Indoor air quality: A guide for UK building surveyors and property professionals

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ABSTRACT

This paper serves as an introduction to indoor air quality for UK building surveyors and property professionals. Historically, the quality of the air we breathe has been a significant health concern, resulting in numerous laws and measures to successfully improve it. These have mainly focused, however, on outdoor air. Only recently has attention moved indoors, where most people spend most of their time, at home and at work. Some high-profile tragic events, where vulnerable children have died, have been key in highlighting the importance of good indoor air quality, resulting in Ella's Law and Awaab's Law. This paper discusses the principal indoor air pollutants, including particulate matter, volatile organic compounds (VOCs), bioaerosols, human bio-effluents, carbon monoxide, nitrogen dioxide, sulphur dioxide, ozone, carbon dioxide and radon. It underscores the importance of effective ventilation in maintaining good indoor air quality. It reviews the current legislative landscape for indoor air quality, finding it to be fragmented, comprising a mixture of industry guidance, health and safety regulations and building certification schemes. This is in contrast to the much clearer laws and guidance around outdoor air quality. The advent of relatively cheap monitoring sensors is described as a 'game-changer', enabling real-time measurement of indoor air pollutants, as well as various other comfort metrics. More detailed monitoring of specific VOCs using inexpensive adsorbent tubes that collect chemicals in the air, which can then be analysed in a laboratory, is also discussed. This article is also included in __The Business & Management Collection__ which can be accessed at https://hstalks.com/business/.

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INTRODUCTION

Air quality has been a UK public health concern for centuries. In 1272, King Edward I banned the burning of sea-coal in London, to protect local noblemen from pungent odours. In 1661, the first book on air pollution was published, John Evelyn's 'Fumifugiam: Or The Inconvenience of the Aer and Smoake of London Dissipated'.[1] It was not until the 1950s, however, when 'pea-souper' smogs caused thousands of deaths, that action to improve conditions culminated in the Clean Air Acts of 1956 and 1968.

Since then, there has been a mixed bag of legislative successes in improving air quality. The overall trend is that air quality has significantly improved, particularly over the last 20 years.[2] This was despite the UK failing to meet European Union (EU) standards in 2015, which led to a number of actions against the government by Client Earth, a vigilante band of eco-lawyers (ultimately, this did not lead to any significant sanctions, not least because the UK left the EU on 31st January, 2020).

So, as air quality outdoors has improved — most effectively due to emissions improvements to motor vehicles, through the Euro emissions standards framework (most air quality management areas (AQMAs) declared in the UK are due to traffic pollution caused by residential areas being close to busy roads) — attention has turned inwards to indoor air quality in our homes and working and leisure spaces.

Outdoor and indoor air quality are quite different things. In general terms, outdoor air quality at similar types of location are quite similar across many parts of the UK, with the most obvious differences being between urban and rural locations. Outdoor pollutants are emitted by traffic and industry, and are transported — sometimes over long distances, where their chemistry can change — by wind and weather. Conversely, there is greater heterogeneity in indoor environments, where instead of wind and weather there are ventilation rates, and where the pollutant parameters and sources are often more varied than they are outdoors. Stuffy homes with poor ventilation rates can cause a build-up of harmful pollutants and increase humidity, which can lead to mould formation. Such conditions are also conducive to the spread of microbial bioaerosols; it was with good reason that during the COVID-19 pandemic, government advice was to open windows and increase ventilation rates in an effort to reduce airborne viral loads and hence reduce disease transmission. Perhaps of greatest relevance in highlighting the importance of good indoor air quality, however, is the simple fact that most people spend more time indoors than they do outdoors; a recent review by the government's expert group[3] states that in developed countries, people spend 80–90 per cent of their time indoors.

As an element of surveying and assessing buildings, the recent focus on indoor air quality has meant that many property professionals are not fully up to speed with understanding it. This paper is an introduction to this topic. It also discusses some of the most important things professionals should know about indoor air quality, particularly because it crosses some other topics and issues in ways that might not be intuitive.

INDOOR AIR POLLUTANTS

The principal indoor air pollutants and their sources are discussed below. A summary of the health effects is provided in Table 1.

- *Particulate matter (PM)*: This includes fine particles that are smaller in aerodynamic diameter (ie the diameter of the particle normal to the direction of the airstream in which it is carried) than the human body is used to dealing with (we have evolved mucous membranes and cilia in our airways to deal with many naturally occurring dusts and small particles). The finer these particles are, the further they can penetrate into our lungs and into our bloodstreams, where they can elicit inflammation and other kinds of immune responses and damage. Particles with aerodynamic diameters of less than 2.5 µm ($PM_{2.5}$) and less than 10 µm (PM_{10}) are the most commonly measured size fractions, with the particles mainly being of anthropogenic origin. Mass concentrations of PM are typically measured in microgrammes per cubic metre of air (µg/m^3). Indoor sources include outdoor infiltration from traffic emissions (the propensity of diesel cars to emit such particles is what led to the decline in their popularity — this despite their carbon-friendlier value compared to petrol cars), domestic burning of wood and other fuels, cooking (while there is no combustion from electric ovens, food can still smoke and burn in them) and cleaning activities that disturb settled dusts.

- *Volatile organic compounds (VOCs)*: These are chemicals that readily evaporate at room temperatures, being emitted as aerosols and gases from a wide variety of indoor sources such as paints, varnishes, solvents, adhesives, foams in furniture, textiles in carpets and furnishings, cleaning liquids and sprays and air fresheners. Some electronic devices and cooking processes increase temperatures and hence cause a wider range of VOCs to be emitted, with smoking oils and greases from cooking being a major indoor source. Formaldehyde is historically a common VOC found in many building materials, expanded foams and furnishings, and for this reason its use has been limited by legislation (eg the ongoing work programme around the UK REACH [Registration, Evaluation, Authorisation and Restriction of Chemicals] Regulations).
- *Bioaerosols*: These are airborne particles of biological origin, including mould spores, bacteria, viruses, pollen and allergens from house dust mites and pets.
- *Human bio-effluents*: These are chemicals emitted during the normal metabolism processes of people. These include CO_2 (a waste product of respiration) and a host of complex VOCs, some of which can be quite smelly and unpleasant.
- *Combustion byproducts*: In addition to VOCs and fine particles from burning fuels indoors for heating and cooking, a number of harmful gaseous pollutants can also be released from these combustion sources. Particularly harmful is carbon monoxide (CO), which remains a devastatingly common cause of death where boilers or cookers are not adequately ventilated — such deaths being historically associated with poor-quality holiday homes. Nitrogen dioxide (NO_2) is another pollutant, more usually attributed to traffic emissions, caused when fuel is burnt in ambient air (the nitrogen coming from N_2, which makes up 80 per cent of the atmosphere). When coal and high sulphurous oils were commonly used in homes, the fumes included SO_2, which is a respiratory irritant — although these days it is generally not a concern (it has been illegal to sell coal for domestic burning in England since 2023[4]).
- *Radon (Rn)*: This is a naturally occurring radioactive gas found in rocks and soil from the decay of uranium in the earth's crust. It can seep into and then concentrate in buildings. Radon is a particular problem in some areas where the geology causes emissions to be elevated. Radon causes over 1,100 deaths from lung cancer each year in the UK.[5]
- *Other pollutants*: These can include pollutants that are associated with how an indoor space is used. Smoking and vaping are obvious sources of VOCs and potentially harmful particulates and aerosols. Ozone (O_3) is a very reactive gas that can irritate airways. It is emitted by some electronic devices, particularly photocopiers.
- *Comfort factors*: While not being regarded as indoor air pollutants in and of themselves, some measurable indoor air parameters can have a significant effect on occupants' comfort and well-being.

> Elevated CO_2 concentrations, caused by breathing and from emissions during combustion, can cause a range of uncomfortable symptoms, from drowsiness and impaired concentration to dizziness and headaches.

Compared to outdoor air quality, indoor air quality is not nearly as well monitored, assessed or managed. As with outdoor environments, indoors there are myriad interactions between chemicals and biology that make it hard to pick out simple cause-and-effect relationships between specific pollutants and clear mechanisms of ill health. Nevertheless, some recent events have brought into sharp focus the need to ensure good indoor air quality, particularly in our homes.

ELLA'S LAW

Still being debated in the House of Commons, Ella's Law — or the proposed Clean Air (Human Rights) Bill — was triggered by the tragic death of Ella Roberta Adoo Kissi Debrah.[6] Ella died on 15th February, 2013 at the age of nine. Her cause of death was the first to be recorded in England as being due to excessive air pollution. Ella lived in London and suffered from asthma, so her vulnerabilities were particularly acute.

Ella's Law seeks to establish the right of everyone to breathe clean air, particularly those who might be more vulnerable to the effects of poor air quality at home, where they ought to be safe. Particularly vulnerable people include children, the elderly and those with respiratory illnesses such as asthma, with locations where these groups congregate (eg schools, care homes and hospitals) typically being most sensitive.

Ella's story has been widely publicised, highlighting the issues of poor air quality and helping bring broader understanding to the effects it has on health.

AWAAB'S LAW

Similarly tragic was the death in December 2020 of two-year-old Awaab Ishak. Awaab died from a respiratory condition caused by excessive mould in the one-bedroom flat he shared with his parents in Rochdale, Greater Manchester. The housing association that owned his home was sanctioned for allowing

Table 1: Summary of the health effects of indoor air pollutants

Indoor pollutant	*Health effects*
PM	Can cause or exacerbate cardiovascular illnesses.
VOCs	Can irritate the airways and eyes. Can cause dizziness and headaches. Long-term exposure can lead to some cancers.
Bioaerosols	Can exacerbate existing respiratory diseases such as asthma. Can elicit allergic responses. Can spread communicable viruses such as COVID-19.
Bioeffluents	Can be the source of unpleasant and offensive odours.
CO	Can cause death through chemical asphyxiation.
NO_2	Can irritate the airways. Long-term exposure can exacerbate respiratory illnesses such as asthma.
SO_2	Can irritate the airways. Long-term exposure can exacerbate respiratory illnesses such as asthma.
Rn	Long-term exposure can increase the risk of cancer.
O_3	Can irritate the airways. Long-term exposure can exacerbate respiratory illnesses such as asthma.
CO_2	Can, at persistently high concentrations, cause drowsiness, headaches and dizziness.

the conditions that caused Awaab's death. A subsequent investigation and petition led to the introduction in July 2023 of the Social Housing (Regulation) Act, of which Awaab's Law forms a part. The Act brings in reforms to ensure that social housing tenants have access to safe and decent homes.

GOOD VENTILATION

Because we spend a substantial amount of our time indoors, if outdoor air quality is bad, as it was for Ella, and if our homes are poorly ventilated, as was the case for Awaab, then the health impacts can be compounded.

Part of the problem with moisture and mould in homes has been the result of increasing airtightness in buildings that were never intended to be sealed in this way, and where large temperature differences between outdoor and indoor surfaces, combined with poor ventilation rates, cause areas of surface condensation where mould can form. This is why metrics associated with moisture formation are key to understanding good indoor air quality. Modern buildings that are effectively insulated and appropriately ventilated should be much better at maintaining good indoor air quality than many older buildings that have had their draughtiness issues inappropriately 'fixed'. In airtight and well-insulated buildings, smart mechanical ventilation with heat recovery (MVHR) systems balance energy efficiency with appropriate ventilation rates to maintain good indoor air quality.

The modern exemplar of a thermally efficient and mechanically well-ventilated home is perhaps the Passivhaus standard.

LEGISLATION AND STANDARDS

The Environment Act 1995 established the Local Air Quality Management (LAQM) regime, which required all local authorities in the UK to complete a series of staged assessments, from baseline screening to action plans, to identify and to then fix poor air quality across the country. This led to the Department of Environment, Food & Rural Affairs (DEFRA) establishing the Automatic Urban and Rural Network (AURN), which was, at the time, probably the largest and most comprehensive air quality monitoring network in the world.

The regulatory framework that sets limit values and standards for pollutants in ambient outdoor air comes from a number of EU and UK laws, such as the Air Quality Standards Regulations 2010 in England. With regard to indoor air quality, however, there is no clear legislative regime. Instead, limit values and standards are based on a mixture of industry guidance, health and safety regulations and guidelines, third party certification schemes and building regulations. Some of these are discussed below.

- *World Health Organization (WHO)*: WHO provides Air Quality Guidelines for selected indoor air pollutants[7] and guidance related to dampness and mould formation in buildings.[8]
- *UK Health Security Agency (UKHSA) (formerly Public Health England [PHE])*: The UKHSA/PHE publication 'Indoor Air Quality Guidelines for selected VOCs in the UK'[9] provides exposure limit values for a number of specific VOCs.
- *National Institute for Health and Care Excellence (NICE)*: NICE co-produced, with UKHSA, guidance on 'Indoor air quality at home',[10] offering recommendations for achieving good indoor air quality. The guidance focuses on raising awareness of indoor air quality and on the pollutant sources associated with materials used in buildings. It also discusses the importance of improving indoor air quality through good ventilation.
- *Building regulations*: Approved Document F (Ventilation) of the Building Regulations[11] sets requirements for adequate ventilation in residential properties

and most other types of buildings in order to maintain good air quality. Radon and methane ingress from ground sources is also considered in Approved Document C (Approved Document C: site preparation and resistance to contaminants; and resistance to moisture).[12]

- *Workplace regulations*: Workplace Exposure Limits (WELs) are set by the Health and Safety Executive (HSE)[13] in order to protect workers from exposure to harmful substances that they might come across at work, which includes many indoor locations such as workshops, warehouses and factories. As they apply to places of work, the WELs are much higher than similar limit values that generally apply to the public. This is because workers are exposed temporarily, during the periods of their working shifts, and they are assumed to be fit and well. The WELs do not, therefore, transfer well to offices, schools, hospitals and other working environments where there might be vulnerable people present, and where concentrations of pollutants would be less acceptable than they might be on a factory floor.
- *Industry guidance*: Professional bodies such as the Building Engineering Services Association (BESA) and the Chartered Institution of Building Services Engineers (CIBSE) publish guidance on healthy indoor environments,[14,15] which focus on good ventilation and comfort metrics. The Institute of Air Quality Management (IAQM) also provides guidance on indoor air quality[16] that is aimed at air quality professionals.
- *Building certification schemes*: Schemes such as the Building Research Establishment Environmental Assessment Method (BREEAM), the Royal Institution of Chartered Surveyors (RICS) Sustainability Knowledge Area (SKA), the US Green Building Council's Leadership in Energy and Environmental Design (LEED), the Fitwell Global Standard and the Well Building Standard (WELL) provide detailed frameworks for the design, construction and operation of sustainable and healthy buildings and/or retrofits/refurbishments. The majority of such schemes include guideline limit values for various comfort and indoor air pollutant metrics, and the specifying of materials that are low emitters of indoor air pollutants. The Passivhaus building standard is another scheme that focuses on improving indoor air quality through the selection of appropriate building materials, and extremely airtight and thermally efficient building designs that are well ventilated.

MONITORING INDOOR AIR QUALITY

The real game-changer in measuring, and hence understanding, indoor air quality has been the recent proliferation of relatively cheap monitoring sensors. The Internet of Things (IoT) has rapidly evolved to encompass a dizzying array of indoor sensors that collect rafts of data that can be analysed, interpreted and shared over the Internet with whomsoever might be interested in it. Associated smartphone apps provide graphs, real-time displays and alerts of the many metrics that modern indoor air quality monitors and other smart building sensors collect.

Indoor temperature and humidity sensors have been cheaply and reliably produced for years, but it is the development of low-cost chemo-electric sensors for the detection of pollutant gases and particulates that have caused a step-change in how indoor air quality can be measured and interpreted.

The latest indoor air quality monitoring devices are small (not much bigger than a typical hardbound book), relatively cheap (the widest range of reliable devices being in the range of a few hundred pounds to around one or two thousand pounds) and measure in real time, with results instantly viewable over an Internet connection (see Figure 1).

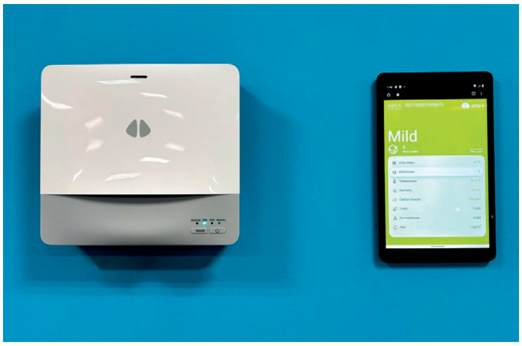

Figure 1: Indoor air quality and environmental monitor (uHoo Aura™) with tablet showing real-time data collected by the various smart, and chemo-electric air pollution, sensors and telemetry within the device.

The integration of indoor air quality monitoring with other types of data-gathering devices in smart buildings offers the potential for large amounts of data on the efficient use of buildings to be assessed and acted on. As with most complex sets of numerical data, there are opportunities for machine learning (ML) algorithms to be used to identify patterns from the swathes of data collected by smart building sensors. From these patterns, information can be extracted that enables occupants and building managers to better utilise automatic ventilation and heating and lighting systems to intelligently manage indoor environments to maximise occupants' comfort and well-being.

Regenerative, Ecological, Social and Economic Targets (RESET) is the world's first sensor-based and performance-driven building standard and certification scheme explicitly designed for the continuous monitoring of indoor environments. As it establishes a handy framework for sensor and data requirements, many professional indoor air quality monitoring devices support the RESET Air data standard. As such, most of the current crop of professional indoor air quality monitoring devices include sensors that collect the following pollutant concentration and comfort metrics:

- *Carbon dioxide (CO_2)*: While not a direct health pollutant at typical indoor concentrations (which can range from the current ambient level of 427 ppm to several thousand ppm in cramped and stuffy rooms), elevated CO_2 concentrations, typically from occupants' breath, are a well-known indicator of inadequate ventilation in buildings. Concentrations persistently above 1,500 ppm suggest poor ventilation, which could indicate that other more directly harmful pollutants are increasing. Approved Document F[17] of the Building Regulations advises that indoor CO_2 concentrations that are consistently below 800 ppm are indicative of good ventilation rates, with the consensus reported by AQEG[18] being that <1,000 ppm represents good, 1,000–1,500 ppm represents moderate and >1,500 ppm represents likely poor indoor air quality.
- *PM ($PM_{2.5}$ and PM_{10})*: While the precise mechanisms of harm caused by fine particulate matter are not clearly understood (studies indicate that particle size and number are more important than their chemical composition) there is no doubt that fine particles are damaging to health. The current WHO guidelines for indoor air are the same for outdoor air, which are that concentrations of PM_{10} should not exceed an average of 50 $\mu g/m^3$ over a 24-hour period and 20 $\mu g/m^3$ over an annual period. For $PM_{2.5}$ the standards are that concentrations should not exceed an average of 25 $\mu g/m^3$ over a 24-hour period and 10 $\mu g/m^3$ over an annual period.
- *Total volatile organic compounds (TVOCs)*: This metric represents the total concentration of a wide range of VOCs in the air. This is often an unreliable measure of indoor air quality as there are many sources of relatively harmless VOCs in buildings, such as from cleaning products and air fresheners. Nevertheless, the Building Regulations Approved

Document F (Ventilation) specifies, from the UKHSA/PHE guidance,[19] a guideline value for residential buildings of 300 µg/m^3 as an 8-hour average, whereas RESET, Fitwell and WELL set acceptable indoor TVOC levels at <500 µg/m^3.

- *Formaldehyde (CH_2O)*: This VOC has long been associated with ill-health effects, and its use in building materials and furnishings has been significantly reduced because of this. WHO sets a limit value of 100 µg/m^3 over a 30-minute averaging period. The UKHSA additionally includes an annual average limit of 10 µg/m^3.
- *Relative humidity (RH)*: Maintaining appropriate RH levels (typically between 40 and 60 per cent in dwellings[20]) is crucial for preventing mould and fungal growth indoors, which can cause harmful spores to be released into the air. Dampness can also increase dust mites and other insect infestations. If RH is too low (ie indoor air becomes very dry), it can lead to significant discomfort.
- *Temperature (T)*: While primarily a comfort parameter, with the effects of it being too hot or too cold inside a building being obvious, in combination with RH, and if there are thermal bridges formed between the warm inside and the cold outside, surface condensation can form, which can lead to increased mould formation. UKHSA/PHE recommends that indoor residential temperatures for sedentary occupants during the winter should be no lower than 18°C.[21]
- *Additional metrics*: Some devices also have additional sensors that measure other health or comfort level metrics. These sensors can include a sound level meter to detect if background noise levels might be uncomfortably high; a lux meter to measure the intensity of light in a room, with the wrong sort of light (eg blue or unnatural light) or too bright or dim conditions potentially affecting mental well-being, leading to eye strain and headaches; and indoor air pressure, which can indicate problems with mechanical ventilation and can lead to stuffiness (high pressure) or cause outdoor air pollutants to be brought indoors (low pressure).

VOC ADSORBENT TUBES

The benefit of telemetric chemo-electric devices is that in a relatively short space of time they can build a very detailed picture of how indoor air quality changes over time (ie minutes, hours, days, seasons or even years). Short-term peaks in TVOC concentrations can be linked in homes to periods when food is being cooked, and elevated concentrations of CO_2 in bedrooms at night can be linked to occupants sleeping there. Conversely, CO_2 concentrations might drop in summer when windows are more likely to be open, causing rooms to be better ventilated.

Temporal variations in indoor air quality metrics can be extremely valuable in identifying sources of peaks in pollutant concentrations or dips in comfort metrics, which can then allow suitable remedial action to be undertaken (such as increasing ventilation rates at appropriate times). As the toxicity of specific VOCs varies hugely, however, and as most devices can only measure the total concentration of all VOCs in the air (ie TVOCs), the usefulness of chemo-electric devices can become limited.

The principal method of speciating TVOCs into their constituent compounds is gas chromatography mass spectrometry (GC-MS), which requires a suitable mass of TVOC material to be sampled. This uses cheap, inert sorbent media, onto which VOCs in the sampled air are adsorbed. This is done by either pumping the sampled air through a tube containing the media, or by leaving the media in an open-ended tube for a period of weeks, in which time the VOCs in the air passively diffuse into the tube and onto the media. At the end of the monitoring period, the media with the VOCs stuck on it is then sealed in its tube and sent to a laboratory, where the media is heated up so that the collected VOCs are thermally desorbed/volatilised and fed into the GC-MS for analysis (see Figure 2).

As VOCs include thousands of compounds, it is usual to limit the reporting of VOCs collected in this way to the top 10 or top 20 compounds of highest concentration in the sampled air. Compounds of high concentration in indoor air that are relatively harmless and are probably linked to cleaning products or air fresheners typically include limonene (responsible for the lemon/orange smell in citrus fruits), ethanol (a solvent that is the alcohol in wine and beer), xylene (a common solvent in consumer products such as paints and adhesives) and isopropyl alcohol (a common solvent). If concentrations of more harmful compounds such as benzenes or aldehydes are found at similar concentrations to the relatively harmless VOCs that are commonly found indoors (ie they are in the top 10 list from the laboratory), then this could indicate elevated emissions of concern, which would likely require further investigation.

Some specific VOCs, such as benzene and formaldehyde, have indoor air quality standards associated with them; however, it can be difficult to match the concentration of the sampled VOC to the averaging period to which the standard applies (eg 1 hour or 24 hours). This is particularly difficult with passively sampled VOCs, which usually need to be left in place for a few weeks, thus making the measuring period the averaging period, when any significant variation in concentration over minutes or hours would be lost in the results. It also means that potential remedial reaction to any measured elevated levels of VOCs would be delayed, due to the time of the monitoring period and the laboratory analysis. Nevertheless, such analyses can prove extremely useful in identifying particular sources of VOCs that might be causing harm in an indoor environment. One example might be the detection of acrylics and acetone in a flat above a nail-painting salon — the VOCs being linked to the solvents and acrylics commonly used to paint nails, which have seeped from the shop into the flat.

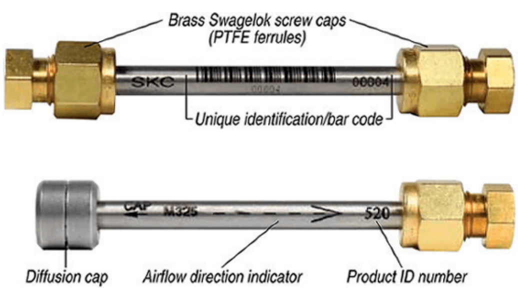

Figure 2: Sorbent media tubes (SKC Passive Thermal Desorption Tubes) used for collecting, speciating and analysing concentrations of VOCs in air.

DISCUSSION

We have known for decades, if not centuries, about the impacts on health of poor air quality. While the regulatory focus has historically been on reducing industrial and traffic emissions outside, this has meant we have perhaps neglected air quality indoors, where we are supposed to feel protected and safe. Recent tragedies, however, have highlighted the importance of clean indoor air, leading to changes in legislation, with more changes proposed (or at least seeming likely). There are already legal requirements for ensuring adequate ventilation in new buildings and in social housing. There also already exists a range of effective limit values and standards for good indoor air quality, and these could become mandatory.

There is also raised awareness among property professionals of indoor air quality, with commercial standards and certification schemes becoming increasingly common. Although standards such as RESET Air have established which pollutants and other metrics should be monitored, it is clear from the research and guidance that indoor air quality comprises a complex mix of chemicals, fine particles, allergens, pathogens and various parameters associated with feeling comfortable. That being said, the use of smarter and cheaper monitoring devices, combined with data from other smart building technologies, is allowing homeowners and building managers to better understand behaviours and usage patterns so that indoor air quality can be effectively managed and improved.

It is perhaps obvious that if you have a well-ventilated building, and as long as the inlet air is clean, then indoor air quality should be good. This is probably why detailed assessment and understanding of indoor air quality has been sidelined in the past. If you focus simply on ensuring good ventilation, suitable insulation and effective moisture prevention — which are in any case considered good management and engineering practices — indoor air quality will probably be good. In newer or refurbished buildings where modern materials are used, there should be fewer sources of indoor air pollutants than there were prior to the regulations that have reduced harmful materials and chemicals in building and decorating products.

So, if sources of indoor air pollution are minimised, outdoor air is relatively clean, and there is a ventilation system (even if it simply comprises openable windows), the key metrics for determining indoor air quality arguably become those that determine the effectiveness of ventilation and those that are associated with comfort.

CO_2 sensors are already included in many smart ventilation systems, in order to assess ventilation effectiveness in real time. These sensors can automatically activate the system, or increase ventilation rates, when threshold CO_2 concentrations are reached. The usefulness of CO_2 concentrations as a metric for determining overall ventilation effectiveness was demonstrated during the COVID-19 pandemic, when the government made standalone CO_2 monitors, with numerical displays and possibly alert functions, available to schools and public buildings.[22] CO_2 concentration can also be a useful indicator of comfort, with high concentrations linked to insufficient ventilation rates in occupied rooms. The principal other comfort level metrics are temperature and humidity, which are both easily measured with simple sensors that are often bundled together with CO_2 and other chemo-electric sensors in modern indoor air quality monitoring devices. So, in most indoor situations, a simple CO_2 monitor with temperature and humidity sensors will likely suffice in keeping check of indoor air quality. Due to their relative cheapness, however, further chemo-electric sensors for other pollutants, such as fine particulate matter, carbon monoxide and TVOCs, are often included in modern monitoring devices — the overall cheapness of the devices typically making the increased cost a relatively minor concern.

Where more detailed monitoring becomes particularly useful is in the speciation of TVOCs into individual VOCs using adsorbent media and GC-MS. This is necessary if there is a specific concern related to the many different types and sources of such compounds in indoor air. Perhaps the most effective use of this monitoring method is in the reactive response to indoor air quality issues, such as to investigate nuisance odours that cannot be easily placed, or as part of investigations into what might be causing occupants headaches or dizziness, particularly when CO_2 concentrations are normal. Currently — and unless and until new regulations on indoor air quality are introduced — it is generally the reactive response to complaints or concerns, such as general feelings of stuffiness, that cause people to notice indoor air quality and to then appoint a professional to assess what has gone wrong.

Considering the availability of relatively cheap technologies and the abundant guidance, there is little excuse for not being proactive in managing indoor air quality. As property professionals, and using an idiom linked to our trade, we should not be waiting for it to rain before we fix the roof.

CONCLUSIONS

The detailed assessment, understanding and regulation of indoor air quality are relatively new areas of building design and management that are still evolving. It is incumbent on building surveyors and property professionals to keep up with developments so that they remain informed and compliant with the law. In doing so, they will contribute to the improvement of occupants' well-being from using safe and healthy indoor spaces.

Some key take-home points are as follows:

- Indoor air quality comprises a complex mix of many different types of pollutants, and some key comfort parameters.
- Good ventilation is of paramount importance in maintaining good indoor air quality.
- Simple measurements of temperature, moisture and CO_2 can give a very good indication of ventilation effectiveness.
- Reactions to tragedies are what have caused, and continue to influence, changes to legislation — let us not have another one before better regulation is enforced.
- Smart monitoring and building technologies are extremely useful in measuring and understanding indoor air quality, particularly because chemo-electric sensors are relatively cheap.
- Monitoring with adsorbent tubes is also cheap and can be very useful for investigating unpleasant odours or feelings of ill-health when ventilation otherwise seems to be good.

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