Metrics of Health Risks from Indoor Air

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In a recent review of 31 green building certification schemes used around the world, IAQ was found to contribute to only 7.5% of the final score on average (Wei et al., 2015). As policy makers strive to reduce the energy demands of buildings by sealing or reducing outdoor air ventilation rates, an unintended consequence could be the reduction in the quality of indoor air with corresponding negative health effects at a population scale. This article summarizes the discussions of an Air Infiltration and Ventilation Centre workshop on IAQ metrics held in March 2017 (AIVC, 2017). It first identifies the types of contaminants found in many buildings today, the mechanisms of exposure to them, and methods of mitigating their effects. It then explores metrics that could be used to quantify the quality of indoor air.

Keywords: Indoor air quality, metric, health, contaminant, pollutant.

Problems

Building materials and systems, and the activities carried out in them, can be a source of contaminants that are harmful to human health. For example, there is evidence that some of the materials used to construct and furnish buildings emit harmful gases and harbour biological organisms. Unvented combustion processes for space and food heating emit gaseous and particulate contaminants and can be a source of moisture that is a primary driver of biological growth. Human activities, such as cooking and vacuum cleaning, also emit particulates, cleaning and deodorizing products emit gaseous contaminants and particulates, and smoking emits over 7000 different compounds of which many are harmful (CfDC, 2010). Pets harbour and transport biological contaminants, and can themselves be allergens. People and pets also emit gaseous bio-effluents that are disagreeable to smell, and harbour pathogens that produce disease. These examples show the many potential hazards and contaminant sources in buildings, for which there are multiple exposure pathways, and not all of them are airborne.

The measurement of airborne contaminant concentrations is generally a task carried out by experts, and reported in academic journals and technical reports. The presence and concentrations of contaminants is often measured without careful consideration of their relevance, and those measured may not be the most prolific or the most harmful. Some contaminants are inappropriately grouped together; for example, there are over 1 million volatile organic compounds (VOCs) and their toxicities are generally unknown, yet they are sometimes reported as single values and referred to as *total VOCs* (TVOC). Carbon dioxide (CO_2) is often used as an indicator of poor IAQ, although it does not negatively affect the health of occupants in the concentrations usually found in buildings, it is a marker of human bio-effluents. Its presence is a function of occupancy, occupant activity, gender, age and physiology, combustion, and transport from elsewhere. Without an understanding of these variables, indoor CO_2 cannot be used to assess indoor air quality or ventilation. And, it can never be used to indicate the presence of other important indoor contaminants, such as formaldehyde emitted from building materials, whose emission is unrelated to CO_2 concentration.

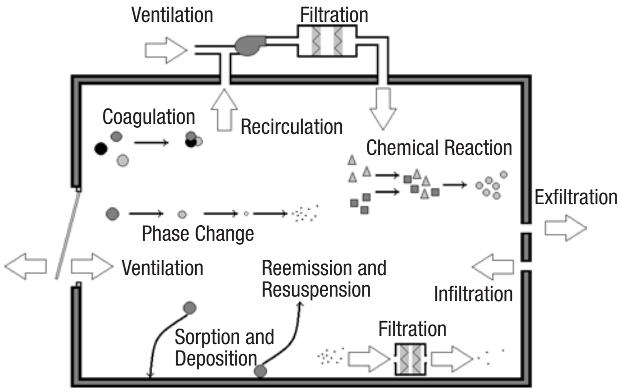
However, existing measurements of contaminants, whose type and toxicity are known, still give cause for concern (Logue *et al.*, 2011). They could negatively affect the health of occupants of any building they were found in and, when extrapolated to larger building stocks, could adversely affect healthcare systems and economies.

What do we think we know about IAQ?

Ventilation is the primary method of contaminant dilution and removal in buildings. Ventilation standards generally agree that indoor air should be perceived as fresh and pleasant by a significant majority of occupants and so they set a baseline ventilation requirement of around 8 l/s per person to dilute bio-effluent odours to an *acceptable* level for anyone who enters an occupied room from relatively clean air (Persily, 2015). They then attempt to account for other contaminants, such as building materials and furnishings, by increasing the baseline rate to around 10 l/s per person, although the increase is not based on specific contaminants (Persily, 2006). Ventilation rates in national standards around the world differ by up to 4 times, and their origins aren't always known or documented (Borsboom, 2017). Comparisons of measured ventilation rates against those prescribed by national standards suggest that there is also a widespread inability to implement them effectively in many building types (Persily, 2016), such as houses (Dimitroulopoulou, 2009) and schools (Chatzidiakou *et al.*, 2012). This suggests that they are smelly, but they could be unhealthy too.

There are limits to the ability of ventilation to mitigate these contaminant exposures. Occupants are exposed to contaminants via three mechanisms: inhalation, dermal absorption (through the skin), and ingestion. For example, infections are carried by fomites, such as skin cells, hair, clothes, bedding, utensils, and furniture, and are spread by all three mechanisms. The pumping action of doors, the movement of bedding, and the action of sitting on soft furniture can all re-suspend fine particles that can be inhaled into the lower respiratory tract. Large droplets produced by breathing, talking, sneezing, and coughing contain mucus, saliva, cells, and infectious agents that are transmitted over distances of less than 1 m.

Such particles can be inhaled into the upper respiratory tract (Atkinson *et al.*, 2009). Semi-volatile organic compounds (SVOCs), such as those emitted by dry cleaned clothing or flame retardants, are absorbed through the skin from clothing and can be sorbed by food and ingested (Weschler & Nazaroff, 2008). Organic

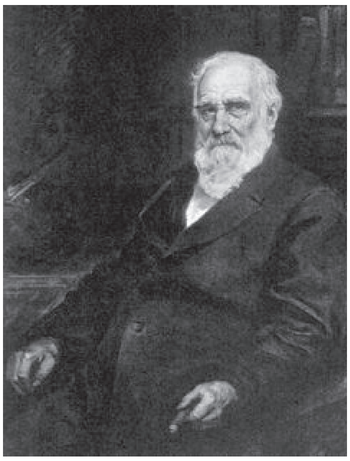


Ventilation Mechanisms and Pollutant Behaviours Indoors.

allergens, such as those produced by dust mites, are contained in bedding, carpets, and soft furnishings and are inhaled (Biddulph *et al.*, 2007). The complexity of such exposures shows that ventilation is an insufficient remediation measure on its own and inherently doesn't deliver acceptable IAQ, especially when contaminant sources are not reduced or eliminated.

Practical solutions

By the mid-1800s, a pioneer of modern hygiene and environmental science, Max Joseph von Pettenkofer, had identified *source control* as the most effective first step towards acceptable IAQ.



"If there is a pile of manure in a space, do not try to remove the odour by ventilation. Remove the pile of manure."

Attributed to Max Von Pettenkofer

Source Control (Fanger, 2006).

When source control is impossible, then local exhaust ventilation, such as a kitchen cooker hood, is effective in removing contaminants before they are able to mix in a space.

These devices are imperfect, and so it is still necessary to dilute well mixed contaminants using ventilation, or to remove contaminants using an air cleaner. These devices can be a useful alternative to ventilation, but they have energy and financial penalties, as well as performance limitations. There is also evidence that they can reemit collected particulates, and serve as sites for microbiological growth or chemical reactions that create secondary contaminants, such as ozone, formaldehyde, and other VOCs (Siegel, 2016). There is a pressing need for standardization and performance data for these devices.

Capture efficiency of a range hood commonly found in the U.S.A (Image courtesy of Iain Walker at the Lawrence Berkeley National Laboratory).

Some contaminants, such as carbon monoxide, are harmful when the exposure is acute and so sensors and alarms can be useful for monitoring indoor levels. However, many others require exposures to be chronic before negative health effects occur. Traditionally, CO_2 has been used as a marker for IAQ although its limitations have already been highlighted. Therefore, devices that are capable of indicating the presence of specific contaminants should be used, but given the plethora of possible contaminants it is not always clear which should be measured first, and what thresholds the measurements should be compared against. To do this, a system of measurement is required.

IAQ metrics

An air quality metric should identify when the quality of indoor air is unacceptable and should be based on its effects on human health and comfort, acknowledging that they may not be immediate.

One method of analysis is to ask occupants to personally assess IAQ. The human nose is as sensitive to some gaseous contaminants as chemical analyses and using it indicates occupant preference and ensures that people are the focus of an assessment. Perceived air quality (PAQ) is the basis of most ventilation standards and is used to assess indoor odours (ISO, 2014) and air quality in buildings (Wargocki *et al.*, 2004). However, its very subjectivity, the inability of the nose to smell all harmful contaminants (CO is odourless, for example), its high dependence on temperature and relative humidity (Fang *et al.*, 1998), and the propensity of people to adapt to malodours after only a few minutes (Berg-Munch *et al.*, 1986), are acknowledged by some as fundamental concerns.

A second method might be to identify properties of a building that are known to affect IAQ directly, for example using a tick-box approach. Each feature could be weighted according to their hazard and aggregated to produce a single metric. This method could be used to develop a third-party rating system, similar to many existing energy rating schemes, and should be helpful to someone who is particularly sensitive to specific contaminants in choosing a house to live in.

To obtain a comprehensive picture of the IAQ in a building it would be necessary to measure a range of contaminants, but their individual concentrations may be incomparable because of different health impacts and time scales, and units; for example, radon ($Bq.m^{-3}$) and particulate matter ($\mu g.m^{-3}$). One approach is to convert the individual contaminant concentrations into sub-indices, which may be a function of their health risks, before they are aggregated into a single index. However, the summing of sub-indices can lead to situations where they are all under individual health thresholds, but the final index shows exceedance. Conversely, the averaging of sub-indices can lead to a final index that indicates acceptable IAQ when one or more sub-indices are greater than their individual thresholds. One solution is to use the maximum of all sub-indices as the final index (Sharma and Bhattacharya, 2012), but this does not indicate overall IAQ. Other methods weight the sub-indices before aggregation (Abadie *et al.*, 2016).

Exposure limit values (ELV) are used in occupational environments to prevent or reduce risks to health from hazards, such as vibrations (HSE, 2008), by setting a maximum quantity experienced per person per day. This principle could be applied when measuring the concentrations of a range of contaminants in a building. Here, the ratios of their maximum concentrations to their respective ELV concentrations give a quick indication of risk, where a ratio 1 might be acceptable but one approaching or exceeding unity may be problematic.

A problem with IAQ indices and ELVs is that it isn't clear how a change to either metric, say by 10%, would affect occupant health and comfort. Here, an indication of the relationship between exposure and health consequences is required.

The disability adjusted life year (DALY) is a measure of time where a value of unity is one year of *healthy* life lost to some disease or injury. DALYs are calculated as the sum of years of life lost to premature mortality and morbidity in a population for some negative health effect. Disability is weighted by its effect on person's life in general, and so can account for mental illness. In the case of IAQ, the burden of disease is a measurement of the difference between the current health status of a population of building occupants and an ideal situation where they all live into old age, free of disease and disability (WHO, 2009). The DALY has been used by the AIVC (2016) to prioritize indoor contaminants found in houses for mitigation.

Next steps

For a metric to be useful and accepted as *best practice*, it must be robust and trusted. Unreliable evidence can be disputed and could lead to litigation. A metric must have robust technical specifications, prescribing

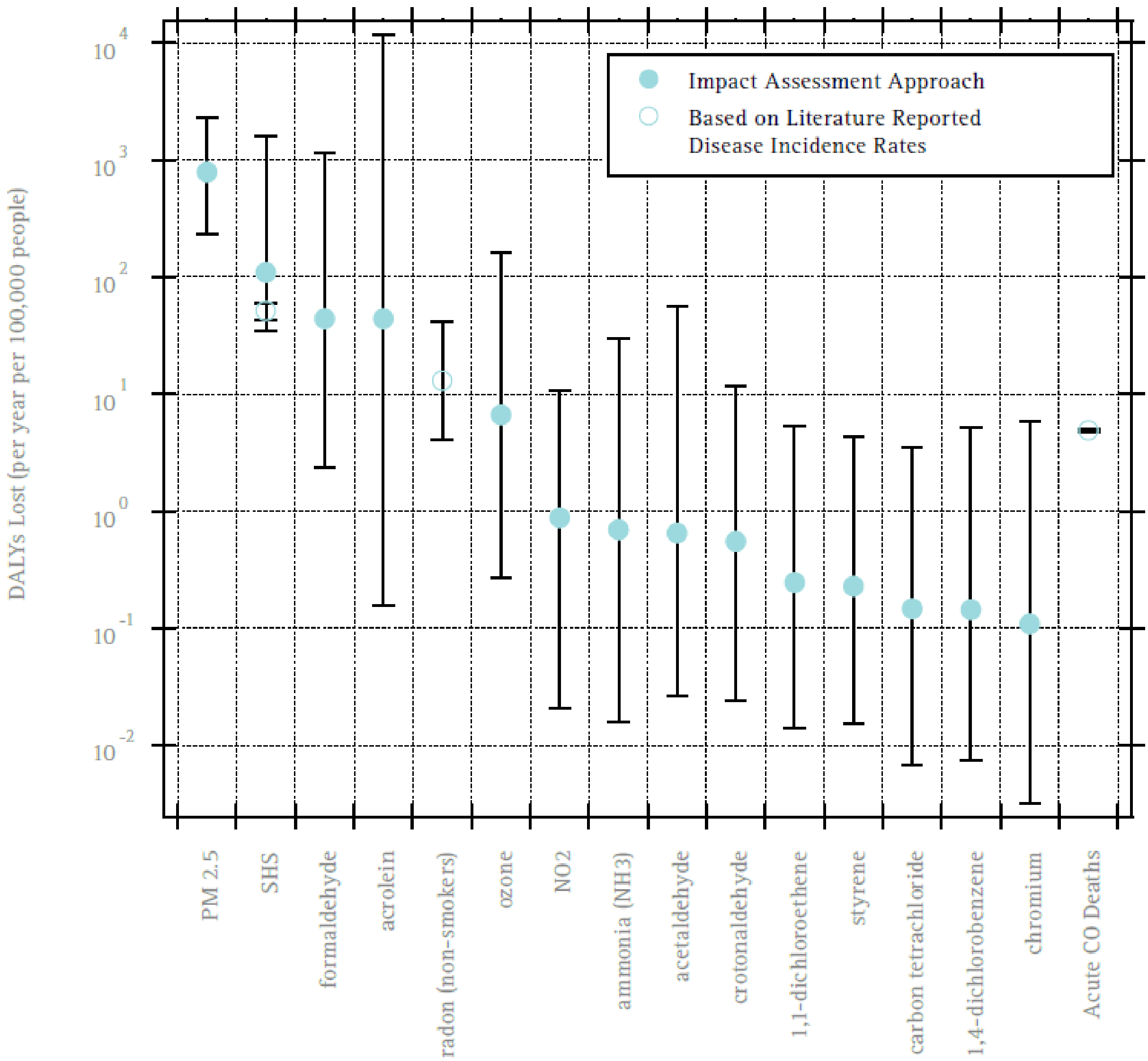


Figure 4. Estimated population averaged annual cost, in DALYs, of chronic air contaminant inhalation in U.S. residences (AIVC, 2016).

the methods of measurement and calculation. It must clearly identify measurement locations, device types, tolerances, calibration intervals, and measurer and analyst competences. This will aid consistency, and increase the likelihood that two different assessors surveying the same building arrive at the same metric score.

Metrics should not be a barrier to innovation, and so it is important that methods of pollution control are not prescribed. This follows the principles of *performance-based building design*, which focus on the end result and not on the means of achieving it. Any remediation measure should consider the need to simultaneously provide acceptable IAQ and energy use reduction, and so they should only be used when they are effective in achieving both ends. This requires good sensing and control devices whose performance is understood.

When non-compliance is identified, then pre-defined sanctions must be imposed. It is also important to define who is liable and the actions in cases of non-compliance. To develop and apply metrics, there is a clear need for resources, such as technical, legal, and administrative staff, and for equipment. Towards this end, it is fundamentally important to actively involve stakeholders so that they ensure they meet any IAQ metric required in their building and support the enforcement of infringements.

There are many hurdles to overcome, but the AIVC has begun to discuss key issues and challenge preliminary ideas. It will continue to research IAQ metrics and to give guidance on their development. The consideration of IAQ and its effects on occupant health and comfort will lead to a new paradigm in building standards and guidelines, moving them beyond the control of odour towards the provision of indoor environ-

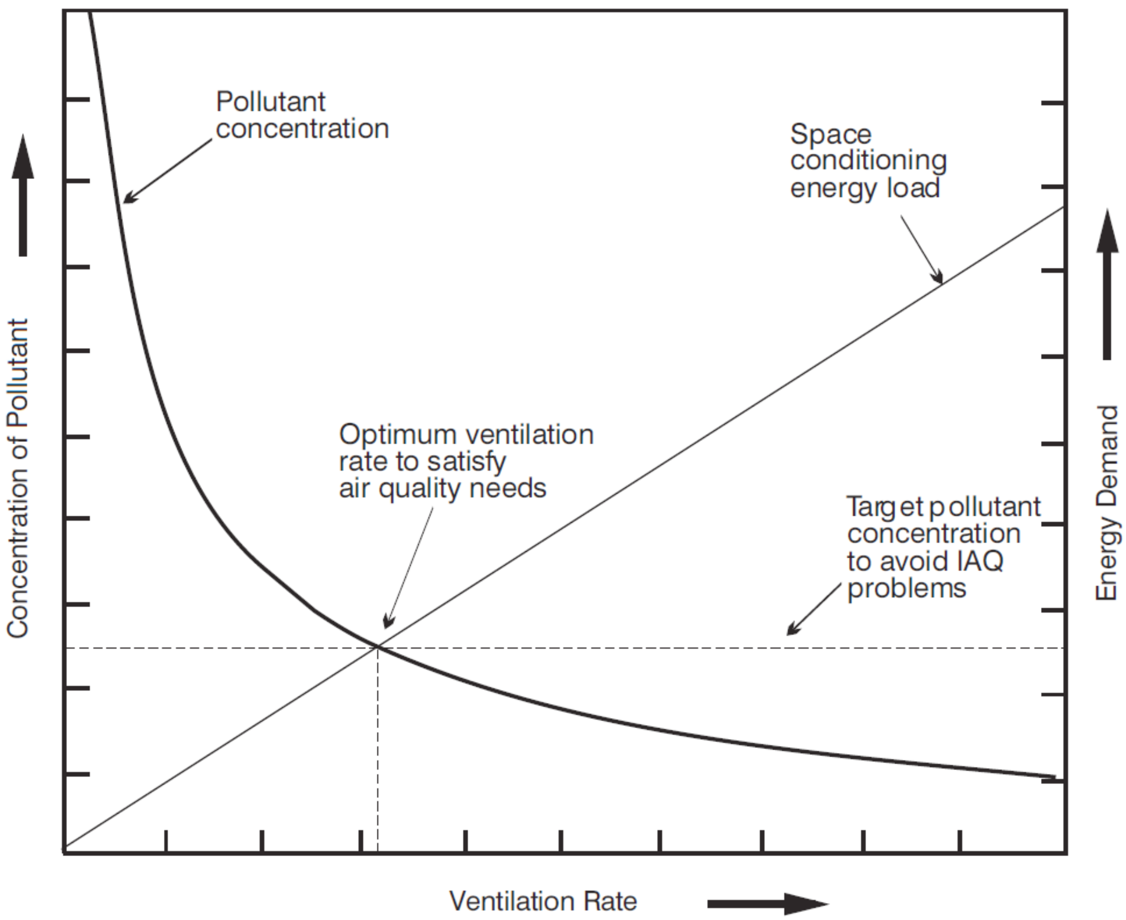


Figure 5. Controlling the Dominant Pollutant (AIVC, 1996).

ments that consider occupant health. ASHRAE 62.2 (ASHRAE, 2016) has begun this transition, and as other standards join, they will begin to have a tangible effect on people, healthcare systems, and economies. ■

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