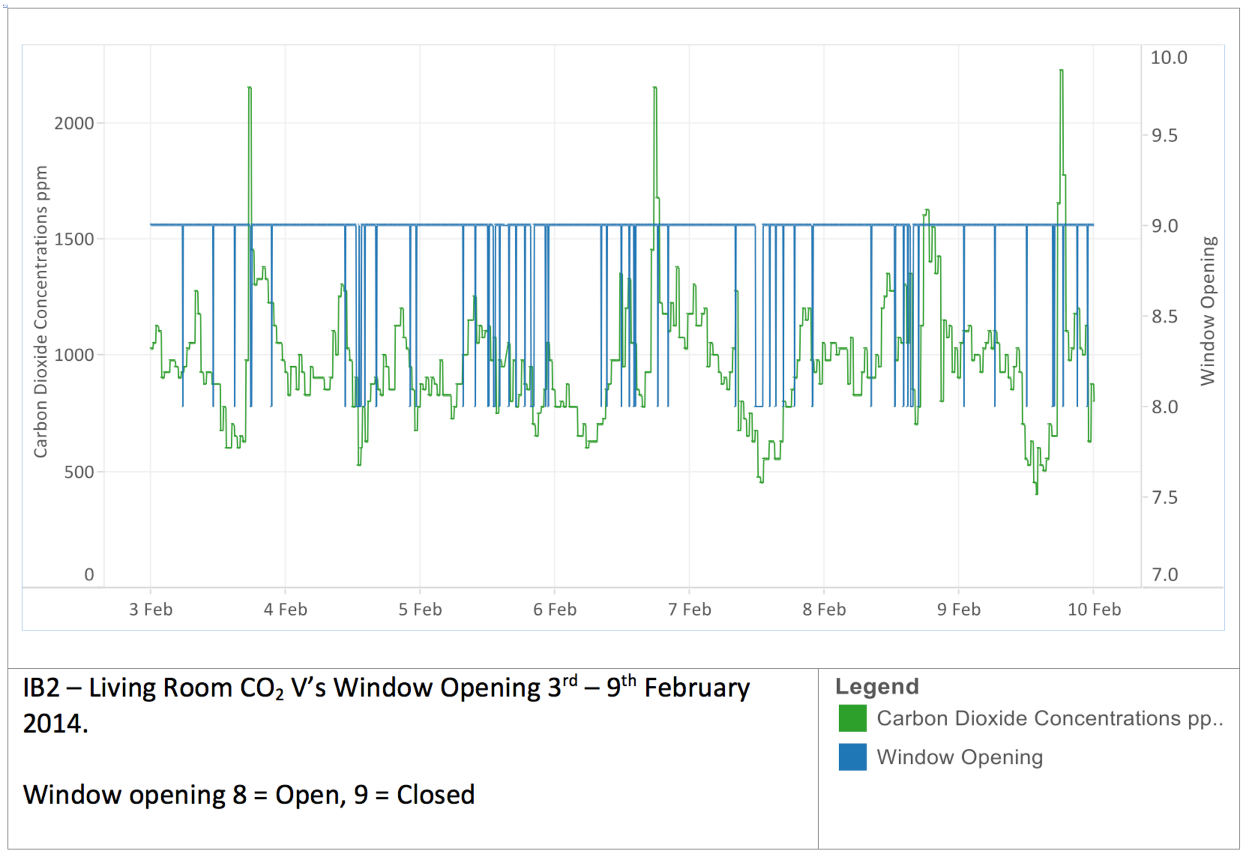


Figure 36: IB2 CO_2 levels and window opening frequency.

The effects of occupancy can be clearly illustrated in comparing IB1 and IB2 (Figures 35 ad 36). These dwellings have the same construction and layout. The former has infrequent use of window opening, but the average and peak CO_2 levels are below those of IB2 and there is no clear pattern of CO_2 (NB variation in left hand x-axis). In IB2, window opening is far more frequent, but overall CO_2 levels are higher, with significant peaks. The difference is higher levels of occupancy in IB2, but as this includes older children, patterns of use in the living room are very variable.

A more accurate assessment of the effects of ventilation, particularly background ventilation strategies, can be made using the bedroom data. In these rooms the hours and levels of occupancy are known, and overnight there are steady-state conditions. In addition it apparent that CO_2 levels are higher for longer periods than living rooms. Both the length and intensity of occupation can be more accurately assessed. The overall results for the bedrooms are shown in Table 10. In this summary bedroom data is confined to occupied hours, 11pm to 7am overnight. In some cases occupancy exceeds these time periods, however this represents the main period when the spaces are used. Occupants were asked to keep their trickle vents open during the period. They were also asked if they would keep windows closed in the period, but if they felt that conditions were uncomfortable to record any window opening and this was verified by the monitoring of window opening states. The diary identified the number of occupants, hours of occupancy, whether the bedroom doors were open or closed, and other contextual information about the house use, for example bathing, cooking and laundry habits.

Examining individual houses reveals a consistent pattern of environmental conditions and typical data shows CO2 levels rising rapidly to a stable point and dropping slightly less quickly in the morning, show shown in Figure 37.

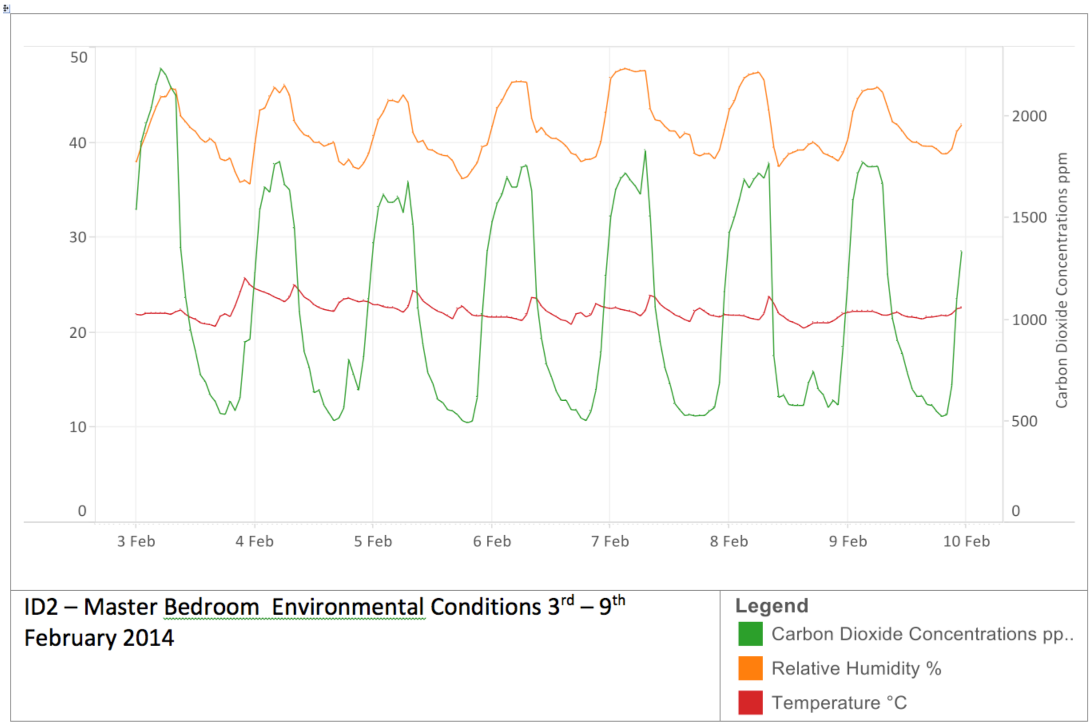


Figure 37: ID2 CO_2, temperature and relative humidity.

In houses with internal doors open, the pattern remains apparent but is less clear. In these cases interaction with other factors due to the open door, such as cross ventilation, increased volume, or external sources of CO_2 will affect the profile.

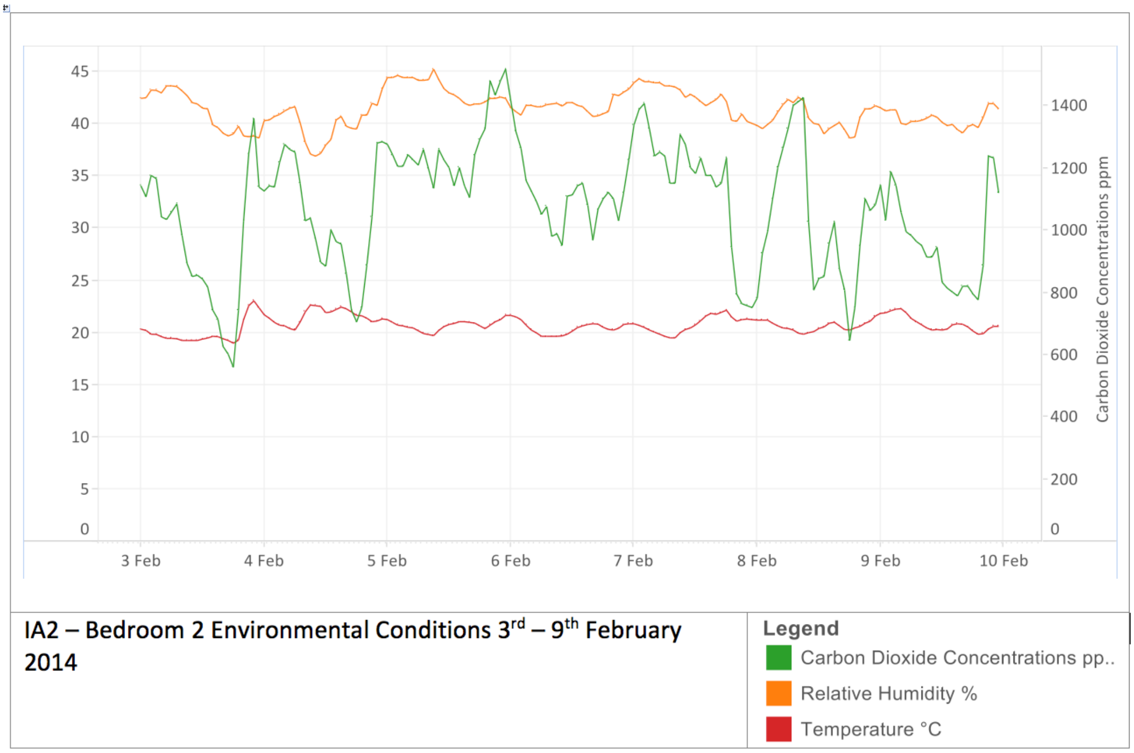


Figure 38: ID2 CO_2, temperature and relative humidity.

For example, window opening in the living room toward the end of the week may be impacting on overall CO_2 levels.

The analysis looks at the overall performance of the houses and the information presented includes the general characteristics of the houses, daily CO_2 averages and the percentage of time that CO_2 exceeds 1000 ppm and these are averaged for a weekly summary.

								ni 3					night 4					night 5					night 6					night 7					night 8					night 9					week	
Old Ref	Ref	House Size (m^2)	Occupant No		Room area (m^2)	Room volume (m^3)		occ no	windows	Door	avg CO_2 ppm	% > 1000 ppm	occ no	windows	doors	avg CO_2 ppm	% > 1000 ppm	occ no	windows	doors	avg CO_2 ppm	% > 1000 ppm	occ no	windows	doors	avg CO_2 ppm	% > 1000 ppm	occ no	windows	doors	avg CO_2 ppm	% > 1000 ppm	occ no	windows	doors	avg CO_2 ppm	% > 1000 ppm	occ no	windows	doors	avg CO_2 ppm	% > 1000 ppm	avg CO_2 ppm	% > 1000 ppm
27MP	BA1	93.1	2	bed 2	12.62	31.23	adult	1	C	?	754	0	1	C	C	943	18	1	C	C	1072	68	1	C	C	1256	100	1	C	C	1229	72	1	C	C	341	0	1	C	C	344	0	849	37
29MP	BB1	75.8	2	bed 1	13.15	31.50	adult	1	C	?	946	24	1	C	C	705	0	1	C	C	600	0	1	C	C	1142	100	1	C	C	1166	94	1	C	C	909	7	1	C	C	990	51	922	40
25BC	LA1	104.0	3	bed 3	11.23	27.40	adult	1	-	?	1013	57	0	-	O	512	0	1	-	C	1054	70	0	-	O	808	0	1	-	C	1188	63	1	-	C	1021	55	1	-	C	1130	51	960	42
26BC	LA2	104.0	3	bed 3	11.23	27.40	adult	1	-	?	732	0	1	-	C	748	0	1	-	C	727	0	1	-	C	1580	100	1	-	C	1305	97	1	-	C	1301	79	1	-	C	663	0	1013	40
CC	DA2	87.0	2	bed 1	14.93	33.68	adult	1	O	?	808	0	1	O	O	789	0	1	O	O	746	0	1	O	O	740	0	1	O	O	693	0	1	O	O	1310	100	1	O	O	636	0	818	15
OC	DB2	102.8	4	bed	10.13	29.00	child	1	C	?	945	30	1	C	C	943	8	1	C	?	898	6	1	C	C	930	19	1	C	?	891	0	1	C	C	1081	40	1	C	C	771	9	922	16
OC	DB2	102.8	4	bed m	12.19	35.76	child	1	C	?	671	0	1	C	C	883	0	1	C	?	816	0	1	O 64%	C	928	24	1	C	?	938	10	1	C	C	1524	100	1	C	C	705	0	928	20
P5	TA1	120.0	5	bed 1	11.83	30.77	child	1	C	?	878	20	1	C	O	852	0	1	C	O	986	48	1	C	O	1117	100	1	C	O	1021	36	1	C	O	702	0	1	C	O	851	0	916	29
P14	TA2	120.0	4	bed 1	11.83	30.77	child	1	C	?	1028	75	1	C	O	917	34	1	C	C	1009	38	1	C	C	765	0	1	C	C	918	28	1	C	C	703	19	1	85% O	C	596	0	845	27
P15	TB1	104.0	2	bed 1	11.83	37.85	child	1	C	?	841	0	1	C	C	780	0	1	C	C	1014	45	1	C	C	1853	100	1	C	C	2145	100	1	C	C	2321	100	1	C	C	1683	100	1532	65
P15	TB1	104.0	2	bed 2 m	14.22	45.50	adult	1	C	?	845	0	1	C	C	728	0	1	C	C	1040	53	1	C	C	1800	100	1	C	C	2189	100	1	C	C	2472	100	1	C	C	3066	100	1751	66
3BS	IA1	110.0	6	west bed	11.17	28.08	child	1	C	?	1948	100	1	C	C	2421	100	1	55% O	C	2523	100	1	O	C	1685	100	1	O	C	1478	100	1	C	C	3231	100	1	C	C	2390	100	2280	100
4BS	IA2	110.0	6	east bed	9.98	24.95	child	1	O	?	1103	93	1	O	O	1193	100	1	O	O	1235	100	1	O	O	1242	100	1	O	O	1301	100	1	O	O	1042	53	1	O	O	1077	66	1172	87
4BG	IB1	90.0	2	bed m	10.63	28.70	adult	1	C	?	1017	62	1	C	O	791	0	1	C	O	636	0	1	C	O	1218	91	1	C	C	1159	78	1	C	C	1559	100	1	C	C	1763	100	1166	62
4BG	IB1	90.0	2	bed east	7.13	19.25	child	1	O	?	1632	100	1	O	O	577	0	1	O	O	445	0	1	O	O	749	0	1	O	O	938	0	1	O	O	772	8	1	O	O	647	0	808	14
5BG	IB2	90.0	4	bed east	7.13	19.25	child	1	?	?	3327	100	1	?	O	3790	100	1	?	O	3770	100	1	?	O	1881	100	1	?	O	3533	100	1	?	O	2160	100	1	?	O	3952	100	3199	100
SF17	GA2	51.0	1	bed	9.00	21.60	adult	1	C	?	912	7	1	C	O	900	6	1	O	O	601	0	1	C	O	974	19	1	C	O	999	33	1	C	O	877	6	1	C	O	1013	38	896	16
MF02	GB1	66.0	1	bed	14.64	35.14	adult	1	C	?	718	1	1	C	O	1082	41	1	C	O	894	34	1	1% O	O	873	14	1	2% O	O	1133	57	1	C	O	1099	38	1	C	O	871	24	957	30
37MP	BC1	75.4	2	bed 2	12.54	30.34	adults	2	C	?	1245	82	2	C	O	1765	100	2	C	O	1612	100	2	C	C	2194	100	2	C	O	2540	100	2	C	O	1450	77	2	C	O	1497	100	1766	94
P5	TA1	120.0	5	bed 3m	14.22	45.50	adults	2	C	?	908	33	2	C	O	791	0	2	C	O	750	0	2	C	O	1315	100	2	C	O	1167	88	2	C	O	828	0	2	C	O	950	21	959	35
P14	TA2	120.0	4	bed 3 m	14.22	45.50	adults	2	28% O	?	1030	60	2	28% O	O	1098	59	2	C	C	1098	73	2	C	C	1137	75	2	C	C	1420	91	2	C	C	755	0	2	C	C	707	0	1035	51
3BS	IA1	110.0	6	east bed	9.98	24.95	adults	2	C	?	2121	100	2	C	C	1129	87	2	C	C	669	5	2	C	O	576	0	2	C	O	526	0	2	C	O	1110	73	2	C	O	2305	100	1077	46
6BS	ID1	76.0	2	bed	9.71	23.30	adults	2	C	?	1839	100	2	C	C	1335	84	2	C	C	1443	97	2	C	C	1459	100	2	C	C	1553	100	2	C	C	1551	100	2	C	C	1342	68	1497	93
7BS	ID2	76.0	2	bed	9.11	21.86	adults	2	1% O	?	1999	100	2	1% O	?	1517	88	2	C	?	1489	100	2	C	?	1593	100	2	C	?	1590	99	2	C	?	1548	99	2	C	?	1549	93	1605	97
5BG	IB2	90.0	4	bed m	10.63	28.70	adults	2	C	?	1374	77	2	C	C	1684	100	2	C	C	1433	85	2	C	C	634	0	2	C	C	1031	47	2	C	C	1475	100	2	C	C	1338	100	1280	73
9BB	IC1	63.0	2	bed	11.80	28.32	adults	2	C	?	1855	94	2	C	C	1537	76	0	C	O	505	0	2	C	C	1441	76	2	C	C	1270	82	2	C	C	1070	64	0	C	O			1101	55
MF03	GB3	73.3	3	bed	10.85	26.04	adults	2	C	?	2622	100	2	C	C	2595	100	2	C	C	2422	100	2	C	C	3218	100	2	C	C	2365	100	2	C	C	1407	100	2	C	C	2971	100	2540	100
MF22	GB2	66.0	3	bed	14.64	35.14	adult	2	O	?	865	7	2	O	C	1147	75	2	O	C	1084	57	2	O	C	1080	56	2	91% O	C	1161	56	2	95% O	C	1171	32	2	79% O	C	775	6	1040	42
4BS	IA2	110.0	6	west bed	11.17	28.08	1 adult/2 children	3	O	?	873	0	3	O	O	1232	100	3	O	O	1107	94	3	O	O	1193	100	3	O	O	1134	100	3	O	O	822	0	3	O	O	1018	30	1058	62

Table 10: Summary of occupancy conditions and CO_2 levels in the core data set

In general overall poor levels of ventilation were apparent in the majority of the bedrooms. On a daily basis an average of 77% of the rooms had periods where CO_2 levels exceeded 1000 ppm. Over the course of the week all the bedrooms experienced some period when CO_2 exceed 1000 ppm, with an average of 53% of the time (about 4 hours a night) when these levels occurred. Two dwellings had very high levels of CO_2 – of note here are that base levels are high indicating that a longer occupancy is occurring (a mother at home with a baby in one case and an elderly occupant in another).

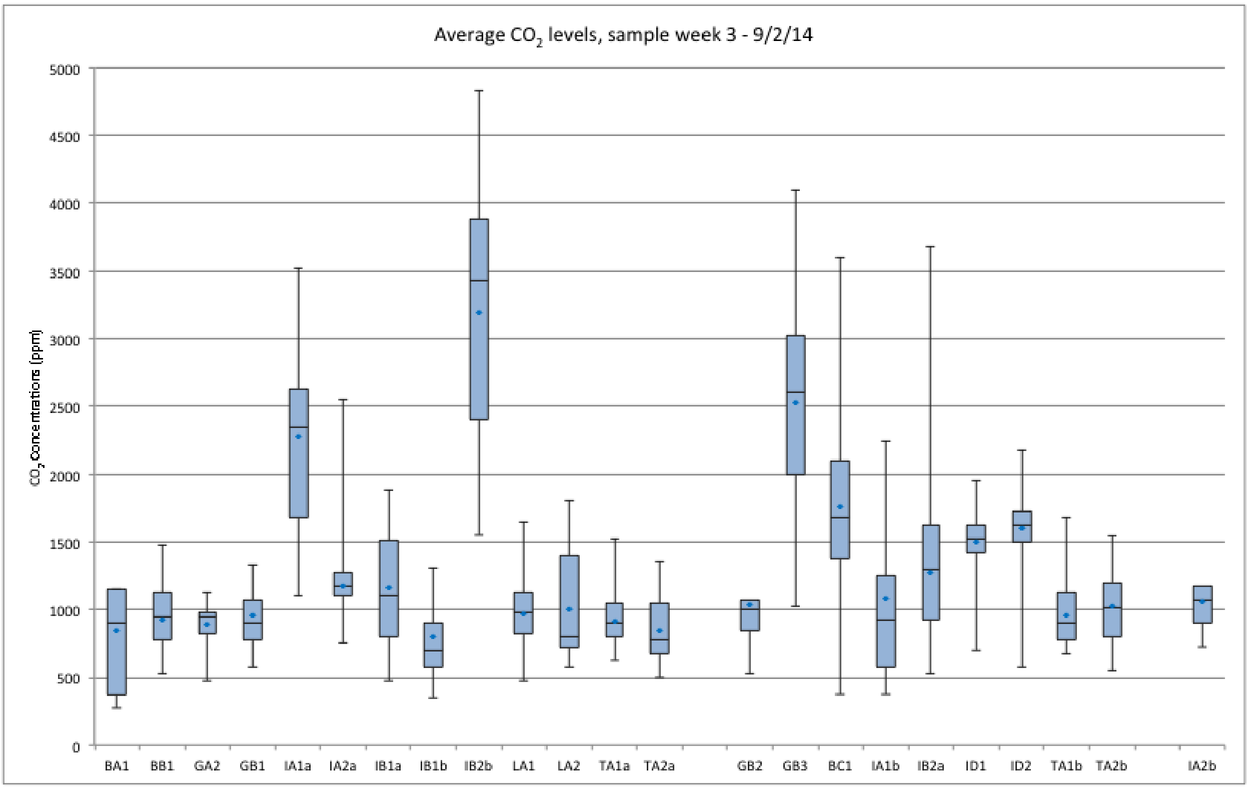


Figure 37: Average CO_2 levels and distribution

It is apparent that some properties are performing at different levels than others. There are a great many variables that might affect ventilation rates, but three areas, number of occupants, door opening and external wind speeds were examined. Examination of relative CO_2 levels in relation to these factors reveals some interesting data. Table 11 shows the variation is average CO_2 levels and % of time >1000 ppm CO_2 for number of occupants and door opening.

	any door state		doors open		doors closed	
No of occupants	avg CO2 ppm	% > 1000 ppm	avg CO2 ppm	% > 1000 ppm	avg CO2 ppm	% > 1000 ppm
any occupants	1224	52	1162	42	1288	60
1	1161	43	1099	26	1232	49
2	1286	60	1226	57	1478	72

Table 11: CO_2 levels and CO_2 intensity (% t >1000 ppm) by door opening and occupancy.

Looking at whether doors were open or closed (omitting properties where data was incomplete or with open windows) shows a clear difference, with doors opening leading to average CO_2 levels 18% lower, and % t >1000 ppm 23% lower. Looking only at number of people indicates that on average CO_2 levels for single occupants are 10% lower, but the CO_2 exposure is more obvious, with % t >1000 ppm 28% lower.

Controlling for number of people in the room gives a clearer picture. With one occupant opening doors results in average CO_2 levels 11% lower, but the intensity of CO_2 exposure drops by 46%. With two occupants, average CO_2 levels reduce by 17% and % t>1000 ppm by 20%.

The values for percentage of time above % t >1000 ppm over the week were compared with the daily average wind speeds. There is a strong correlation observed, with CO_2 levels rising as wind speed decreases. This illustrates quite clearly the important effect that wind has in driving ventilation, but also begs the question of what the drivers are when wind is not available, or effects are reduced by the built form.

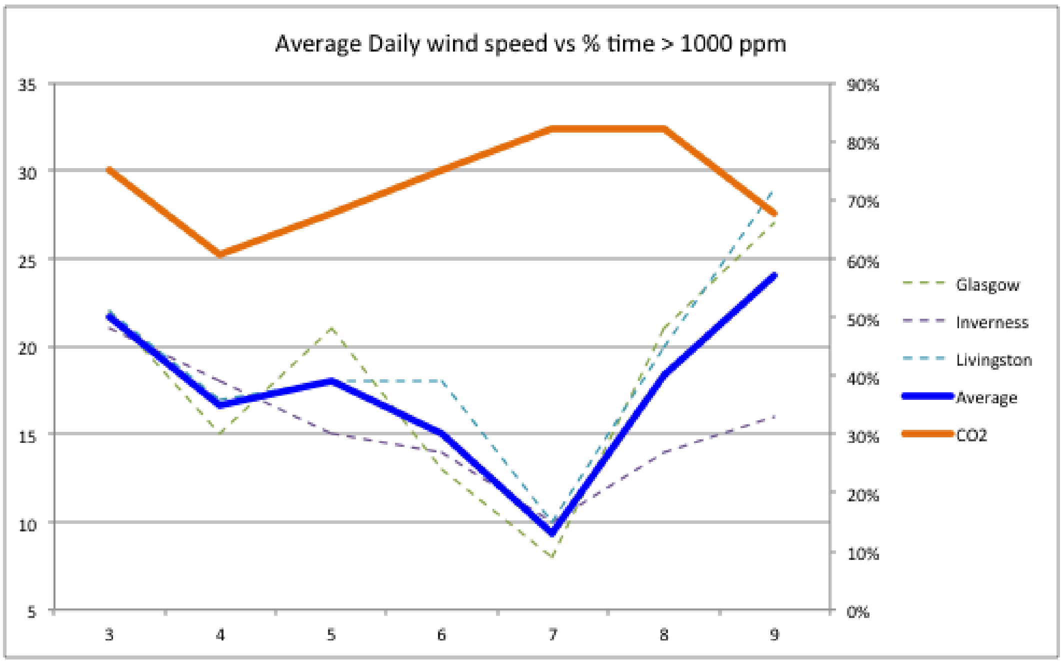


Figure 38: Effects of wind on ventilation

This data indicates that a reasonable ventilation rate is dependant on a number of unplanned factors, including the number of occupants, the degree of internal air movement due to door opening (and by implication the built form) and ambient weather conditions. However, even in ideal circumstances (7th May with highest wind, one occupant, doors open) only one of these dwellings did not exceed 1000 ppm. Two others did achieve good ventilation, but these had open windows. Given the data on door opening, and a general expectation from occupants about issues such as privacy and noise, and other regulatory requirements such as fire protection, means that such an extemporaneous strategy is not robust enough to deliver adequate ventilation and is the exception rather than the rule. Given that in all these cases the trickle vents were operational, it is apparent that relying on the current regulatory provision does not result in adequate ventilation rates.

Where the occupancy and the CO_2 level are known, the apparent ventilation rate can be calculated based on assumed metabolic rates. These back calculations have been applied in a previous study [105] to relate observed CO_2 levels to ventilation rates and use of windows and doors in both living rooms and bedrooms. The air change rates reported were around 0.25 ac/h with doors and windows closed, and around 0.6 ac/h with either windows or doors open. The study concluded that for 2 persons sleeping in a 14m^2 bedroom the required air change would be 1.4 ac/h to maintain 1000 ppm which would require window 'wide open', how 'wide open' was not specified, the authors did not comment on whether this CO_2 level should be a requirement in bedrooms.

As a part of the literature review a calculator was developed to reproduce these back calculations allowing CO_2 levels to be related to occupancy and infiltration rates (Figure 39).

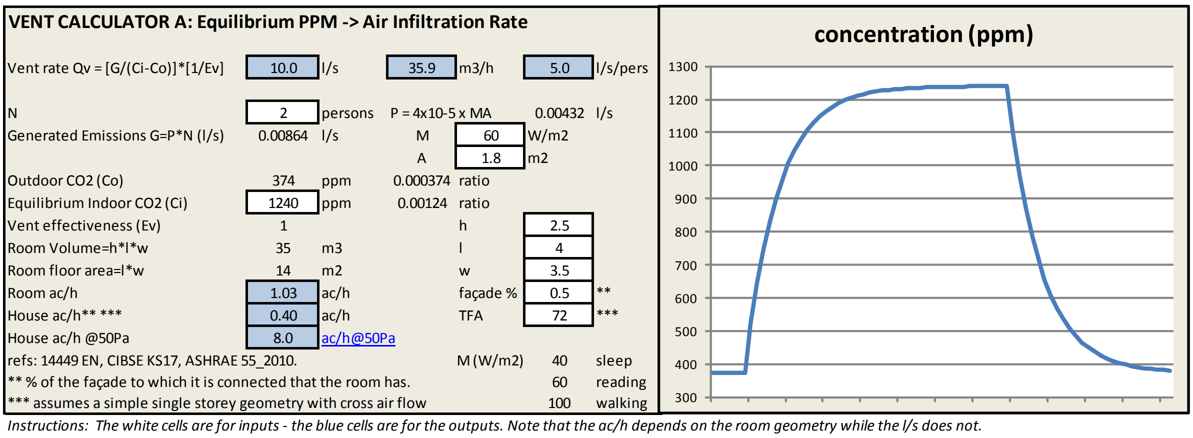


Figure 39: Calculation tool relating ppm levels to ventilation rates and occupancy.

This tool was then used to reproduce the results reported in the previous study and generate similar results from measurements made in this project (Figure 40). If non-human pollutant levels and the ventilation rate are known (or vent rate calculated from CO_2 and occupancy levels) then it is possible to calculate the non-human pollutant emissions rates. From these calculations it is also then possible to calculate the required ventilation rate to keep non-human pollutants at acceptable levels, which could be associated with a CO_2 level for a known or assumed occupancy. Similarly if pollutant sources and occupancy were assumed to be 'standard' then a CO_2 level associated with this assumed 'standard' situation could be set which could be associated with both human and non-human pollutants.

[105] Hasselar E. (2006) Health Performance of Housing Indicators and Tools, Delft University Press. Sustainable Urban Areas Series.I ISBN 10: 1586036890 / ISBN 13: 9781586036898 (pdf free download from Delft University repository

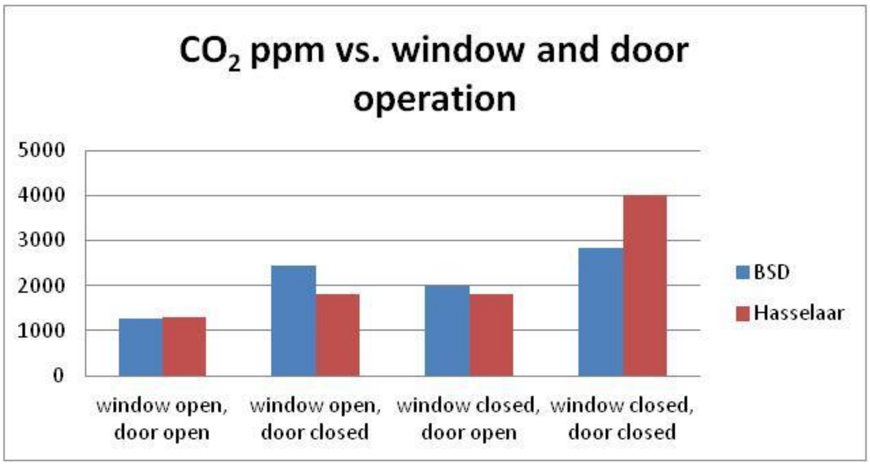


Figure 40: CO_2 ppm levels vs. window and door use for the 1995 Netherlands study (Hasselaar) and a sample of data from this current study.

Temperature and relative humidity

Whilst the main aim of the study was to examine ventilation, data on temperature and humidity was also gathered through the monitoring and the results are shown in Table 12 and a summary shown in Figure 41.

								night 1			night 2			night 3			night 4			night 5			night 6			night 7			week	
Ref		House Size (m^2)	Occupant No		Room area (m^2)	Room volume (m^3)		no	temp °C	RH %	no	temp °C	RH %	no	temp °C	RH %	no	temp °C	RH %	no	temp °C	RH %	no	temp °C	RH %	no	temp °C	RH %	Avg temp (week)	RH (week) %
MF02	GB1	66.0	1	bed	14.64	35.14	Ad	1	17.72	45.51	1	18.56	44.95	1	17.43	47.18	1	17.25	50.42	1	17.45	47.89	1	18.32	45.37	1	19.28	43.26	18.01	46.38
SF17	GA2	51.0	1	bed	9.00	21.60	Ad	1	27.95	33.38	1	27.88	35.51	1	27.87	30.73	1	27.73	34.49	1	27.89	36.33	1	27.49	35.63	1	26.65	35.45	27.63	34.53
P15	TB1	104.0	2	bed 1	11.83	37.85	Ch	1	17.62	47.21	1	16.84	44.55	1	15.86	45.84	1	17.53	51.84	1	16.38	52.38	1	17.86	56.04	1	18.33	56.27	17.20	50.65
29MP	BB1	75.8	2	bed 1	13.15	31.50	Ad	1	17.87	52.22	1	17.48	49.81	1	16.47	51.55	1	17.48	51.81	1	17.17	56.15	1	17.27	52.37	1	17.56	52.78	17.32	52.39
27MP	BA1	93.1	2	bed 2	12.62	31.23	Ad	1	17.79	44.67	1	18.15	44.70	1	19.00	46.53	1	19.62	48.97	1	20.53	47.95	1	15.70	43	1	15.41	44.92	18.03	45.84
P15	TB1	104.0	2	bed 2 m	14.22	45.50	Ad	1	18.33	49.86	1	18.90	46.28	1	16.66	48.83	1	18.65	56.32	1	17.35	56.26	1	19.22	56.79	1	19.53	62.10	18.38	53.85
4BG	IB1	90.0	2	bed m	10.63	28.70	Ad	1	22.44	39.73	1	22.34	35.80	1	21.61	35.15	1	22.80	38.09	1	22.69	38.01	1	22.73	40.81	1	23.19	42.49	22.55	38.56
4BG	IB1	90.0	2	bed east	7.13	19.25	Ch	1	25.69	48.69	1	22.90	39.53	1	22.45	37.92	1	23.56	40.14	1	23.22	41.49	1	22.47	41.32	1	22.98	43.18	23.28	41.63
CC	DA2	87.0	2	bed 1	14.93	33.68	Ad	1	26.88	32.39	1	22.70	31.53	1	24.68	30.54	1	25.93	31.59	1	25.36	30.39	1	26.01	33.03	1	23.71	32.73	25.00	31.73
26BC	LA2	104.0	3	bed 3	11.23	27.40	Ad	1	24.00	26.81	1	21.59	26.45	1	22.24	28.48	1	22.71	31.90	1	22.29	31.03	1	21.32	31.46	1	21.71	29.84	22.23	29.47
25BC	LA1	104.0	3	bed 3	11.23	27.40	Ad	1	22.43	40.26	0	22.01	35.25	1	22.64	38.14	0	22.97	38.25	1	22.95	41.40	1	22.47	38.10	1	22.33	39.94	22.54	38.74
P14	TA2	120.0	4	bed 1	11.83	30.77	Ch	1	21.27	41.39	1	20.90	40.22	1	20.82	39.11	1	20.45	40.21	1	19.73	41.98	1	19.90	38.08	1	18.66	39.10	20.23	39.99
OC	DB2	102.8	4	bed m	12.19	35.76	Ch	1	20.61	35.12	1	21.67	35.74	1	21.58	37.16	1	22.15	38.33	1	19.56	39.60	1	23.41	38.33	1	21.60	38.01	21.53	37.51
5BG	IB2	90.0	4	bed east	7.13	19.25	Ch	1	21.53	37.78	1	21.58	41.33	1	22.34	39.43	1	21.76	37.88	1	22.53	42.33	1	20.45	39.17	1	21.58	43.17	21.69	40.20
OC	DB2	102.8	4	bed	10.13	29.00	Ch	1	23.10	40.07	1	22.45	38.23	1	22.33	38.68	1	23.49	39.79	1	20.95	40.55	1	23.27	40.65	1	22.52	40.71	22.58	39.81
P5	TA1	120.0	5	bed 1	11.83	30.77	Ch	1	18.39	60.55	1	18.19	57.40	1	17.68	59.45	1	18.00	60.01	1	17.65	60.53	1	17.48	56.23	1	17.19	57.91	17.79	58.84
4BS	IA2	110.0	6	east bed	9.98	24.95	Ch	1	19.77	43.05	1	21.01	40.63	1	20.71	44.26	1	20.78	41.57	1	20.29	43.86	1	20.86	40.59	1	21.86	40.89	20.77	42.10
3BS	IA1	110.0	6	west bed	11.17	28.08	Ch	1	24.40	45.53	1	24.17	46.69	1	24.11	44.17	1	24.87	40.81	1	24.50	35.87	1	24.17	48.54	1	24.53	51.35	24.39	44.59
9BB	IC1	63.0	2	bed	11.80	28.32	Ads	2	21.68	52.68	2	21.53	48.50	0	16.23	45.18	2	20.87	48.75	2	16.63	52.10	2	13.79	51.17	0	11.68	46.03	17.41	49.14
6BS	ID1	76.0	2	bed	9.71	23.30	Ads	2	21.82	38.94	2	21.72	37.08	2	22.04	35.85	2	22.51	35.74	2	22.63	34.44	2	22.18	33.81	2	21.77	32.10	22.10	35.36
7BS	ID2	76.0	2	bed	9.11	21.86	Ads	2	21.96	42.00	2	24.08	43.03	2	22.68	42.88	2	21.52	44.25	2	22.30	46.90	2	21.65	45.43	2	22.13	43.70	22.34	44.06
37MP	BC1	75.4	2	bed 2	12.54	30.34	Ads	2	22.96	38.09	2	22.18	39.56	2	22.52	37.25	2	23.32	39.05	2	21.89	40.93	2	22.19	36.81	2	22.41	38.78	22.49	38.64
MF03	GB3	73.3	3	bed	10.85	26.04	Ads	2	19.90	58.58	2	21.46	55.54	2	19.01	57.63	2	19.62	60.64	2	18.14	60.04	2	17.88	55.30	2	20.89	57.96	19.59	58.01
MF22	GB2	66.0	3	bed	14.64	35.14	Ad	2	20.63	34.55	2	23.90	32.59	2	22.59	38.81	2	21.89	36.86	2	24.01	37.60	2	24.97	35.28	2	20.74	35.71	22.65	35.96
P14	TA2	120.0	4	bed 3 m	14.22	45.50	Ads	2	21.77	42.25	2	20.70	42.44	2	19.60	42.49	2	20.89	43.91	2	21.18	45.45	2	20.15	38.64	2	20.29	41.35	20.63	42.36
5BG	IB2	90.0	4	bed m	10.63	28.70	Ads	2	19.59	39.60	2	22.50	44.30	2	23.57	40.08	2	21.13	34.50	2	22.35	39.78	2	22.45	39.20	2	22.59	43.34	22.07	40.12
P5	TA1	120.0	5	bed 3m	14.22	45.50	Ads	2	18.59	60.11	2	18.01	56.70	2	17.94	56.71	2	18.35	60.09	2	18.59	59.05	2	18.01	56.38	2	17.70	57.82	18.16	58.09
3BS	IA1	110.0	6	east bed	9.98	24.95	Ads	2	20.80	49.18	2	20.80	42.59	2	18.59	34.74	2	24.73	34.22	2	21.85	29.87	2	21.30	41.75	2	22.38	51.01	21.59	39.26
4BS	IA2	110.0	6	west bed	11.17	28.08	1 Ad/2 Ch	3	19.90	43.17	3	21.35	42.38	3	21.33	44.08	3	21.01	42.19	3	20.95	43.95	3	21.37	40.37	3	22.13	41.94	21.17	42.57

Table 12: Daily average temperature and humidity levels 2 – 9 May 2014

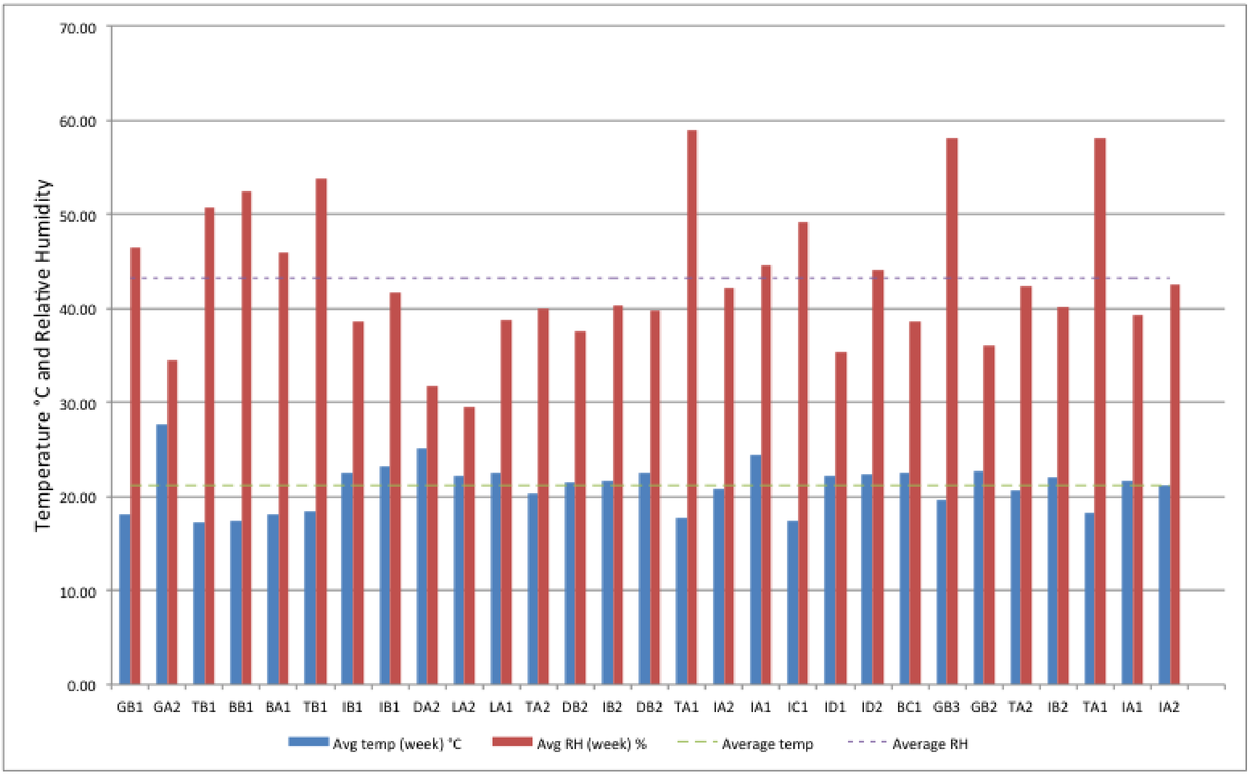


Figure 41: Weekly average temperature and relative humidity 2 – 9 May 2014

The data indicates that in general the dwellings are warm and dry. The overall tendency is for bedrooms to have higher temperatures and resulting lower RH. There was a considerable range across the set – lowest average weekly temperature was 17.2 and the highest was 27.6. External temperatures for the week were around 6°C. Overall 19 out of 31 (63%) rooms had averages over the recommended comfort level of 21. The RH levels were in general within accepted limits, however the range was great varying from 29.4 to 58.8. There is an underlying concern that the high temperatures may be masking moisture content and further analysis of the data would be required to examine vapour pressure levels.

There is generally a clear overall relationship between RH levels and CO_2 levels. However, what the data also indicates is that the RH levels were generally quite low due to the higher temperatures. This would have implications for a strategy, which relied on RH levels to control ventilation. A number of RH control passive vents are on the market, but this data would suggest that RH does not approach levels that would activate these.

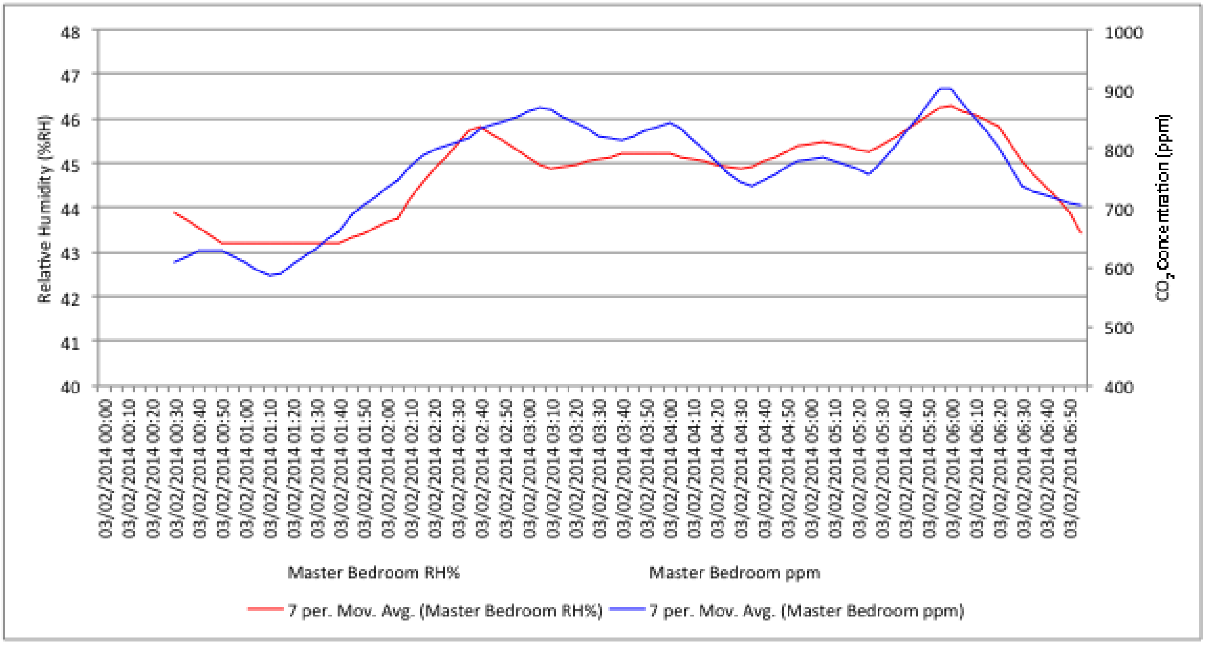


Figure 42: Example relationship between CO_2 and RH

Exceptions to this occur due to window opening. For example BB1 night 2, the window is open and RH is affected by external condition, so a sudden rise in external RH from 76% to 81% impacts on the room.

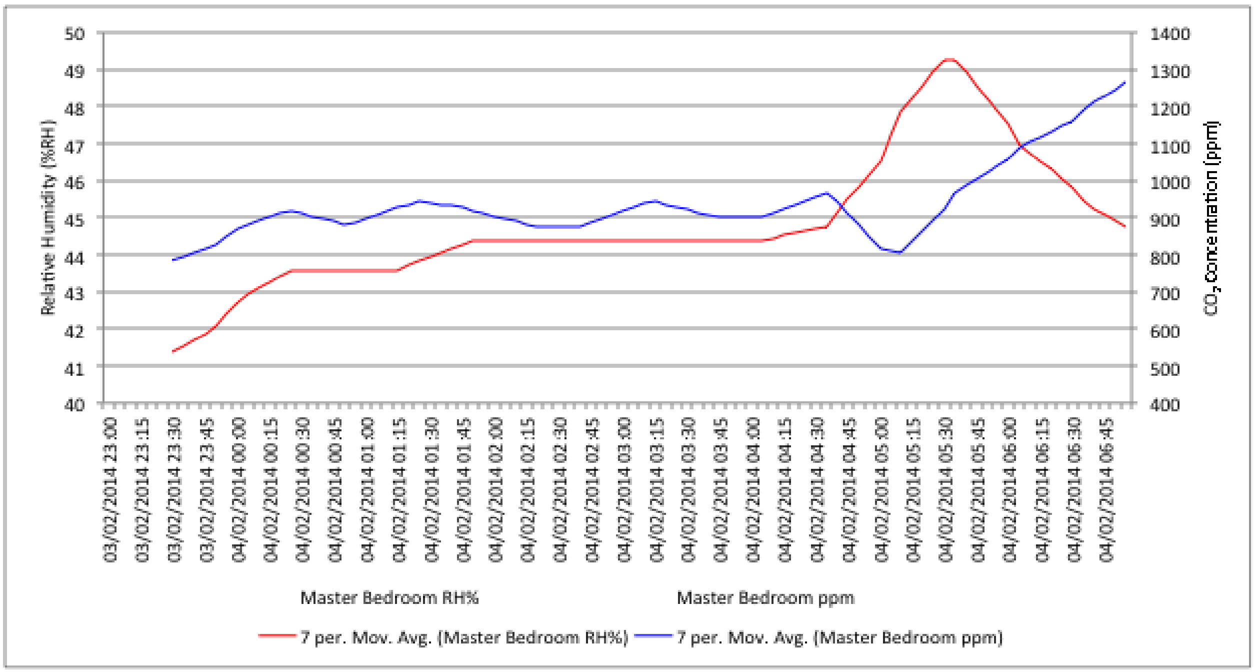


Figure 43: Example relationship between CO_2 and RH

VOC testing

The core houses are also subject to testing of IAQ. The project uses a DirectSense IAQ Tablet Standard Indoor Air Quality Survey & Monitoring kit includes IQ-410 Probe (measures CO_2, CO, %RH, temperature, dew point & additional derived moisture readings), GrayWolf 6 Channel Particle Counter kit with colour touch screen, 0.3 µm threshold, 0.5µm, 1.0µm, 2.5µm, 5.0µm, 10.0µm size channels plus mass concentration and formaldehyde meter along with associated installation equipment and software.The original intention had been to undertake VOC testing in all the core houses, but access for this has been difficult and noisy monitoring equipment has resulted in a poor response from residents. Despite this monitoring has been conducted on several properties at 3 locations across Scotland with 3 full sets of 48 hour data recorded.

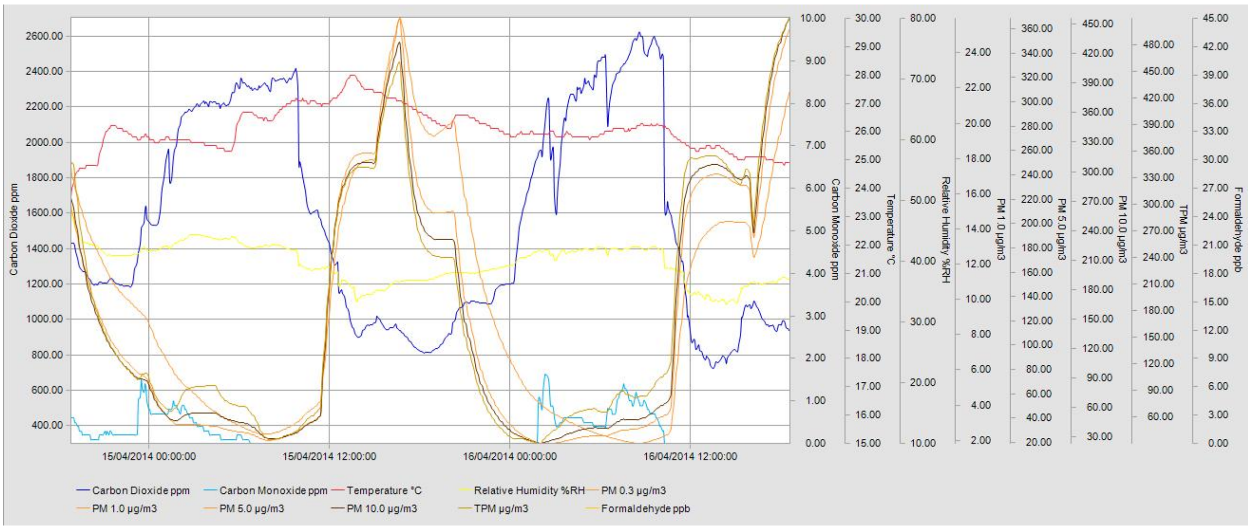
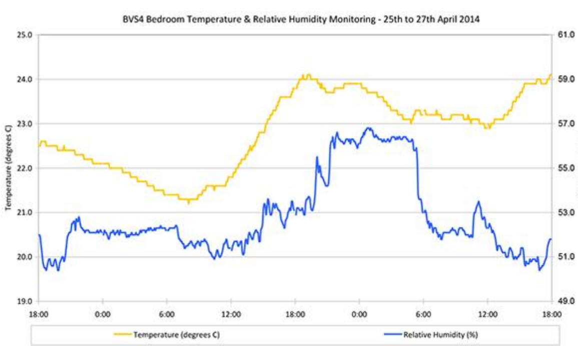
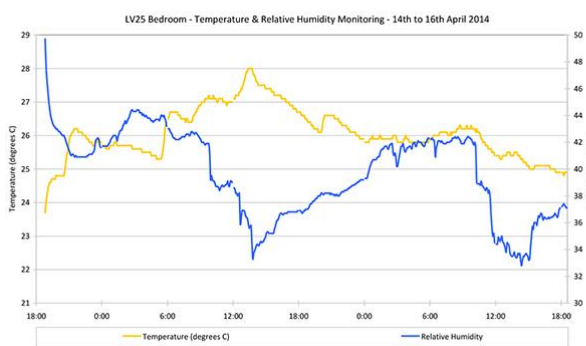


Figure 44: VOC concentrations 14-16 April, LA1.

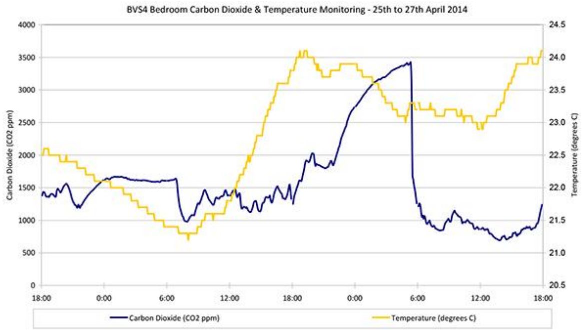
Sample data shown in Figure 44 provides an overview of how a typical house may perform. In this instance the bedroom has high CO_2 levels, well above 1000 ppm and peaking at 2483 ppm overnight. In addition high internal temperatures are constant ranging from 23.7 to 28 ^{o}C. It is also clear that relative humidity is slightly lower than would be desired falling below 40% for much of the day. Low levels of both Carbon Monoxide and formaldehyde are also present while Particulate Matter (PM) appears to greatly increase when the room is unoccupied which is more likely to be a result of window opening.

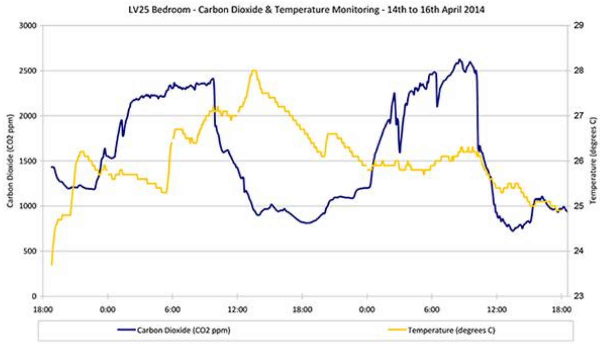
The data provided in 2 homes reporting high levels of CO_2 have been separated to identify potential relationships between CO_2 levels and pollutants.



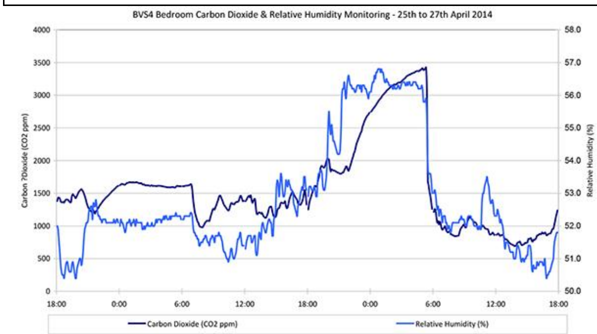


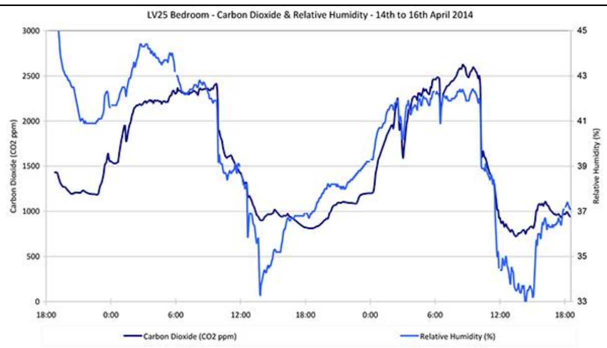
Figures 45 & 46: Temp & Relative Humidity in bedroom of IB1 and LA1 over 48 hrs.





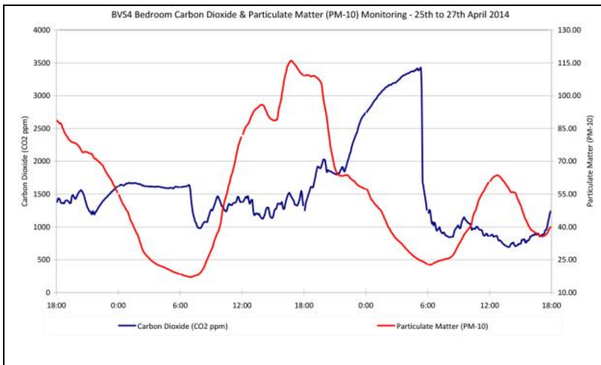
Figures 47 & 48: CO_2 & Temperature in bedroom of IB1 and LA1 over 48 hours.

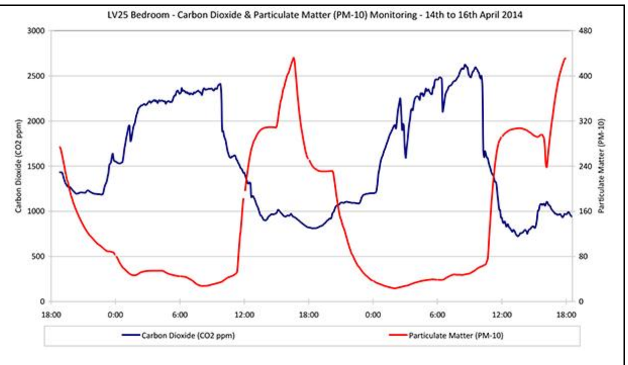




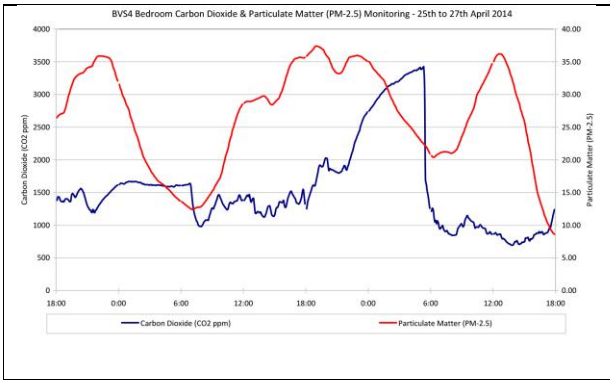
Figures 49 & 50: CO_2 & Relative Humidity in bedroom of IB1 and LA1 over 48 hours.

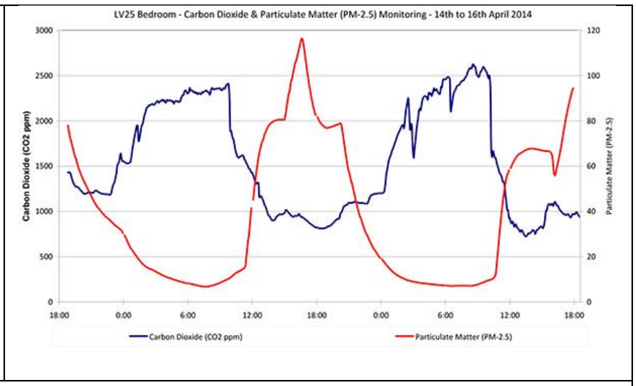
While both houses indicate higher levels of CO_2 they are performing quite differently with IB1 showing lower temperatures, although the range of 20.9 to 24.5 ^oC would generally be considered warm, with higher humidity in a comfortable range between 47.2 and 59.8%. On the other hand, dwelling LA1 is even warmer peaking at 28 ^oC but presents with lower RH levels reaching a minimum of 32.8% which is likely to cause the occupant to notice the atmosphere to feel dry. The pattern for CO_2 and relative humidity follow closely when the room is occupied which would be expected given that the main source of both is present.





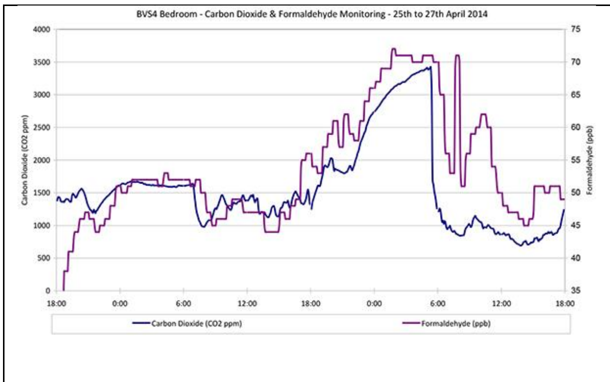
Figures 51 & 52: CO_2 & PM-10 in bedroom of IB1 and LA1 over 48 hours.

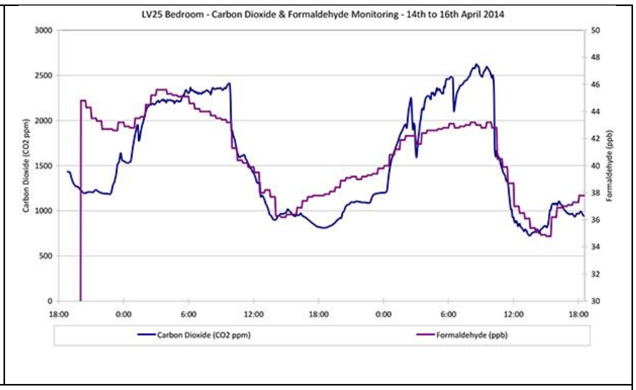




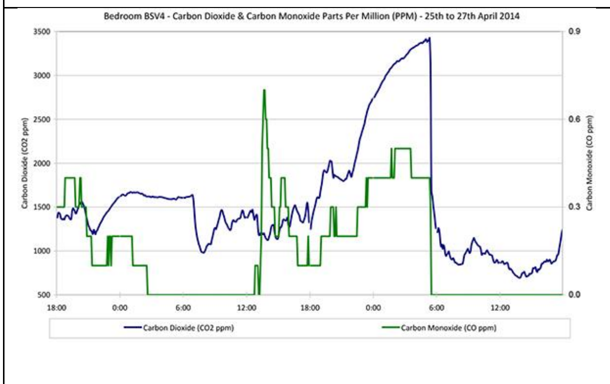
Figures 53 & 54: CO_2 & PM-2.5 in bedroom of IB1 and LA1 over 48 hours.

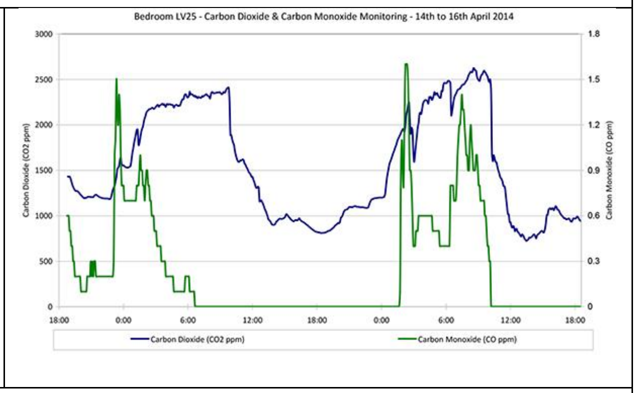
In the case of particulates the pattern is inverse, with the particulate matter reducing overnight as CO_2 rises. In both instances the windows were open in the afternoons and the door was closed overnight. This indicates that increased ventilation flow increases particulates when windows are open. Therefore when the residents isolate themselves at night the PM drops. In this period IB1 measured CO_2 figures (11pm - 7am); Min CO_2 = 943 ppm; Peak CO_2 = 3425ppm; % Time CO_2 > 1000ppm = 98% while LA1 measured Min CO_2 = 1149 ppm; Peak CO_2 = 2482ppm; % Time CO_2 > 1000ppm = 100%. However there are increases in other pollutants overnight, including Formaldehyde and Carbon Monoxide. Whilst CO does not rise to dangerous levels, the effect of reduced ventilation seems clear.





Figures 51 & 52: CO_2 & Formaldehyde in bedroom of IB1 and LA1 over 48 hours.





Figures 53 & 54: CO_2 & CO in bedroom of IB1 and LA1 over 48 hours.

In this case there are clear associations between CO2 & these pollutants. Of significance is the rapid reduction in formaldehyde in the mornings when the door is opened. Increases in formaldehyde follow the levels of ventilation resulting in a swing of up to 9.9ppb with a peak of 44.8 ppb and min reading of 34.9 ppb in LA1 representing a 22% reduction from peak. Similarly in IB1 levels of formaldehyde again follow ventilation with a greater swing of up to 41 ppb reaching a peak of 72 ppb and min reading of 31 ppb. The CO recorded in both cases is not at a level which causes concern, but does illustrate the effect of the reduced ventilation.

As discussed in the literature review, sources of pollutants may be unrelated to occupant presence, but this data illustrates the potential rise in pollutants with reduced ventilation overnight. However, it does also identify possible risks with purge ventilation during the day which may increase exposure to particulates from external sources. This may require context for ventilation strategies depending on the external context.

Summary

The results from this detailed monitoring confirms the findings from the sample monitoring and corresponds from other studies identified in the literature review concerning the effects of occupant interaction with available ventilation strategies. The key finding is that, even with trickle vents open, high CO_2 levels were observed for significant periods of time. The main planned mitigating factor was window opening, but fortuitous effects were the number of occupants, internal door opening and external wind conditions.

Accepting that the 1000ppm threshold identified in the literature review remains a satisfactory goal for ventilation strategies, the evidence is that these houses fall short of that standard. Calculated air change rates are relative low in relation to desired rates for good indoor air quality. High CO_2 levels correlated with increases in the levels of VOCs, however, with more liberal window opening, levels of particulates increases. Whilst the levels of air change, and observed levels of relative humidity, appear to be sufficient to address moisture, further analysis would be required to examine actual vapour pressure, and the relatively high temperatures may be masking moisture content in the air. High levels of CO_2 were observed in living rooms, but the complexity of living room conditions and opportunities for adaptive behaviour (such as window opening) hampers an assessment of the effects of background ventilation provision.

6.0 Conclusions

This research gives a vital insight into the ventilation habits of dwelling occupants in Scotland. The overview survey provides a consistent picture of the relative lack of trickle vent use in contemporary housing, and confirms evidence from previous studies. Most trickle vents are infrequently controlled, the majority being left in a closed state. Windows are used for purge ventilation, primarily to control overheating in living rooms, but window opening for purge ventilation is not a reliable or practical solution in bedrooms overnight.

The main drivers and barriers for ventilation are thermal comfort. In terms of occupant experience, poor ventilation is not generally seen as a problem as occupants do not easily perceive the fundamental drivers for ventilation, which are moisture control and pollutants. It is posited that adaptive responses to temperature, rather than IAQ, are the primary drivers for window opening, but these events are relatively infrequent (as evidenced by both the survey and the monitored data from the in-depth houses). However, some window opening is habitual (rather than adaptive) and is driven by ventilation perceptions. It would seem that the trickle vents do not have an immediate or significant enough effect to persuade occupants of their use over the more immediate use of windows which are in any case designed to be easier to physically access and control.

The survey responses suggest that occupants are aware of energy issues (citing concerns about heat loss as barriers for ventilation) and are attempting to tread the line between ventilation and energy use and comfort. This suggests that regulatory guidance for ventilation provision needs to be considered in relation to energy use in general and heating provision in particular – a ventilation strategy aimed only at high rates of ventilation could lead to excessive heat loss.

The survey also undermines a view that occupants turn heating up and open windows. Clearly the majority of occupants are concerned about unnecessary heat loss, to the extent that ventilation is restricted. Occupants are attempting to balance warmth and fresh air with the tools at their disposal, but with warmth being the more immediate and discernible need, ventilation may be compromised.

Whilst adaptive behaviour for purge ventilation may be a reasonable model in some parts of dwellings such as living rooms, in other rooms it is a limited strategy. Occupants of bedrooms, asleep overnight are not able respond to changing conditions.

The lack of guidance for occupants was also apparent and greater knowledge about the benefits of ventilation and reassurance about likely energy impacts could be beneficial. A reasonable proportion of the population habitually ventilate overnight.

The monitoring data indicates that lack of use of ventilation provision leads to low ventilation rates as evidence by the CO_2 levels, and in the smaller sample, associations between CO_2 and VOC levels were evident. Of concern however is that these problems remain, even in dwellings where the ventilation provision is used as intended, with trickle vents left open

With regard ventilation strategies for use by occupants, it is noted that the current guidance supporting regulations make no reference to door opening and other statutory requirements. For example fire safety in some house types, would expressly prevent this. The monitoring indicates that the use of trickle vents does improve ventilation rates, as does internal door opening, but not to a reasonable or reliable standard. The current guidance is thus very sensitive to fortuitous effects and does not account for known variables including the likely level of occupancy, built form, and availability of cross ventilation. Ventilation rates are reliant (and sensitive to) to uncontrolled factors including external weather, internal door opening, and occlusion of vents by curtains and blinds.

With increasing airtightness leading to a lack of fortuitous ventilation, paths for air movement are very much reduced. The condition may be worse in UK housing, which has smaller space standards, with a tendency to smaller rooms [106].

The findings suggest that some revision of the guidance may be required. Whilst it is envisaged that better guidance to occupants could lead to improved ventilation habits, the indication is that the purpose of the vents is known and in general occupants are satisfied with their perceived air quality, and greater ventilation may be compromised by concerns about energy use and costs. Requiring internal doors to be left open is neither a practical, nor acceptable solution.

Lack of occupant perception of poor ventilation and pollutants is a barrier to adaptive behaviours. Given the potential health effects of poor ventilation, and precedents through other ventilation issues such as combustion for appliances and carbon monoxide, strategies that do not rely on specific occupant interaction may be necessary to provide backstop rates. Alternatively, better information on IAQ is needed for occupants.

The need to provide a reasonable ventilation rate, whilst not compromising drivers for energy consumption is a difficult balancing act. Whilst greater use of mechanical ventilation offers a particular solution, this is also not without its risks and costs.

An obvious solution would be to reduce or omit the provision for trickle vents to be entirely closed. Having vents opened, perhaps permanently, would be more reliable if effects of wind and draughts could be avoided. Baffles to reduce wind pressure and noise would be needed to improve acceptability. Care is needed to avoid solutions that may have unintended negative consequences, for example making vents permanently fixed open or much larger which leads to draughts and causes occupants to block them. However, the evidence from this study suggests that this would still not lead to acceptable ventilation rates.

[106] RIBA (2011) The Case for Space accessed at http://www.architecture.com/Files/RIBAHoldings/PolicyAndInternationalRelations/HomeWise/CaseforSpace.pdf June 2014

Provision for air movement in mechanical strategies includes the use of undercuts and pass vents and this strategy could be applied in buildings with natural ventilation, but considerable caution is required here. In a mechanical system there is a driver for air movement, which may not be present in a natural ventilation strategy. Furthermore, part of the effectiveness of the doors being open in these studies is that the net volume of the space is increased. Making a vent large enough to replicate an open door (a standard door opened by 50mm provides an opening of approximately 110000 mm^2) may lead to unintended negative consequences – e.g. noise transmission, space (limited above doors) appearance, etc. and would need to address issues of fire protection in flats. The effectiveness of vents through doors also presupposes other vents being open on the other side of the house. Some performance criteria, in terms of noise transmission and fire safety are required to avoid such provision being disabled. However further research is required to determine the effectiveness of this as a solution.

Providing paths for air movement within spaces may be more effective. It is a well-established principle in natural ventilation that high and low level openings provide a more effective path for air movement. Again, care is needed to avoid solutions that are perceived as draughts or nuisance. The co-location of vents with heat sources may address this, but there is an increasing tendency for radiators not to be placed near openings.

Whilst airtightness of buildings has been driven by energy conservation measures, greater ventilation of bedrooms at night may not be a significant energy loss – heating is likely to be off. Furthermore this may also help to counter possible effects of overheating in summer, for which there is emerging evidence and which may be a related ventilation issue not addressed directly in this study, although relatively high temperatures are apparent.

Some acknowledgement of varying known elements is also needed. This includes volume, occupancy, built form, and location.

What is less clear are the consequences of this in terms of health. There is a robust body of knowledge indicating the appropriateness of the 1000 ppm CO_2 level, and the majority of results seen here clearly exceed levels. By accepted standards of air quality (CIBSE Guide A), the air change rates achieved are generally moderate (IDA3 6-10 $l.s^{-1}$/person) or low (IDA4 <6 $l.s^{-1}$/person). They do correspond with air change requirements for mechanical systems, which have minimum rates of 0.5 ach but it is important to recognise that these levels are determined by moisture control rather than IAQ. Further work is needed to establish IAQ standards for dwellings and clearer relationships to health and ventilation evidenced through CO_2 levels and other pollutants in housing.

The literature review also identified a number of concerns about the health effects of indoor pollutants and there is limited regulation on the sources of these. Whilst the study was focussed particularly on issues of ventilation as a means of removing pollutants, control of the source is required in the context of warmer, tighter buildings. The remit of Building Standards would be limited to building materials and other agencies would need to address other sources such as furniture and carpets, and further research is required to determine what limits are required for different pollution sources.

In addition to revision of the standards, a further area that needs development is that of ensuring compliance. Of particular concern is the performance gap between expectations at design and compliance stages and the as-built performance, and lack of compliance with the regulations. More rigorous inspection may help to address this issue, compliance remains the responsibility of clients, developers and contractors and work is needed in the industry to improve standards of design, construction, installation and commissioning. Particular problems identified here were higher than intended air tightness and defective mechanical systems, but this does reveal that compliance with recommendations in the standards is largely achieved at design stages but may not be achieved on site on site. One notable exception to this is ironically air tightness, where the prescribed on-site testing is clearly leading to improved performance in this area. Improved on-site testing and compliance is therefore an important consideration in the development of any revision to the standards.

One of the difficulties facing regulation is the increasing complexity of buildings, materials and systems to address primarily energy issues, but which have unintended consequences on other aspects. It may therefore be useful to consider a regulatory strategy that passes some of this design responsibility back to architects and builders through the provision of in-use performance standards. Not only would this allow designers to develop their own solutions, it may assist in compliance in the finished building. It may also provide some incentive for manufacturers to develop more innovative solutions.

In the light of the findings of the study a number of possible mitigating solutions might be considered. These are grouped in terms of relatively simple revisions to the guidance to the standards which may improve performance, but which are unlikely to entirely resolve the problem, against more significant improvements that may be more effective.

Minimal revisions to guidance supporting Standards

- Occupant guidance on ventilation - Require specific handover guidance on ventilation use. Clearly occupant interaction is an important factor, and whilst occupant knowledge of vents was clear, greater information could be provided on their importance, benefits and relative impacts on energy use.

- Provide guidance to leave vents open at handover. This measure could increase the propensity for vents to be open, but is unlikely to be overly effective.

- Monitoring and indicators for CO_2 and pollutants. Following the precedents set for smoke and CO detectors, installation of detectors or indicators of IAQ would provide occupants with information about IAQ levels which might act as drivers for adaptive behaviour. There is an increasing awareness of IAQ issues amongst consumers as evidence by growing popularity of CO_2 monitors

- Specify in guidance undercuts and/or pass vents on internal doors. This could assist with air flow, but research is required to determine the overall effectiveness of this as a strategy. As discussed above, this is unlikely to replicate the benefits of open doors and there may be confounding factors such as noise and appearance, and conflict with fire safety guidance that should be explored.

- Specify in guidance trickle vents with a permanent background opening. Given that modern airtight dwellings rely on some form of background ventilation, having a system that can be closed makes less sense. Permanently open vents might include some degree of adjustability. At present this seems an unused function, but could be improved with better usability. Given the importance of other factors such as door opening, its effectiveness as a stand-alone measure may be limited.

- Improved guidance for wind protection for trickle vents to prevent draughts. There would seem to be scope for improved design of vents that allow air movement but that prevent draughts, particularly if this can allow for larger vents.

- Specify in guidance accessibility and useability for control of background ventilation. Ensuring that vents are within reach, easily visible and accessible, or can be operated remotely (i.e. by pull cords) may improve user interaction, particularly in conjunction with better occupant guidance. Nevertheless, without additional strategies overall effects are likely to be limited.

- Specify in guidance humidistat controlled passive vents. As demonstrated in the data there can be a good relationship between CO_2 and RH, and vents that respond to RH could give more demand driven ventilation. However, development is needed to ensure that the responsiveness is delivered with the relatively low RH levels seen in contemporary warm housing.

- Specify in guidance high and low level vents. Having multiple openings provides a better opportunity for air movement. Guidance calling for vents outwith the window frame may overcome barriers to effectiveness in terms of occlusion, accessibility and awareness. However 'air-brick' type solutions that give rise to draughts needs to be avoided.

- Encourage use of DMEV, but include requirement for undercuts or pass vents. This would still require the revision of the trickle vent provision to prevent unnecessary closure and minimised nuisance effects of draughts, but would provide a backstop ventilation level.

- Make DMEV necessary in buildings without provision for cross ventilation. Certain 'high risk' building types may not be able to provide a background level of ventilation without some form of driver. However considerable care is needed with mechanical strategies to ensure that they are compliant, do not result in additional costs (or perception of cost), noise or maintenance. On-site testing for compliance should be carried out.

- Clarify in guidance remedial action for buildings exceeding airtightness, e.g. upgrading extract provision to DMEV. An issue identified in this, and previous studies are buildings that exceed their airtightness requirements. In these cases a remedial action might be to upgrade the extract ventilation. Care is needed to discourage 'loosening' of fabric to meet specific airtightness levels.

- Specify in guidance passive stack vents in central areas to assist with airflow (especially in deep plan).

- Improved and increased compliance testing of ventilation provision (trickle vent size, location, etc.), post completion testing and commissioning of extract ventilation systems. Better testing of compliance is required so that design measures are installed correctly and are fit for purpose.

Enhanced revisions to guidance supporting Standards

- Evaluate 0.5 ach level against 8 l/s/person/ 1000 ppm. It is clear that further work is required to establish ventilation rates that deliver good IAQ. Current standards have been mainly driven by moisture control on top of an assumed permeability, and the indications are that greater ventilation rates are required to maintain healthy IAQ.

- Revise the guidance for particular occupancy types, for example older people, or restricted mobility to enable access to ventilation measures.

• Revise the building standard guidance on ventilation for different building situations. This can be determined by likely built form, occupancy load, sleeping risk, degree of exposure. A relatively simple calculation can be developed to determine ventilation required. The amount of outside air required to maintain the CO_2 concentration at an acceptable level can be established using the methodology in CIBSE Application Manual AM10, section 4.5. Two approaches can be adopted. The amount of outside air can be calculated to achieve a steady state dilution of CO_2 to an acceptable level. Using the methodology provide in the AM the amount of outside air per person to control the CO_2 to say 1000 ppm would be 8 litres/second. A methodology is also provided by which the reservoir effect of a room can be used to accommodate short periods of higher occupancy.

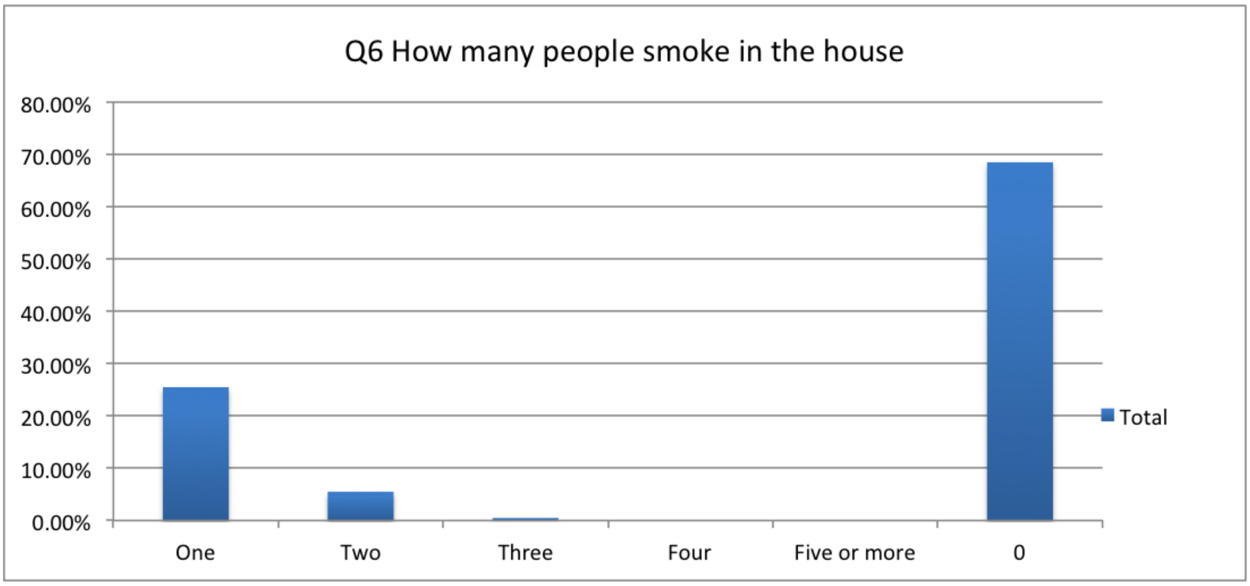
• Develop and specify in guidance a modification of the airtightness test to calculate actual ventilation rate (not just fabric losses). The current purpose of the air permeability test is to evaluate the fabric ventilation losses. The test could be modified to identify actual ventilation rates with vents open, and a performance level set in relation to this.

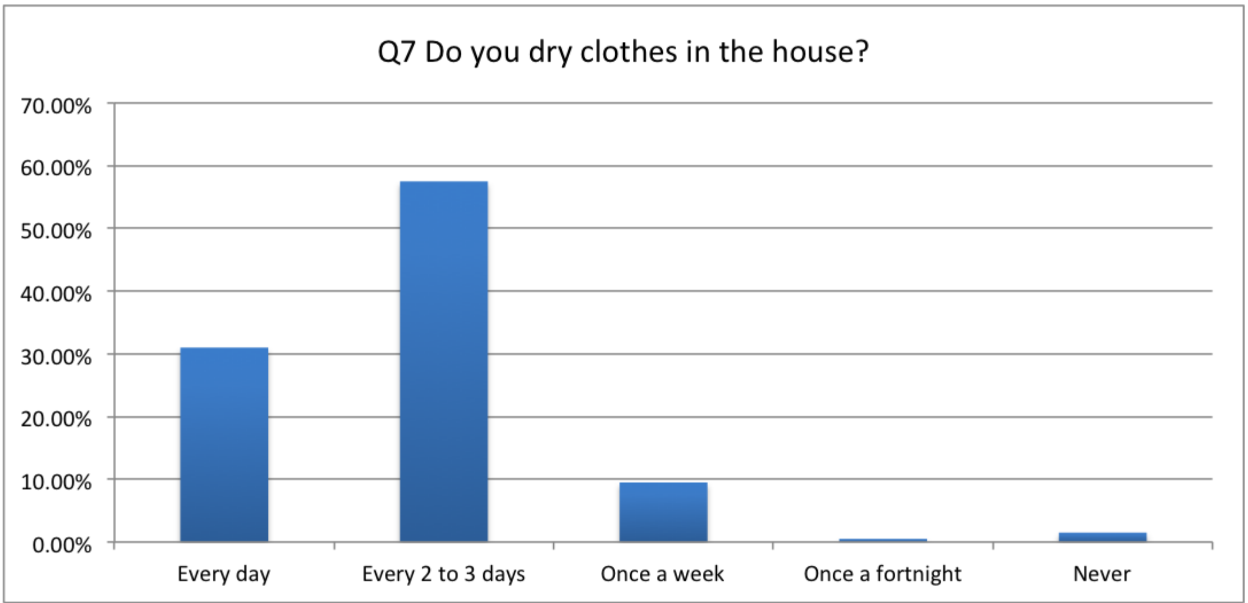
• Develop an option for a performance related ventilation standard (capable of maintain a given level of ventilation with specific levels of occupancy). As well as providing a delivered level of performance this would allow designers freedom to determine a range of strategies to meet the requirement. Research is needed to determine the performance levels, but this could be introduced in the same way as elective standards in Section 7.

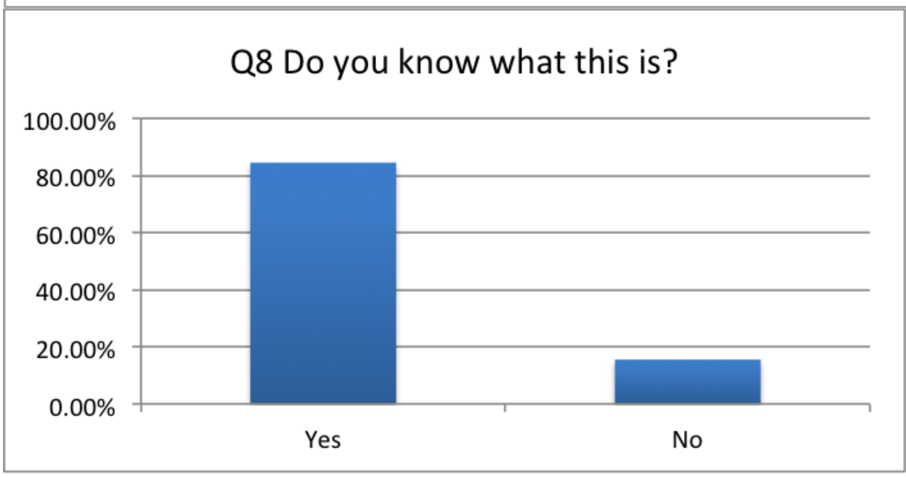
• Ventilation could be considered in relation to heating. Currently heating and ventilation are in separate sections, but their agendas are clearly related. Recommendations or requirements for positioning of heat sources close to ventilation sources could prevent cold air, draughts and also provide drivers for air movement. At the same time, a requirement for improved levels of ventilation should not confound measures for energy and carbon reduction.

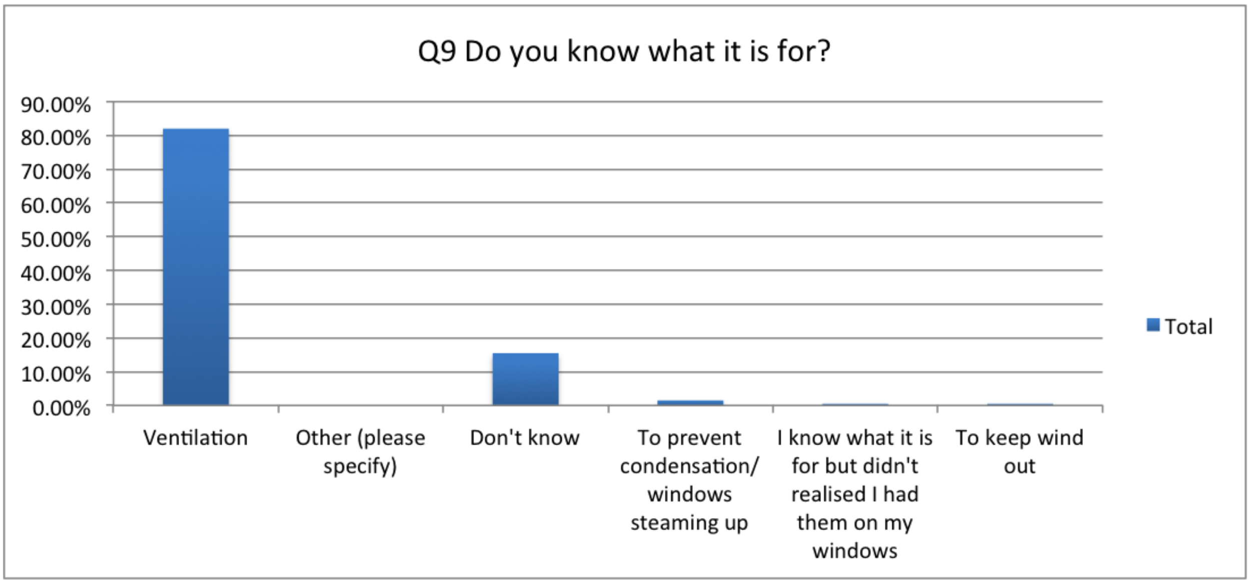
• Extract from bedrooms. Dilution of pollutants is not as effective as extract so forms of extract may be more effective. Drawing air from occupied bedrooms may then (subject to opportunities for cross flow) draw relatively warm air from other unoccupied parts of the house. This may also be helpful in addressing overheating problems. Clearly noise and running costs may be an issue. There may be opportunities to extend ventilation provision from adjacent bathroom spaces.

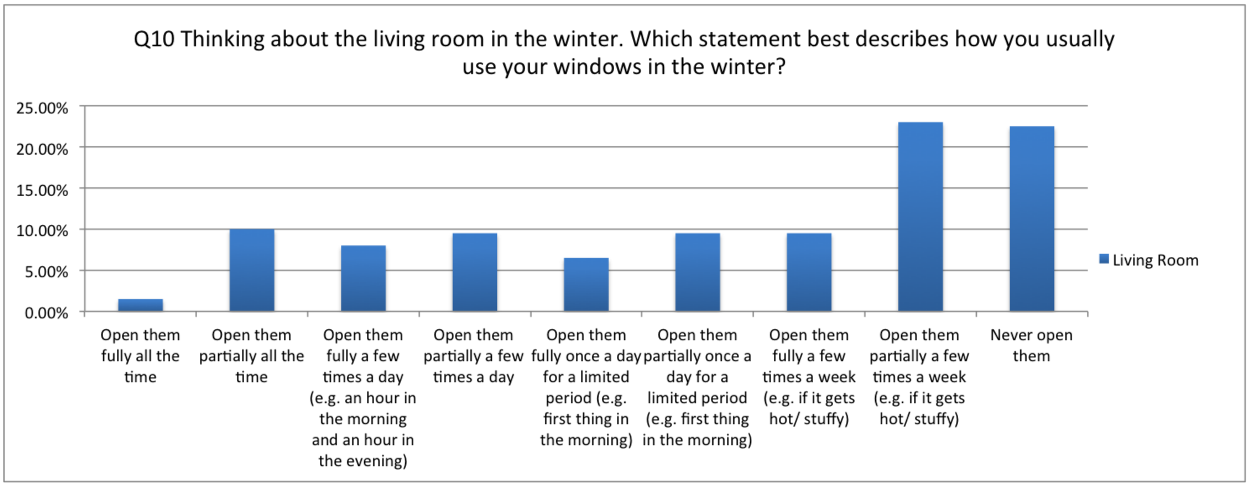
Although this sits outwith the remit of building standards, there is a clear case for improved post occupancy testing for compliance. This is needed to ensure that existing standards are being met, and that safe and efficient environments are being provided. However, in all these case, further research is required to test the efficacy of the various measures proposed. In the context of this work there is a strong argument for the development and use of performance standards as a means of determining compliance. In this case a performance requirement is set (for example energy use or levels of acceptable IAQ), and these would be tested post completion. Not only would this check whether the necessary standards are being met, it would also be more effective than attempting to develop general design requirements that can be applied in a range of buildings and conditions. It would pass design responsibility back to architects and developers. However further research is required to establish what these standards might be, and how they might be effectively and reliably measured.

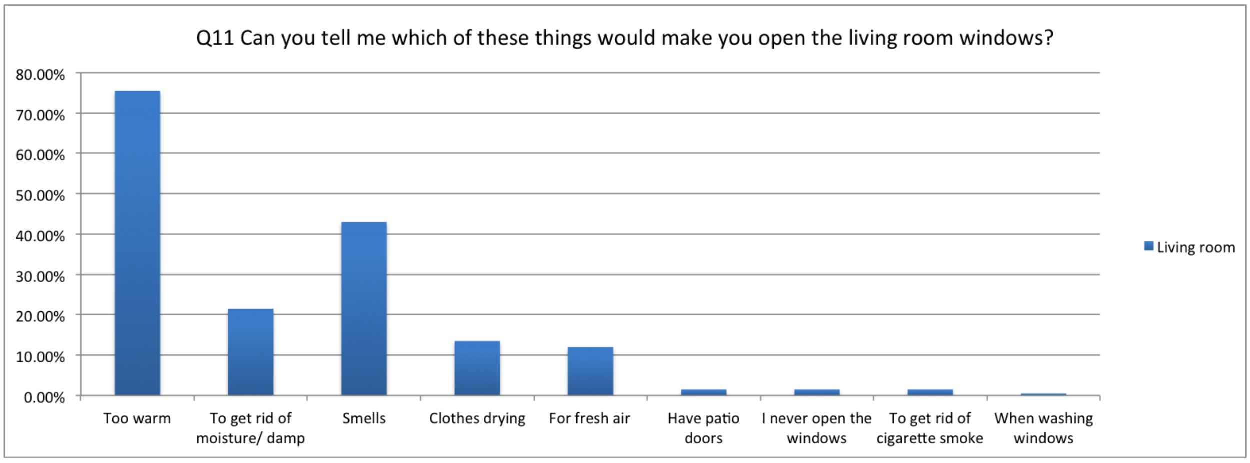

Q6 How many people smoke in the house
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
One
Two
Three
Four
Five or more
0
Total

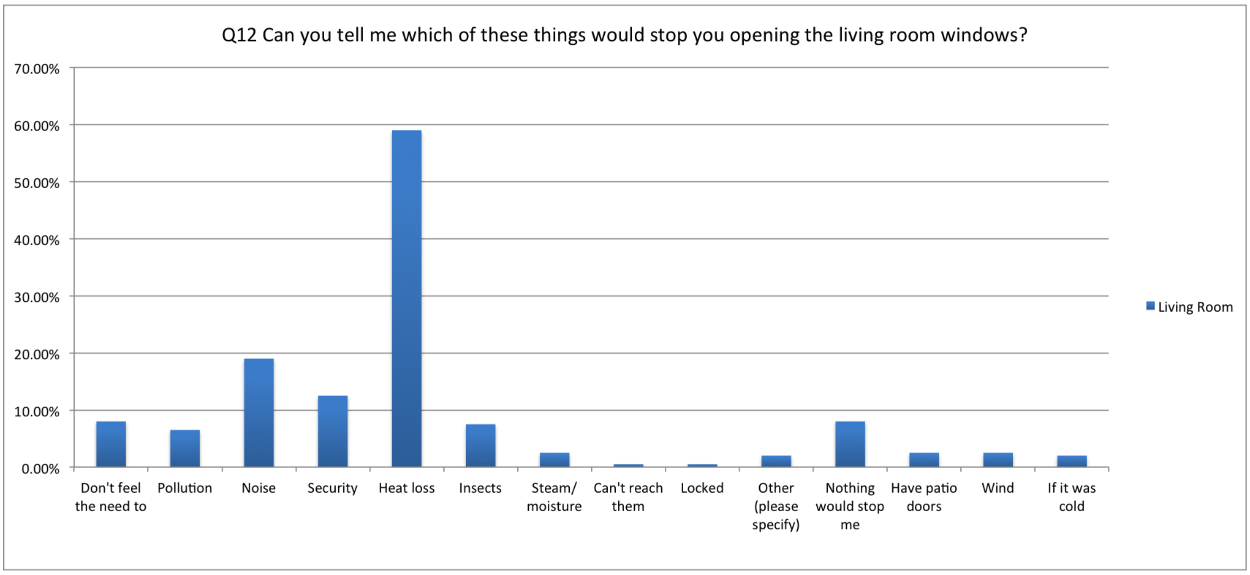

Q7 Do you dry clothes in the house?
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Every day
Every 2 to 3 days
Once a week
Once a fortnight
Never

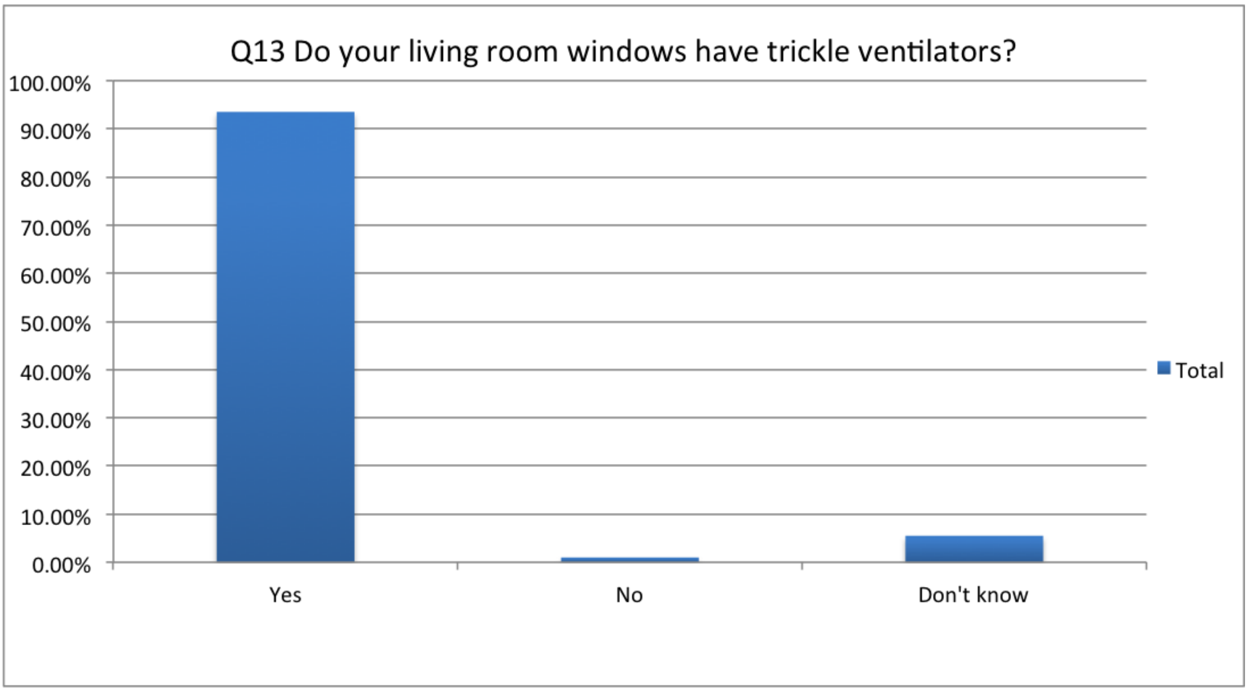

Q8 Do you know what this is?
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%
Yes
No

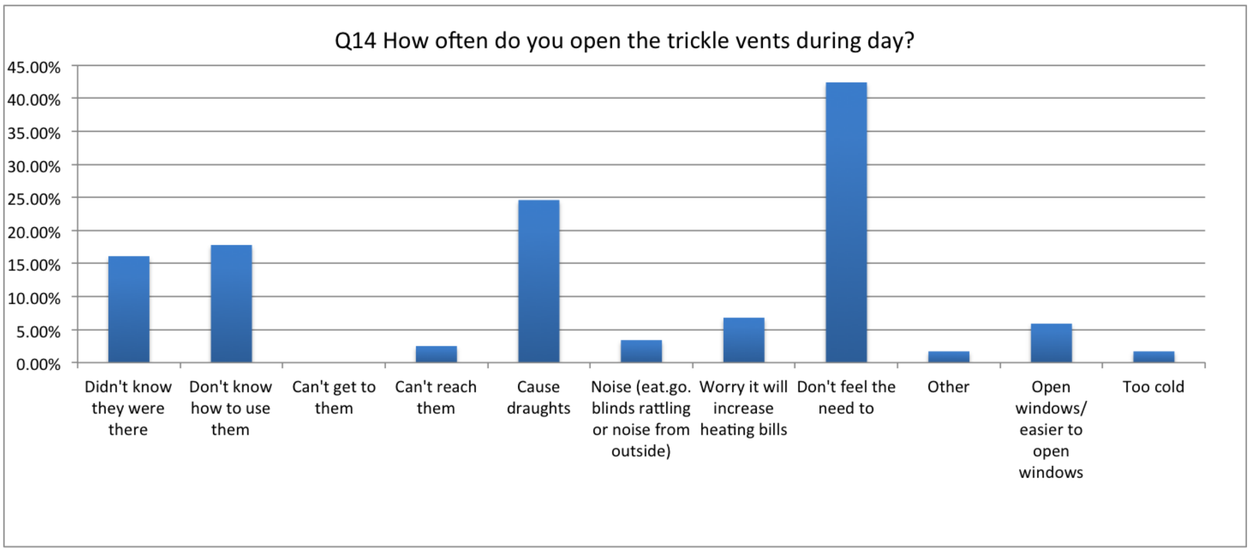

Q9 Do you know what it is for?
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Total
Ventilation
Other (please specify)
Don't know
To prevent condensation/ windows steaming up
I know what it is for but didn't realised I had them on my windows
To keep wind out

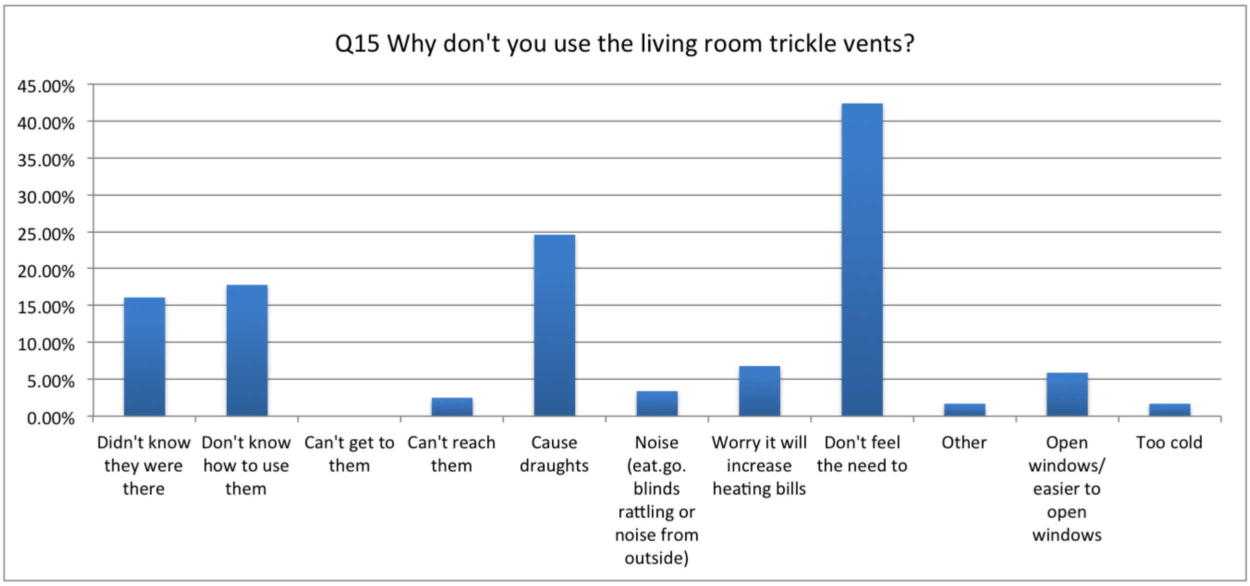

Q10 Thinking about the living room in the winter. Which statement best describes how you usually use your windows in the winter?
25.00%
20.00%
15.00%
10.00%
5.00%
0.00%
Living Room
Open them fully all the time
Open them partially all the time
Open them fully a few times a day (e.g. an hour in the morning and an hour in the evening)
Open them partially a few times a day
Open them fully once a day for a limited period (e.g. first thing in the morning)
Open them partially once a day for a limited period (e.g. first thing in the morning)
Open them fully a few times a week (e.g. if it gets hot/ stuffy)
Open them partially a few times a week (e.g. if it gets hot/ stuffy)
Never open them

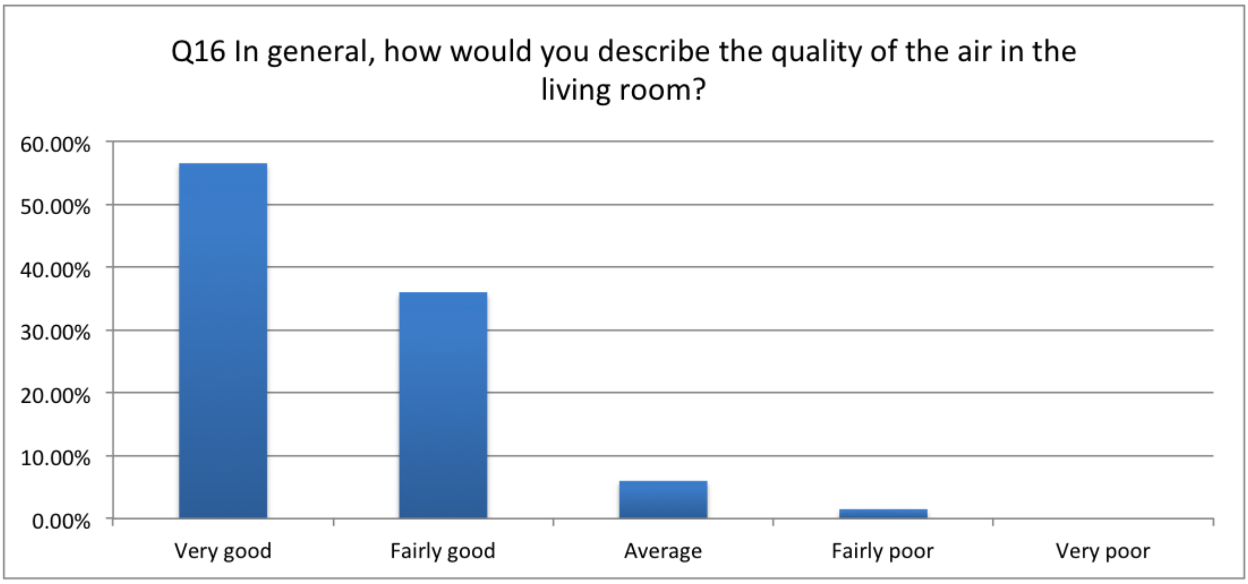

Q11 Can you tell me which of these things would make you open the living room windows?
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Living room
Too warm
To get rid of moisture/ damp
Smells
Clothes drying
For fresh air
Have patio doors
I never open the windows
To get rid of cigarette smoke
When washing windows

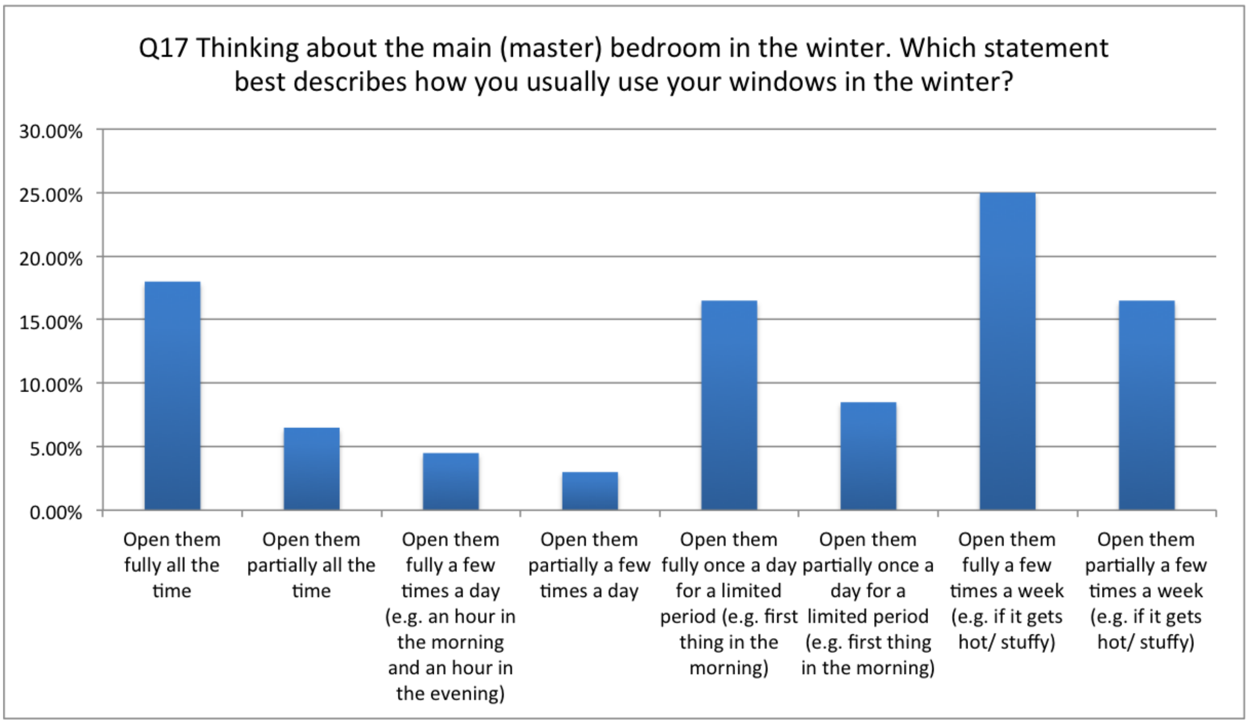

Q12 Can you tell me which of these things would stop you opening the living room windows?
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Don't feel the need to
Pollution
Noise
Security
Heat loss
Insects
Steam/ moisture
Can't reach them
Locked
Other (please specify)
Nothing would stop me
Have patio doors
Wind
If it was cold
Living Room

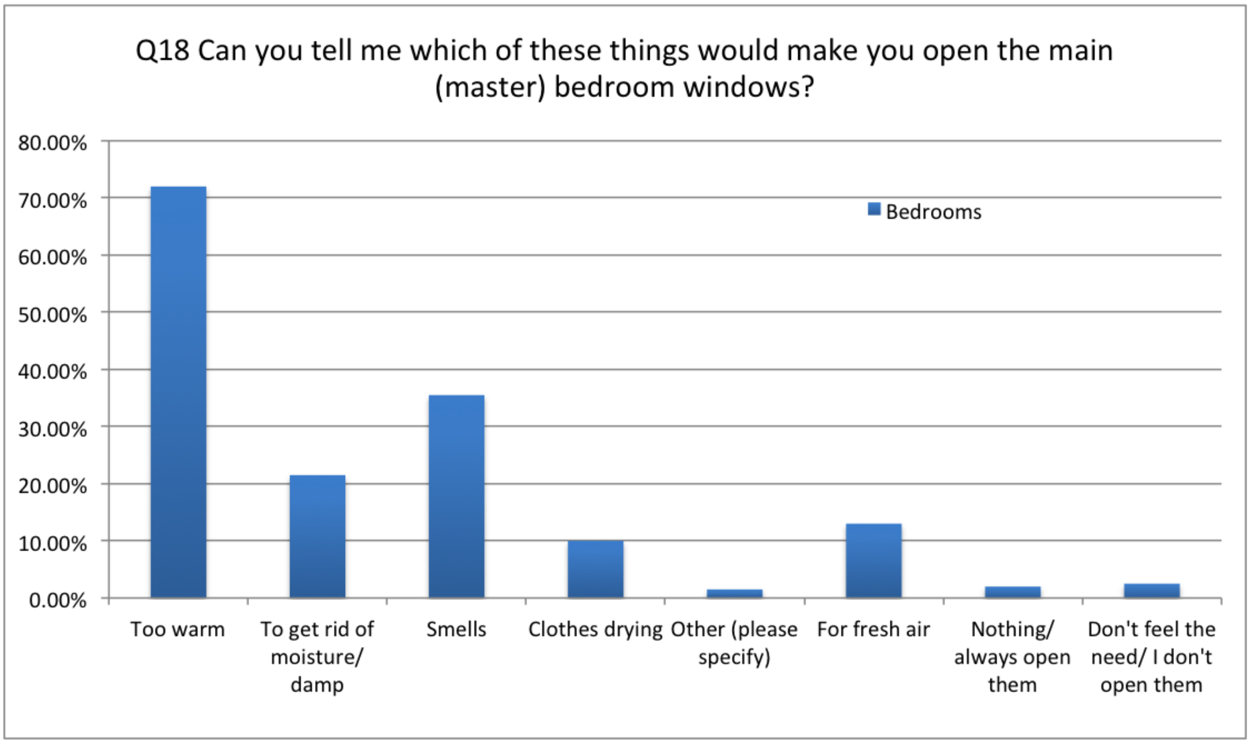

Q13 Do your living room windows have trickle ventilators?
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Yes
No
Don't know
Total

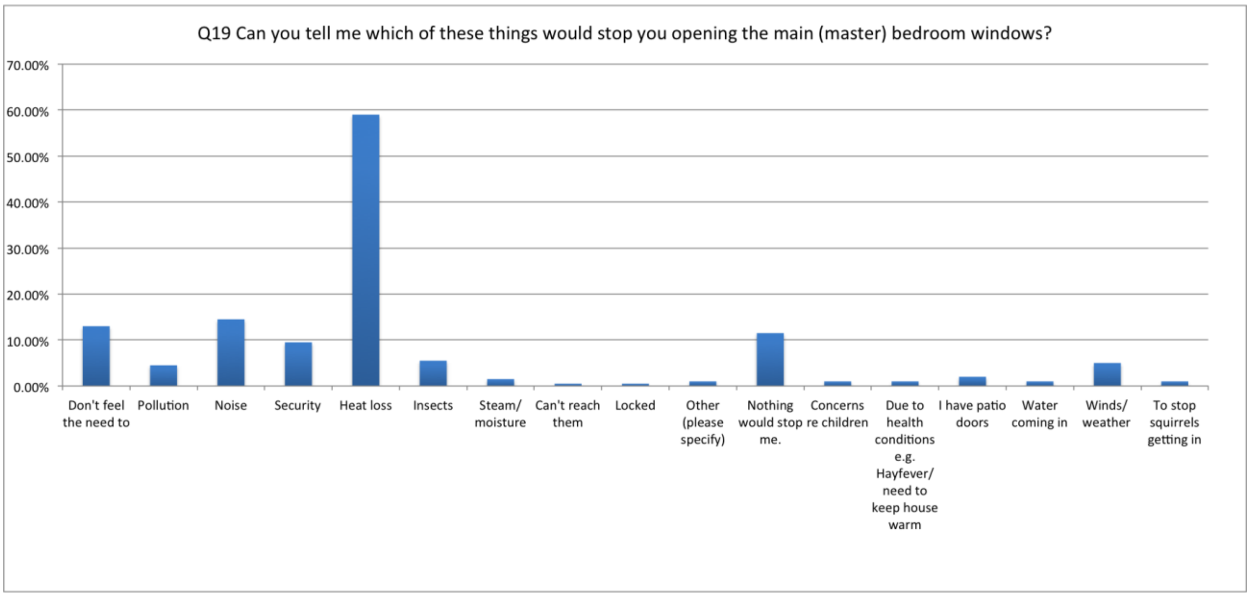

Q14 How often do you open the trickle vents during day?
45.00%
40.00%
35.00%
30.00%
25.00%
20.00%
15.00%
10.00%
5.00%
0.00%
Didn't know they were there
Don't know how to use them
Can't get to them
Can't reach them
Cause draughts
Noise (eat.go. blinds rattling or noise from outside)
Worry it will increase heating bills
Don't feel the need to
Other
Open windows/ easier to open windows
Too cold

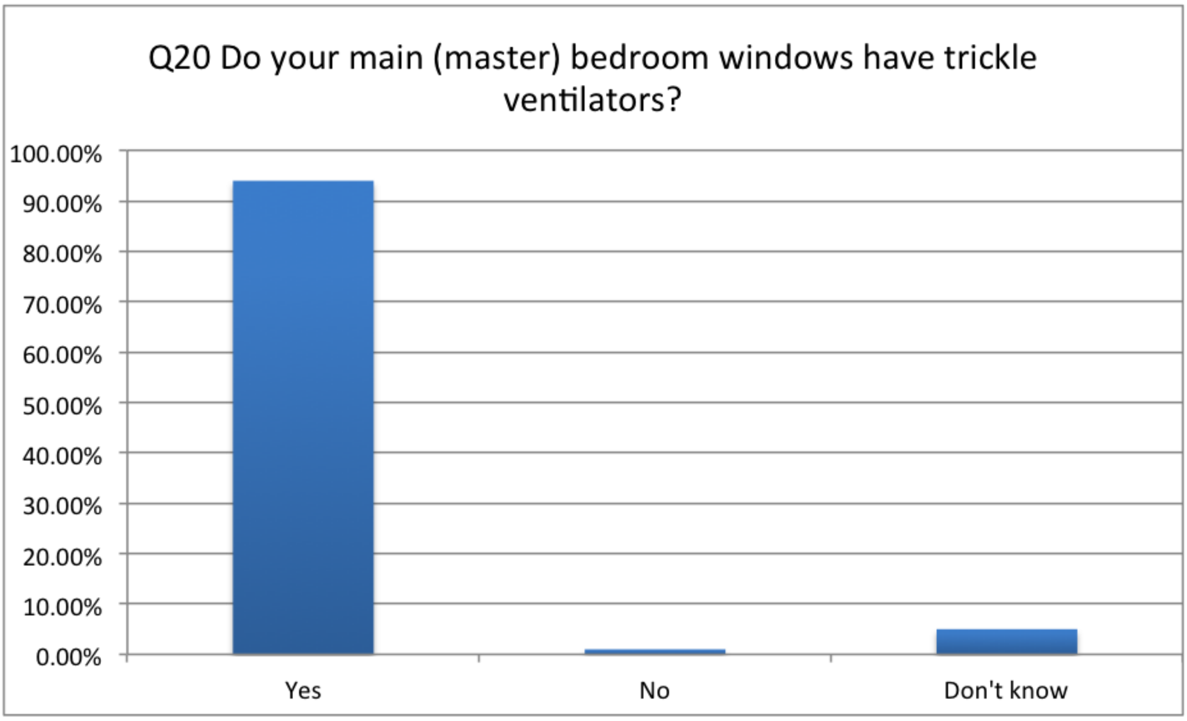

Q15 Why don't you use the living room trickle vents?
45.00%
40.00%
35.00%
30.00%
25.00%
20.00%
15.00%
10.00%
5.00%
0.00%
Didn't know they were there
Don't know how to use them
Can't get to them
Can't reach them
Cause draughts
Noise (eat.go. blinds rattling or noise from outside)
Worry it will increase heating bills
Don't feel the need to
Other
Open windows/ easier to open windows
Too cold

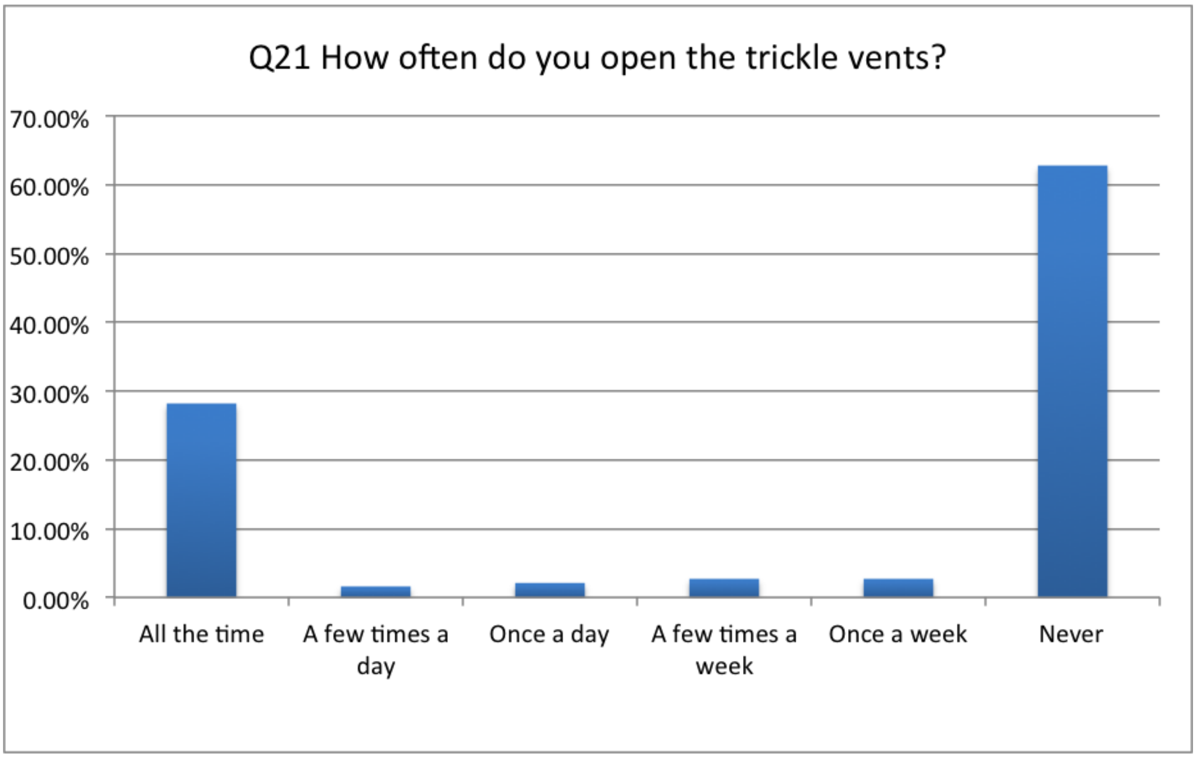

Q16 In general, how would you describe the quality of the air in the living room?
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Very good
Fairly good
Average
Fairly poor
Very poor

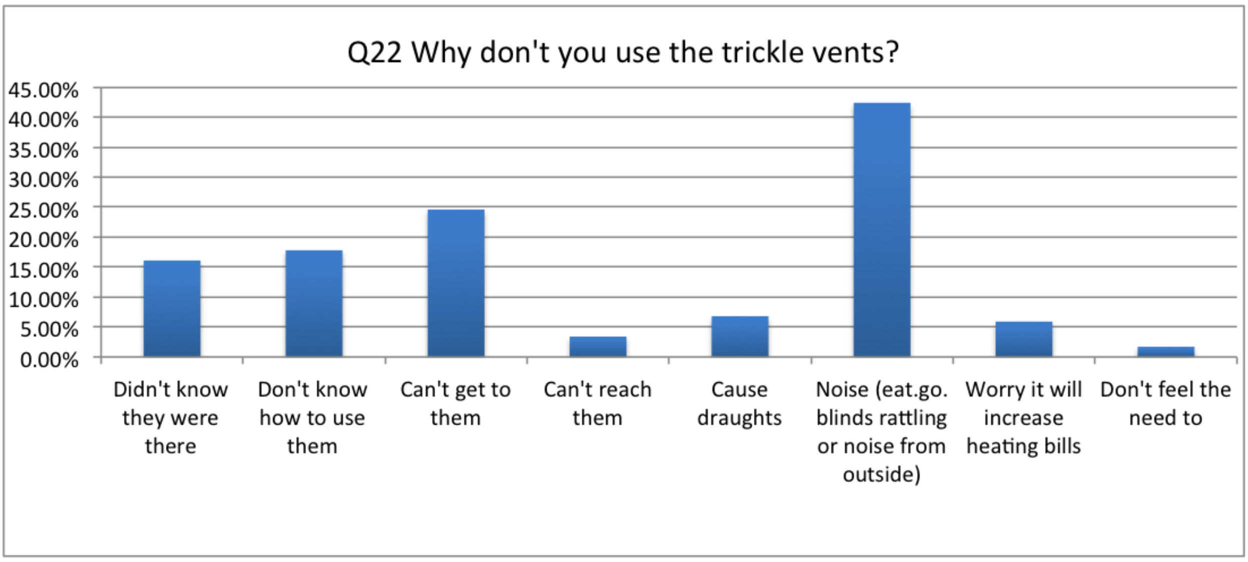

Q17 Thinking about the main (master) bedroom in the winter. Which statement best describes how you usually use your windows in the winter?
30.00%
25.00%
20.00%
15.00%
10.00%
5.00%
0.00%
Open them fully all the time
Open them partially all the time
Open them fully a few times a day (e.g. an hour in the morning and an hour in the evening)
Open them partially a few times a day
Open them fully once a day for a limited period (e.g. first thing in the morning)
Open them partially once a day for a limited period (e.g. first thing in the morning)
Open them fully a few times a week (e.g. if it gets hot/ stuffy)
Open them partially a few times a week (e.g. if it gets hot/ stuffy)

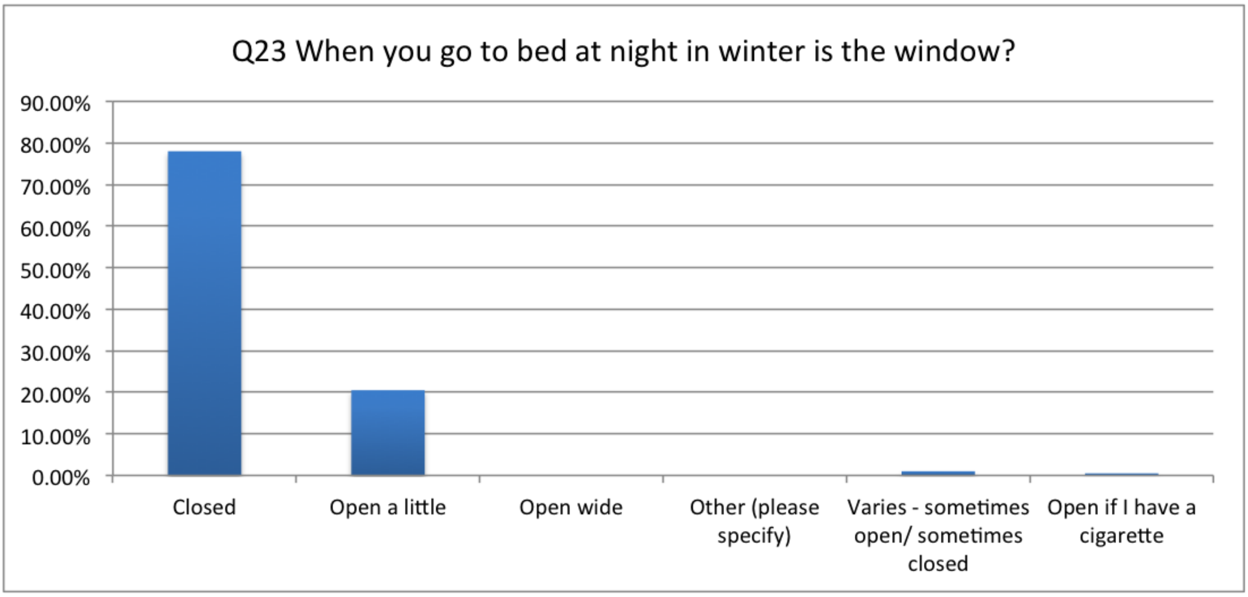

Q18 Can you tell me which of these things would make you open the main (master) bedroom windows?
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Bedrooms
Too warm
To get rid of moisture/ damp
Smells
Clothes drying
Other (please specify)
For fresh air
Nothing/ always open them
Don't feel the need/ I don't open them

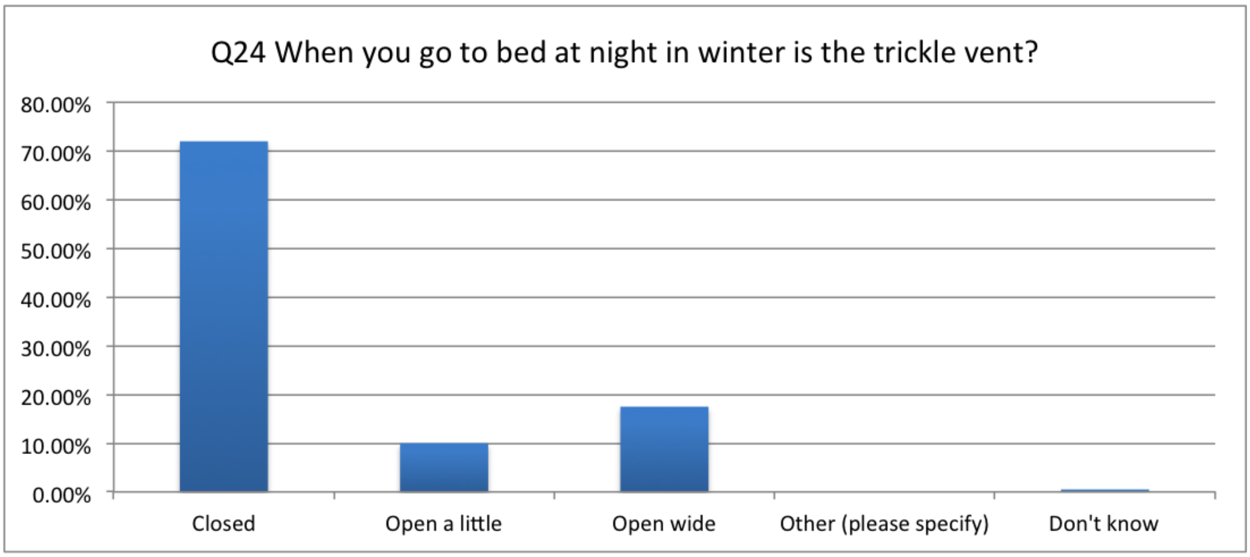

Q19 Can you tell me which of these things would stop you opening the main (master) bedroom windows?
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Don't feel the need to
Pollution
Noise
Security
Heat loss
Insects
Steam/ moisture
Can't reach them
Locked
Other (please specify)
Nothing would stop me.
Concerns re children
Due to health conditions e.g. Hayfever/ need to keep house warm
I have patio doors
Water coming in
Winds/ weather
To stop squirrels getting in

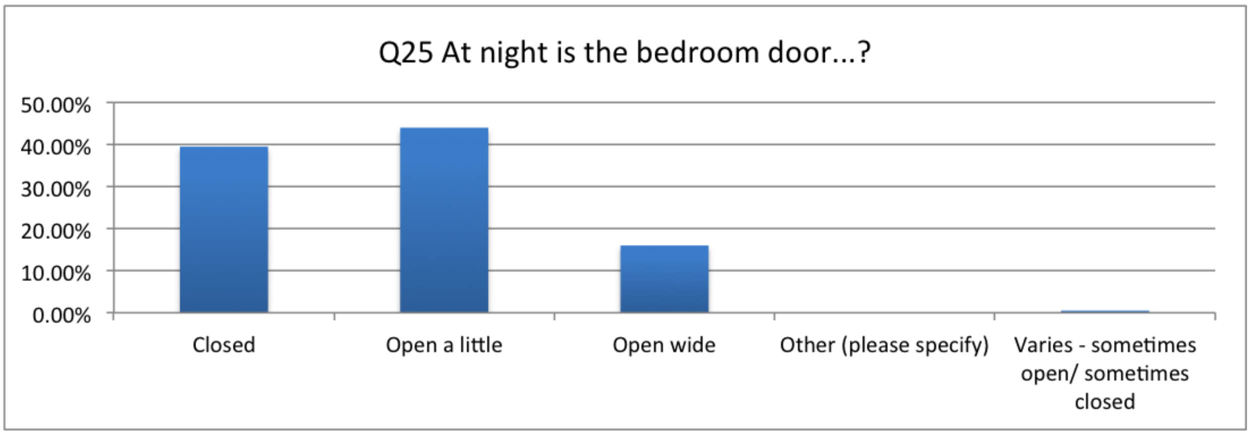

Q20 Do your main (master) bedroom windows have trickle ventilators?
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Yes
No
Don't know

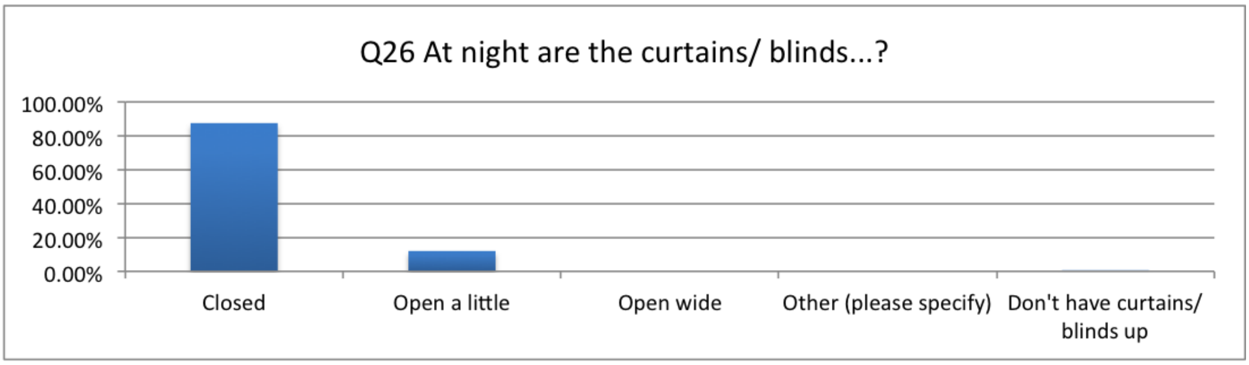

Q21 How often do you open the trickle vents?
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
All the time
A few times a day
Once a day
A few times a week
Once a week
Never

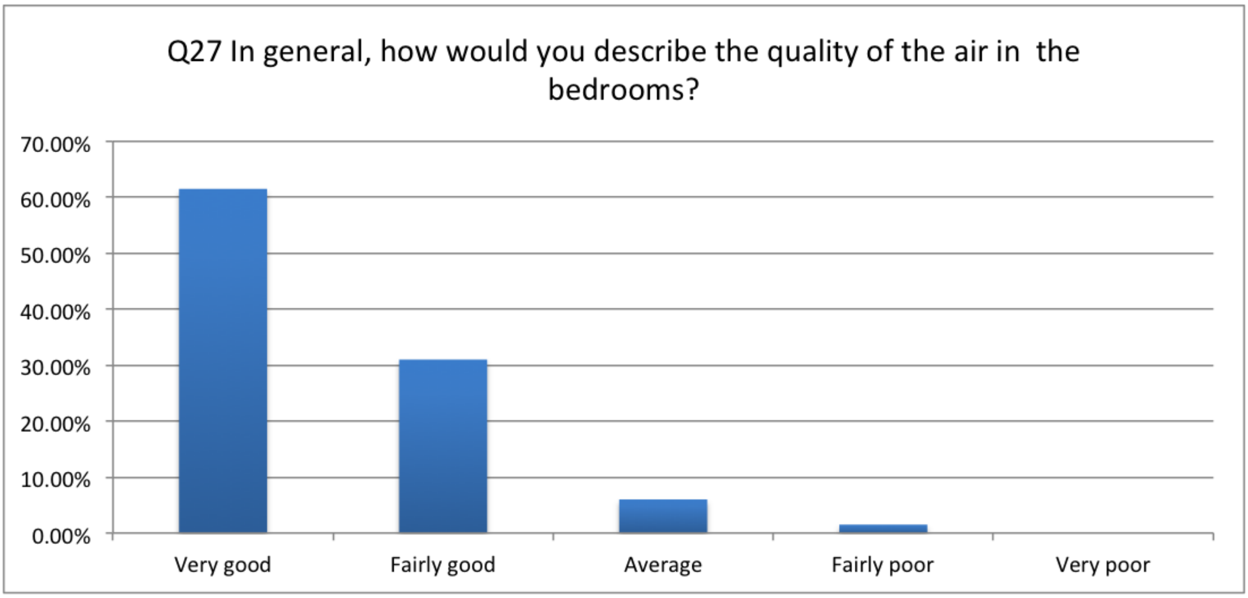

Q22 Why don't you use the trickle vents?
45.00%
40.00%
35.00%
30.00%
25.00%
20.00%
15.00%
10.00%
5.00%
0.00%
Didn't know they were there
Don't know how to use them
Can't get to them
Can't reach them
Cause draughts
Noise (eat.go. blinds rattling or noise from outside)
Worry it will increase heating bills
Don't feel the need to

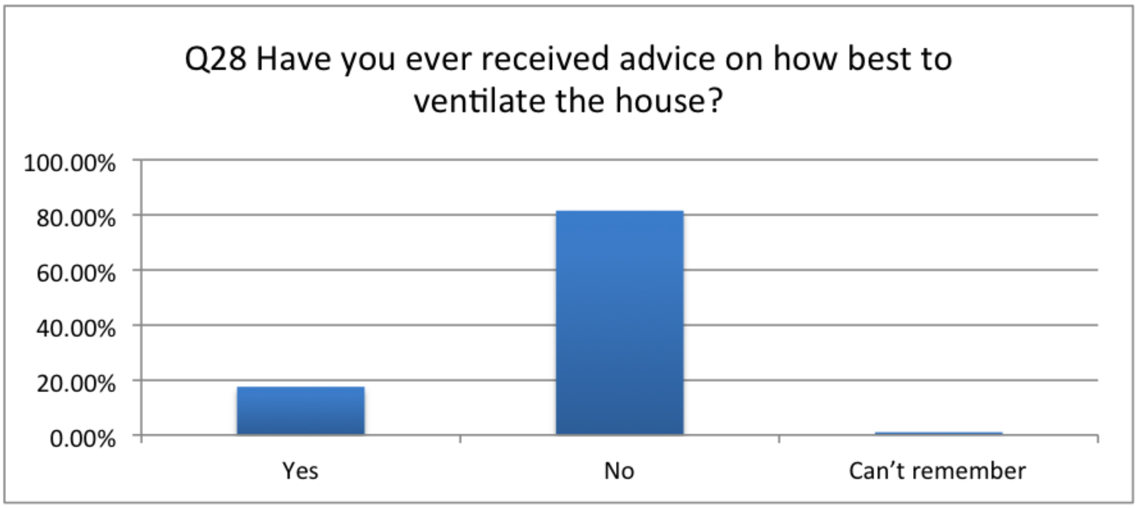

Q23 When you go to bed at night in winter is the window?
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Closed
Open a little
Open wide
Other (please specify)
Varies - sometimes open/ sometimes closed
Open if I have a cigarette

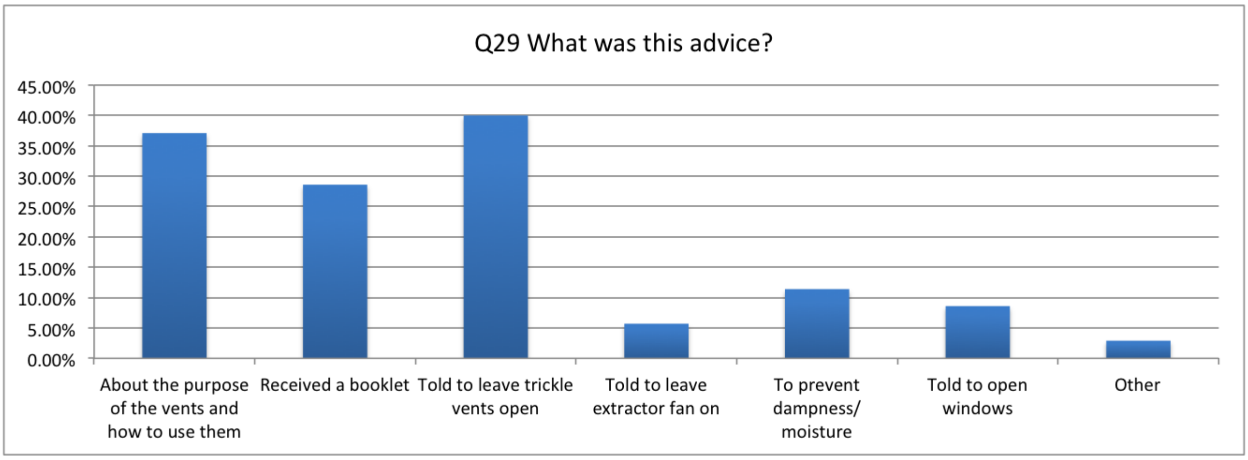

Q24 When you go to bed at night in winter is the trickle vent?
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Closed
Open a little
Open wide
Other (please specify)
Don't know

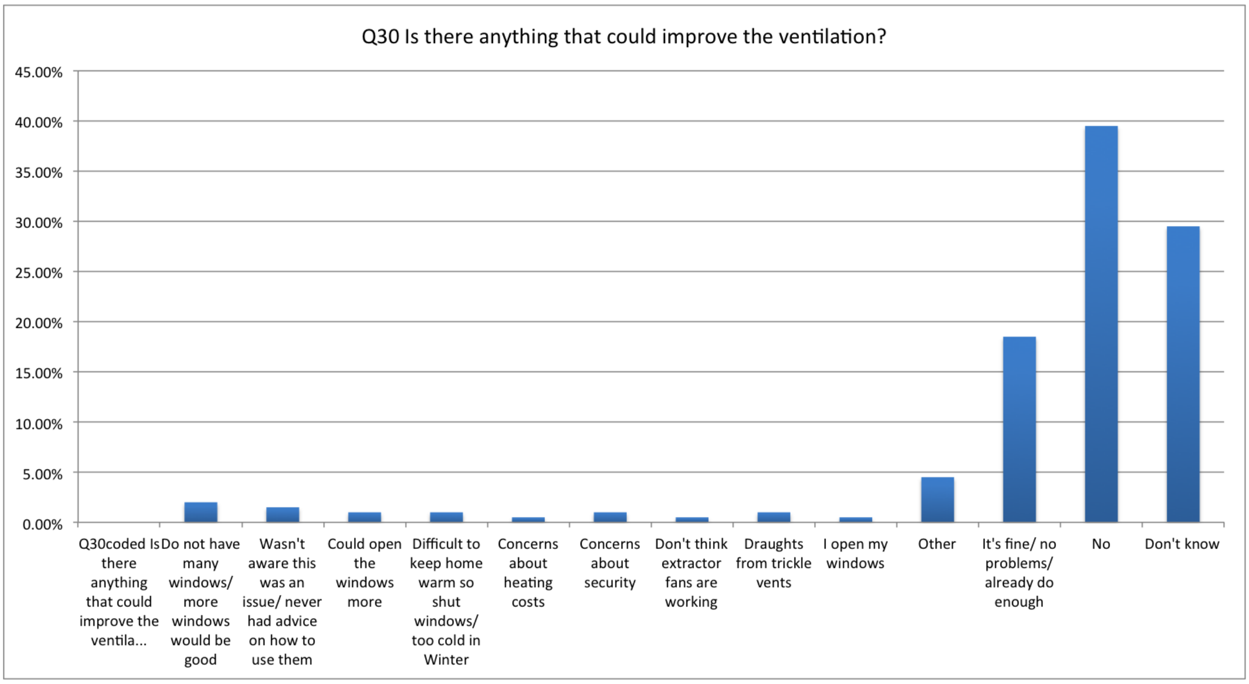

Q25 At night is the bedroom door...?
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Closed
Open a little
Open wide
Other (please specify)
Varies - sometimes open/ sometimes closed


Q26 At night are the curtains/ blinds...?
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%
Closed
Open a little
Open wide
Other (please specify)
Don't have curtains/ blinds up


Q27 In general, how would you describe the quality of the air in the bedrooms?
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Very good
Fairly good
Average
Fairly poor
Very poor


Q28 Have you ever received advice on how best to ventilate the house?
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%
Yes
No
Can't remember





Appendix B: Survey Form

Template email

Dear [Insert Name]

It was good to speak with you, as requested see below a brief description of the project and what assistance we would like to request.

Background

Anderson Bell Christie have in partnership with Glasgow School of Art MEARU, Assist Architects and University of Strathclyde been commissioned by Scottish Government Building Standards Division to carry out research into occupant use of natural ventilation strategies.

The research findings will be the basis of a white paper which will be passed to Scottish Ministers to inform the next building regulations.

The primary aim of the study is to determine *are people using their ventilators*? The study focuses on 2010 (and subsequent) domestic regulation dwellings.

A secondary outcome will be, *what are levels of Indoor Air Quality like in these homes*?

The Study

We have been commissioned to complete 200no. surveys from homes in Scotland. These homes must be naturally ventilated and built to 2010 or subsequent regulations. To do so we must collate a list of around 800no. homes (based on a 25% respondent success rate).

This questionnaire will be a short 15 minute doorstep survey carried out by professional social researchers. It will ask occupants about their knowledge and use of their natural ventilation system.

Your Assistance

We would like to seek your assistance in collating the database of addresses. Building Standards need the survey to be representative of the industry so homes built for private sale are particularly useful to us to ensure a fair representation.

We would very much like to work with you to collate a list of addresses. With your permission we would then like to letter residents to advise them of the study and that researchers will be in their area on certain dates. It would then be up to individual residents to decide if they wished to participate or not.

Information we require is as follows:

- Full address and postcode.

- Building Warrant reference number (and date registered if you have this available).

- Type of ventilation system (ie trickles + 24hr extract / trickles + intermittent fans / trickles + passive stack etc).

Stage 2 of the Study

If residents were keen to be involved and consented to it we could offer them additional data monitoring. This would record temperature, CO_2 levels and humidity in the primary living and sleeping rooms.

Benefit to [Insert Company Name]

If this was of interest to you we could provide you with a presentation on anonymised datasets at the end of the project to give you feedback on the actual performance of your dwellings. This would be an extremely valuable asset when considering future strategy for the energy regulations in 2015.

You would also be a part of a process that will steer the next iteration of the building regulations.

Timescales

Our intention is to collate the list of addresses over the next few weeks and begin the survey work around mid-January. The study is to complete by April 2014.

I look forward to hearing from you soon.

Kind Regards

Jonathan McQuillan

Research Project to investigate Indoor Air Quality in Dwellings	University of Strathclyde Glasgow; Mackintosh School of Architecture, The Glasgow School of Art
Protocol – CO2, Temperature, Humidity, PM Particulate & Formaldehyde Monitoring Revision P03	

Project Contacts:

Person	Organisation	E-mail	Telephone
Paul Farren	University of Strathclyde	paul.farren@strath.ac.uk	07759817008
Janice Foster	MEARU, Glasgow School of Art		
Donald Shearer	MEARU, Glasgow School of Art		

Methodology / Action Summary The intended process for the monitoring is as follows:

1. Arrival, Introductions & Identity Check
2. Explain Process to resident – 48 hours
3. **Physical Survey**

3.1				
Address				
Date	Time of Arrival	External Temperature	Wind Speed & Direction
		(To be recorded from nearest MET office data after completion)	

3.2	House Information		
Type of Dwelling	Detached	Semi-Detached	Flat

Number of Storeys		Number of Apartments		Number of Bedrooms	
Number of Occupants		Construction Type			

3.3	Room Measurements: Draw shape & record position of doors & windows. Photograph windows, doors including vents, undercuts & obstructions.			
	Length (mm)	Width (mm)	Height (mm)	Volume (m3)
Bedroom				

3.4	Number of openable windows?	Number of trickle vents?	Does internal door have undercut? (cm)	Is there possibility of Cross Ventilation?
Bedroom				Yes / No

3.5	Position of trickle vents as found		
		Open (% or all)	Closed (% or all)
Bedroom			

3.6	Obstruction to trickle vents (If yes note type of obstruction e.g. blinds, curtains, tape etc)		
	Yes	No	
Bedroom			

3.7	Other ventilation in room (If yes note type of vent e.g. open plan with kitchen hob extract, kitchen extract fan, en-suite with extract fan etc)		
	Yes	No	
Bedroom			

3.8	Other ventilation fans in house (If yes note type (e.g. extract fan), operation (e.g. constant or intermittent or always off), door undercut, and perceived noise level (e.g. very noisy, noisy, quiet or silent)					
	Yes	No	Type	Operation	Undercut (mm)	Noise level
Kitchen						
Bathroom						
Other:						
Other:						

4. Set Up Monitoring Equipment

4.1 Set up table in central location in Master Bedroom within reach of electric socket using the multi plug extension cable.

4.2 Connect Acer handheld tablet to extension socket using power cable provided. Position on table.

4.3 Connect Belkin Multi USB port to Acer handheld tablet using JKase USB conection port.

4.4 Connect Greywolf IQ410 Indoor Air Quality Probe to multi USB port. Position on table.

4.5 Connect Greywolf Handheld 3016 IAQ Particulate Meter to USB port using data cable and plug into extension socket using power cable provided. Remove plastic cap. Position on table.

4.6 Connect Greywolf FM-801 Formaldehyde Multimode Monitor to USB port using data cable and plug into extension socket using power cable provided. Check that a sensor cartridge is inserted and remove the plastic cap. Position on table.

4.7 Turn mains power, Acer Tablet, IAQ Particular Meter and Formaldehyde monitor on.

4.8 Using the Acer tablet, scroll to right hand side and open Wolfsense 2014 Lap software. The software will search for probes and begin providing a list of measurements in real time.

4.9 Using the Greywolf FM-801 Formaldehyde Multimode Monitor, select Measurement / Continuous / Sampling Number. Enter the survey number and select Next. This will bring you to the Initial Check screen. Select Start. The FM-801 will now confirm life expectancy of sensor cartridge and run for an hour to ensure optimum exposure. It will return the first reading after 90 minutes and every 30 minutes thereafter.

4.10 Using the Greywolf Handheld 3016 IAQ Particulate Meter, confirm 5 minute readings is selected (main screen should read Sample 4:30 and Hold:0:30) and press Start. The fan will begin and the first full set of readings from 0.3pm to 10pm will appear on the Acer Tablet after 5 minutes.

4.11 To start data logging press Log on the bottom left hand side of the Wolfsense software on the Acer tablet. You will be prompted to set up a Log.

4.12 Ensure that Trend is selected with readings at 5 minute intervals.

4.13 Select New Loc and create a location file name to be recorded in the ScotGovMonitoring folder. The File name should be the Address followed by the date in format YearMonthDay. For Example, 10ABCStreetTown20140302.

4.14 Select OK and Start Log. You will be able to view live readings as before but ensure Log button is now red.

4.15 When monitoring is complete stop by pressing the Red Stop button on the Wolfsense software.

4.16 To Download; Copy files from folder Libraries/Documents/Wolfsense/ScotGovMonitoring to pen drive using JKase connector & email to Paul

5. Resident Instructions

The aim of the study is to measure the conditions in the bedroom under normal use so there is no need to alter your normal behaviour. The only exception to this is that the trickle vent position is not adjusted. The equipment will measure temperature, humidity, carbon dioxide, particulate matter and formaldehyde levels only. There is no noise or video recording. Please read the background information provided below and feel free to contact Paul at anytime.

5.1 The trickle vents should not be adjusted for the duration of the monitoring.
5.2 Windows and doors should be used normally but please note open / closed times in diary.
5.3 Recording equipment has been placed in the room. Please so not switch off or unplug.
5.4 When complete, after 48 hours (unless otherwise instructed), we will return to collect equipment.

Person	Organisation	E-mail	Telephone
Paul Farren	University of Strathclyde	paul.farren@strath.ac.uk	07759817008

6. Resident Diary

6.1	How many people occupied room?			
DAY 1	Morning	Afternoon	Evening	Night
Bedroom				

DAY 2	Morning	Afternoon	Evening	Night
Bedroom				

6.2	Please note time & duration when **WINDOWS** are open OR closed	
DAY 1	For example, "Living Room window open from 10am to 12noon"	
Bedroom	Open	
	Closed	

DAY 2		
Bedroom	Open	
	Closed	

6.3	Please note time & duration when **DOORS** are open OR closed	
DAY 1	For example, "Bedroom door closed from 11pm to 8am"	
Bedroom	Open	
	Closed	

DAY 2		
Bedroom	Open	
	Closed	

Diary Notes - Please indicate time of occupation for each day:
For example, “Occupied living room from 7pm to 11pm. Went to bed at 11pm and got up at 8am”