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IMPROVING INDOOR AIR QUALITY

EDITORIAL

Why indoor air quality matters

Indoor air pollution is not new. Most people spend the vast majority of their time inside various types of building, so it is not surprising that the inhalation of pollutants indoors affects their health and wellbeing.

Research into indoor air pollution goes back many decades. Some of the early studies, in the 1960s, were on the health effects of tobacco smoke. In the 1970s research identified the possible health effects of exposure to nitrogen dioxide from gas cooking appliances, and in the 1990s, following the installation of urea-based foam insulation, the health effects of formaldehyde as a cause of asthma were the subject of many studies. In the mid-2000s the World Health Organization started work on its indoor air quality guidelines, which they published in 2010, and in 2019 Public Health England published its guidelines for selected volatile organic compounds.

Of course we have known for a long time that excessive smoke in buildings from the burning of solid fuels and cigarettes, high carbon monoxide levels due to faulty heating appliances and radon from granite beneath our homes are all bad for our health. But there are more subtle air pollutants in buildings that may also adversely affect our health, reduce wellbeing, and contribute to lost productivity and absenteeism at work.

Amongst the general public, awareness of the adverse effects of exposure to poor air quality outdoors is relatively good. The same is not true for the indoor environment, as noted in the government's Clean Air Strategy 2019. One of the objectives of this strategy is to raise awareness of the potential impacts of air pollution at home and ensure that consumers have reliable information for making informed choices to protect themselves, their families and their neighbours. Yet, two years later, there does not seem to be any evidence of a public information campaign.

Government interest in any issue does not occur in isolation. It is always the result of pressure from a myriad of sources. Through organisations such as the Green Building Council, the building industry has been promoting the economic advantages of healthy buildings for many years. The introduction of the WELL building performance standard, which requires the monitoring of several air pollutants, has been important in drawing attention to the issue, as has Public Health England's review of guidelines for volatile organic compounds from other countries, concentrations in different building types, indoor sources and the health effects.

Knowledge of air quality indoors is in its infancy compared to the vast body of evidence on outdoor air, but it is growing. UK Research and Innovation has provided funding through its Strategic Priorities Fund Clean Air Programme to support the development of research networks pulling together knowledge from disparate academic and professional disciplines working on improving air quality within buildings. This includes urban designers, architects, air quality scientists, building services engineers, materials scientists, fluid mechanics, behavioural scientists and many more specialists. This issue of the environmental SCIENTIST is important in helping a wider audience appreciate the issues.

Dr Claire Holman is Director of Air Pollution Services and Vice Chair of the Institute of Air Quality Management (IAQM). She chairs the IAQM Sub-Committee on Indoor Air Quality. Claire has worked on a wide range of issues related to the quality of air both outdoors and indoors during her 40-year career.

IAQM Institute of Air Quality Management

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INTRODUCTION

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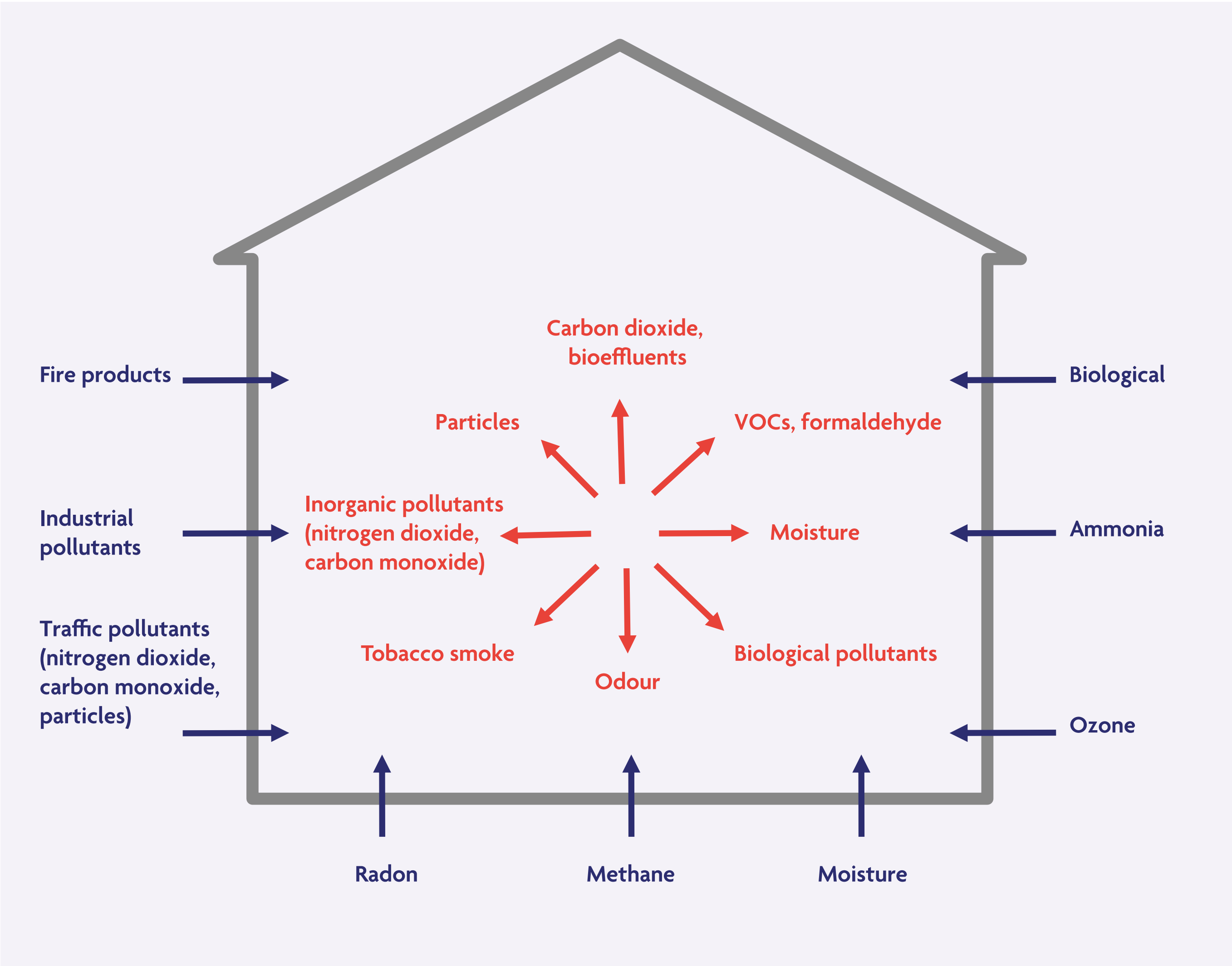
The importance of good indoor air quality

Vina Kukadia reviews the sources, health effects and costs of indoor air pollution.

Good quality indoor air is paramount for everyone's optimum health, wellbeing and productivity, as well as for keeping indoor environments free from pollutants. This is particularly important because we spend an average of 90 per cent of our time indoors, and the most vulnerable individuals, such as young children, the elderly and those chronically ill, may spend almost all of their time indoors. However, indoor air is often contaminated with pollutants from indoor sources, as well as those that have migrated from outdoors via building infiltration and ventilation processes.[1] In fact, reports have indicated 'that indoor air pollution (ultrafine particles) is 3.5 times worse than outdoor air' and that 'the combination of indoor and outdoor air pollution sources is turning our homes into toxic boxes, with pollution trapped inside'.[2] Thus, the risks to our health may be greater indoors due to the cumulative effects of air pollution from both indoor and outdoor sources.



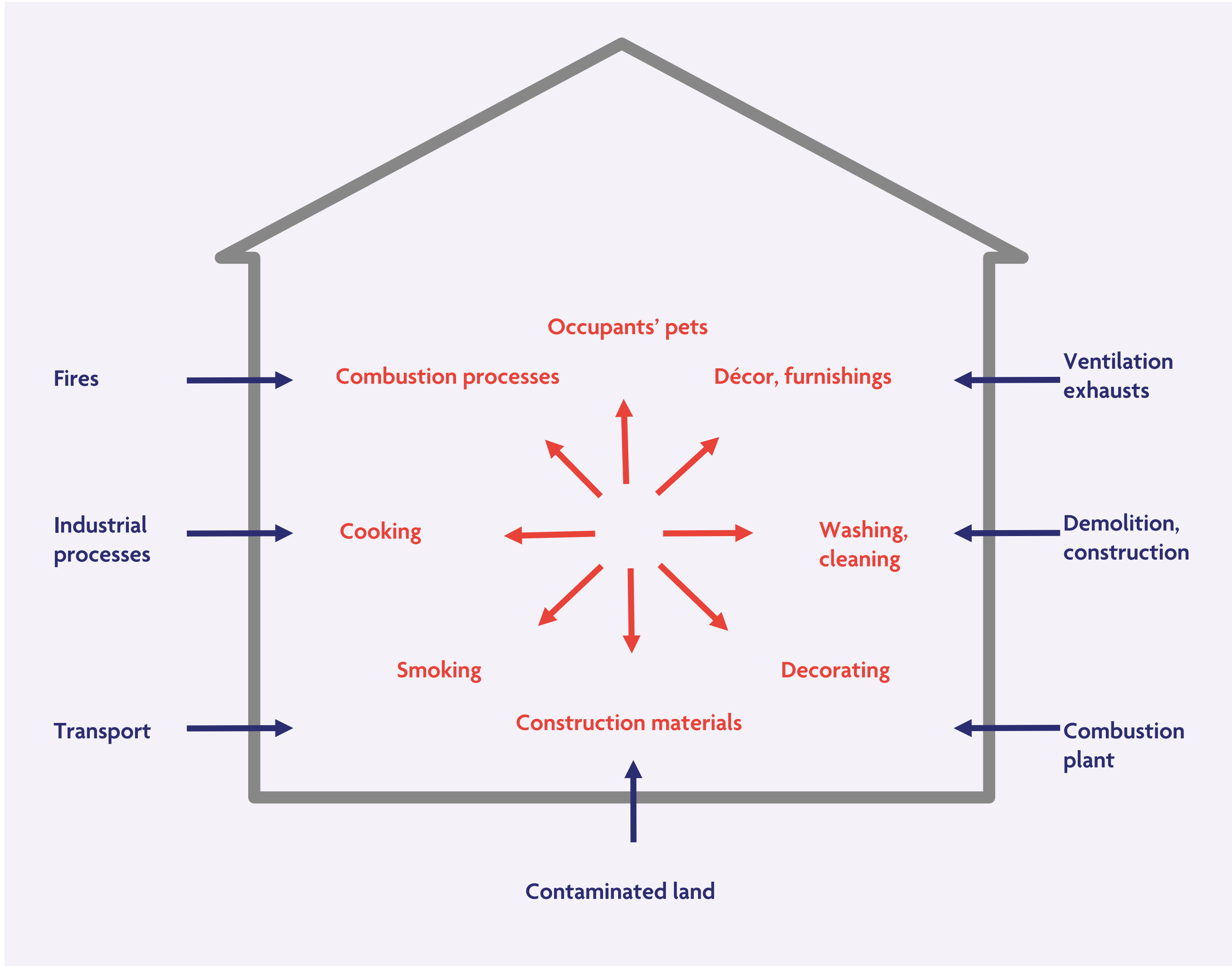
▲ **Figure 1. Examples of typical pollutants found indoors.[1]**

To add to this, the drive to make buildings more energy efficient, and hence more airtight, can worsen indoor air quality further, especially in buildings where effective ventilation with outdoor air, to remove internal pollutants, is not provided. When ventilation rates are low, indoor pollutants can accumulate to high levels and hence pose a risk to our health. In addition, the Covid-19 pandemic has led to people having to spend even more of their time indoors, resulting in increased pollutant-generating activities there and hence further deterioration of indoor air quality. Since the airborne transmission of Covid-19 has now been recognised,[3,4] improving indoor air quality is regarded as key to preventing its spread.[5]

AIR POLLUTANTS AND THEIR SOURCES

Building occupants may be exposed to airborne pollutants of different types – organic, inorganic and biological – in both the gaseous and particle forms. Some emissions may be odorous, such as those from cooking, and the perceived air quality considered poor. However, the odorous volatile organic compounds (VOCs) actually present in the air may not be harmful, whereas chemicals in indoor air that may be toxic to human health may have little or no odour, such as carbon monoxide.

Figure 1 shows examples of typical pollutants found in indoor environments, while **Figure 2** shows their potential sources.[1] All types of building, domestic (from detached and terraced homes to flats) and non-domestic (from offices to schools, hospitals, hotels, restaurants, museums, airports and industrial premises), are likely to be exposed to pollutants from most of the sources shown. The quality of air in a building is therefore the result of a complex relationship between all these pollutants from both the indoor and outdoor sources, and interactions with a number of variables including:



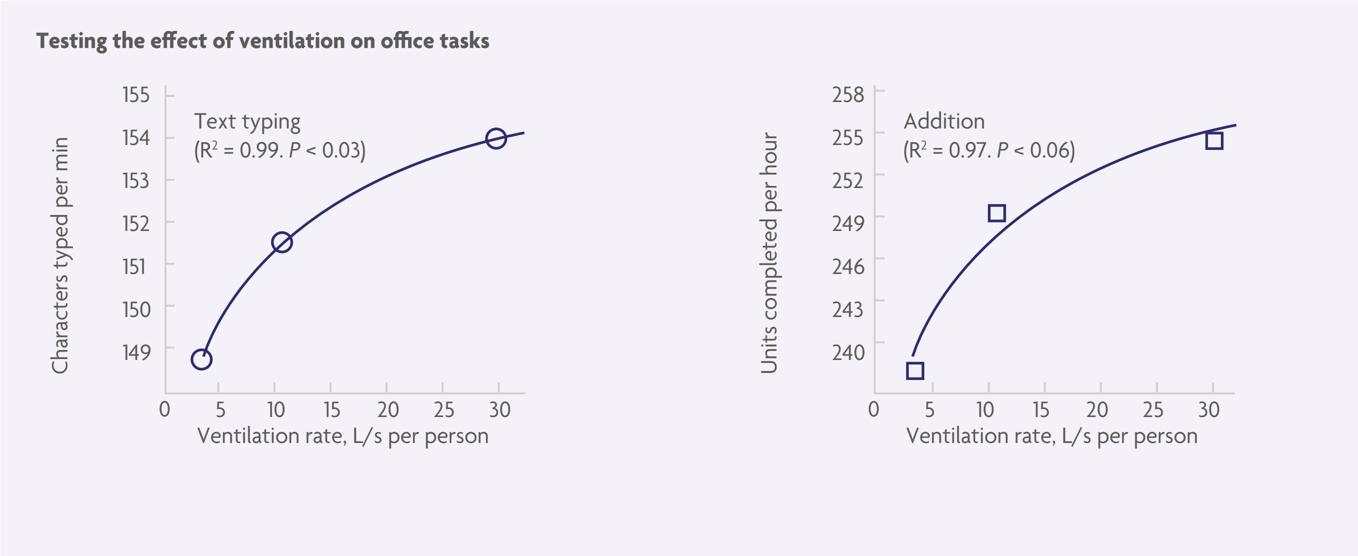
▲ **Figure 2. Examples of typical sources of pollutants affecting indoor air quality.[1]**

- Location of building and its surroundings;
- Type and use of building and its construction characteristics;
- Ventilation strategy (e.g. natural, mixed-mode or mechanical);
- Internal contents and furnishings; and
- Type of activities being carried out within it.

For example, pollutants from cooking are far more likely to exist in a home or restaurant than in an office, and ozone from photocopiers more likely to be emitted in an office than in a home. In some areas of a hospital there are likely to be higher levels of ethanol and isopropanol from hand sanitising gels than in other areas. In industrial premises and factories, the chemicals associated with the processes that are taking place may predominate. In museums, there may be emissions of naphthalene, for example, which is often used to preserve historic artefacts. Even within a particular building the indoor air quality is likely to vary between different areas.

AIR POLLUTION IMPACT ON HEALTH AND COSTS

The health effects of different pollutants are well documented.[6,7,8] The extent of the effect of a particular pollutant on human health depends on the concentration of the pollutant and the duration of the exposure to it, as well as on the age and gender of the person exposed.[9] Globally, exposure to air pollution from the combined effects of pollutant-generating activities, both outdoors and indoors, causes about seven million premature deaths every year, as a result of increased mortality from stroke, heart disease, chronic obstructive pulmonary disease, lung cancer and acute respiratory diseases such as asthma and bronchitis. In the UK each year, between 28,000 and 36,000 deaths a year are attributed to long-term exposure to air pollution,[10] while in London alone, nearly 9,500 people die due to air pollution. The first death certificate in the world with air pollution



▲ **Figure 3. Fresh air ventilation rate versus performance in an office environment.[13]**

formally recorded as a cause of death was that of a nine-year-old asthmatic girl, Ella Adoo-Kissi-Debrah, who died in February 2013 from acute respiratory failure as a result of exposure to high levels of nitrogen dioxide and particulate matter from traffic emissions.[11]

In recent years, there has been increased interest in air pollution levels in and around schools, since these are often located in areas where air pollution levels breach air quality limits. Young children are amongst the most at risk, due to their high physical activity and breathing rates, and because their lungs are still developing. Polluted air can also restrict their growth. While considerable research in this area is ongoing, some new guidance on mitigating children's exposure to traffic pollution in and around schools is available.[12]

Poor indoor air quality can cause headaches, dizziness, nausea, irritation of the eyes, nose and throat, and skin problems such as dermatitis. It can also cause behavioural problems in children, adversely affect brain health, learning ability, cognitive function and academic performance, and prolong healing and recuperation of the ill. For example, some studies have shown that when carbon dioxide (CO_2) concentrations increase to levels that are common indoors (about 950 ppm), cognitive function scores decline significantly;[13] other studies show limited evidence of acute impacts to human health or cognition below 5,000 ppm.[14] Increasing ventilation lowers concentrations of CO_2, VOCs and other indoor contaminants, resulting in reduced exposures and hence increased cognitive function scores.[15] **Figure 3** shows that increasing the office ventilation rate improved indoor air quality and, in turn, improved the performance of tasks such as typing.

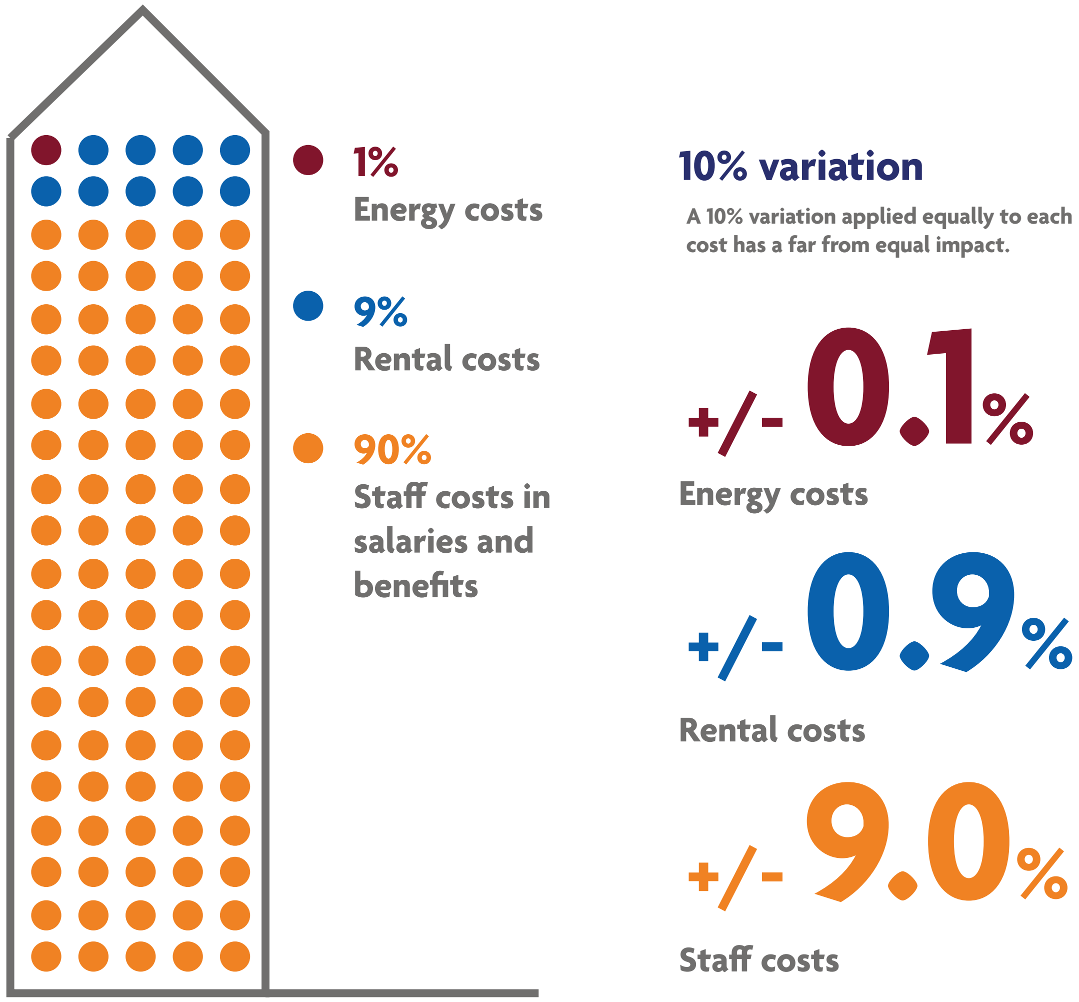
Furthermore, there is now evidence that poor indoor air quality also impacts mental health, exacerbating depression, bipolar disorder, schizophrenia and personality disorder, for example.[16]

Medically treating those exposed to air pollution can cost up to £20 billion each year in the UK.[10] Poor indoor air quality can also lead to business costs from reduced staff performance; higher costs for the operation and remediation of buildings; and reduced market and rental value of buildings. **Figure 4** shows that, in commercial environments, typically up to 90 per cent of the operational costs to an organisation are from the staff (through salaries and benefits, for example), with the remaining 10 per cent covering building rental and energy expenditure.[17] Poor health and reduced staff performance through poor indoor air quality is likely to increase the staff costs. Although improving indoor air quality can add to energy costs through, for example, upgrading heating, ventilation and air conditioning (HVAC) systems, much greater resultant cost benefits may be achieved through increased staff productivity and the potential to increase rental incomes.

SUMMARY

It is clear that good quality indoor air in buildings is vital for the health, comfort, wellbeing and productivity of the occupants. As people have become more aware of the adverse impacts of indoor air pollution on their physical and mental health and wellbeing, it has now become nationally recognised as an issue of major concern and is high on the UK agenda as a subject that needs to be addressed urgently.

Major building owners and specifiers are also now increasingly demanding high-performance office buildings,



▲ **Figure 4. Typical business operating costs for a building.[17]**

recognising that those with high quality indoor environments including good indoor air quality, can command higher rental incomes from improving staff health, wellbeing and productivity. However, though the benefits of healthier buildings are increasingly being recognised, there is still a general lack of understanding and knowledge of the issues involved, and so guidance on how to achieve healthy buildings with good indoor air quality is limited.

It is important to note that the science of indoor air quality is extremely complex, with many contributing factors, including:

- Different types of air pollutants and their sources (outdoors and indoors);
- The age, type and construction of the building;
- The building's internal properties, such as its décor and furnishings;
- Temperature and humidity;
- Ventilation strategy (for example, natural, mixed-mode, mechanical and intake location); and
- Occupant activity and behaviour.

In this issue of the environmental SCIENTIST some aspects that are important to understanding how to achieve good indoor air quality are covered. There are articles on the IAQM's new guidance on indoor air quality; regulations; ventilation; a monitoring campaign in nurseries and schools; human health risk assessment of inhalation exposure; the work of Public Health England; and a fascinating interview about how a large company plans to return to the office following Covid-19. **ES**

Dr Vina Kukadia, is an independent consultant and Research Development Manager at the Global Centre for Clean Air Research at the University of Surrey. She has 30 years' experience in air pollution dispersion, ingress into buildings, ventilation and indoor air quality. She has produced more than 250 publications, including practical guidance and confidential, technical client reports. In 1998, Vina was awarded the John Edward Worth Medal from the Royal Society for the Promotion of Health in relation to her work on indoor–outdoor air pollution.
✉ **vina.kukadia@gmail.com**
✉ **v.kukadia@surrey.ac.uk**

INTRODUCTION

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FEATURE

Ventilation

Emma Gibbons explores building ventilation, indoor air quality, and their links with good building design and operation.

As an airborne disease, Covid-19 has brought into focus the importance of good ventilation in indoor spaces. But how does ventilation affect indoor air quality? What effect does providing outdoor air have? And what other factors might be at play?

Often the focus for good indoor air quality is on maximising the amount of air drawn in, to reduce indoor pollutant concentrations. However, sources of indoor air pollution can originate from both indoors and outdoors. This can lead to a conflict between reducing levels of pollutants generated indoors, such as volatile organic compounds (VOCs) released from materials and products, and drawing in pollutants generated outdoors, such as nitrogen dioxide (NO_2) from vehicle combustion engines. So achieving good indoor air quality can be a complex task. Through considered design, addressing potential design conflicts, the careful operation and maintenance of ventilation systems, and the inclusion of cleaning technologies, we can work to achieve good standards of indoor air quality.

BUILDING DESIGN

Indoor air quality. The decisions taken during the design phase are key to ensuring good indoor air quality during operation. The ideal solution is a reduction at source, and this can be achieved through collaborative work at the project's design phase. For example, through the choice of materials, and whether to include indoor combustion sources, such as wood-burning stoves or gas cookers. The main elements to consider are:

- The method of building ventilation;
- The air-tightness of the building fabric;
- The selection of construction and fit-out materials; and
- The location of the building in relation to outdoor pollution sources.

In terms of pollution coming into a building, building owners and occupiers do not often have much control over pollution in ambient (outdoor) air. But good design choices can reduce the amount of ambient air pollution ingress and therefore affect indoor pollutant concentrations. For example, considering the location and surroundings of a building can inform where best to locate air intakes.

Different ventilation methods. When considering incoming ambient air pollution and the extraction of air pollutants from indoor sources, ventilation has a key role to play. Ventilation indoors relies on sufficient air exchange between the indoor and outdoor environments, and in most instances the amount of ambient air brought indoors should be maximised to improve indoor air quality.

FEATURE


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There are three main ventilation methods: natural, mechanical and a combination of the two.

- Natural ventilation is generally either wind driven or buoyancy driven (stack ventilation) – this is where cooler air enters the building at low level, is heated, becomes less dense (more buoyant) and therefore rises and exits the building at a high-level. This can be more effective than wind-driven ventilation, but the mix needs to be carefully managed.
- Mechanical ventilation relies on fans and ductwork to move air into and around a building. It is often used in situations where natural ventilation is not suitable, such as spaces that require conditioned or filtered air, or spaces with high air demand.
- Hybrid ventilation is a combination of natural and mechanical ventilation. In domestic bathrooms and kitchens, for example, the main method can be natural ventilation aided by a mechanical fan system.

Mechanical and hybrid ventilation systems are typically used in non-domestic buildings and some apartment buildings. The systems require an air handling unit (AHU) and associated ductwork, which need to be designed into a building from the outset. As technology progresses, demand-controlled ventilation is becoming more widely used. For example, air quality sensors can be placed in the return air duct, and measured concentrations of the air pollutants present alter the amount of air flow in a system as necessary. Sensors that measure CO_2 are typically included in this type of system. In the future it may be common to have sensors that also measure a range of pollutants such as NO_2, particulate matter or VOCs.

Mechanical ventilation can be energy intensive, with the main power requirements being the fans and for heating and cooling. An AHU often has two fans, one for the supply and one for the extract of air. To reduce heat losses and reduce the energy demand, a heat recovery system is usually integrated into the system. The different types of heat recovery include a thermal wheel, a plate heat exchanger and air recirculation, although the latter is not recommended as a result of Covid-19. At the design stage it is important to consider the energy trade-off between the amount of heat recovered by the system and the energy demand of the fans needed to make it work.

Building ventilation design. The designed ventilation strategy needs to deliver the optimum amount of air to the right place at the right time. The required air flow rates for a building are determined at the design stage, and these are based on comfort and indoor air quality. The elements to consider include:

- Building location and orientation;
- Nearby roads and local sources of ambient air pollution and noise;
- Weather data and the prevailing wind conditions;
- Solar exposure, daylight and shading;
- The proposed building use and needs of the occupants.

To calculate ventilation requirements, different tools can be used, including dynamic thermal modelling, the AM10 guidance from the Chartered Institution of Building Services Engineers (CIBSE),[1] Computational fluid dynamics (CFD) modelling and the Building Research Establishment (BRE) environmental design manual. Getting these calculations right at the outset will help to ensure the building operates in the best way possible later on.

Poor or low ventilation can occur when there is not enough air flow into a building or into a particular area of a building. CIBSE identifies poorly ventilated spaces as those with air flow rates of below 5 L/s/person or CO_2 concentrations above 1,500 ppm for a prolonged period.[2] The Health and Safety Executive (HSE) listed some key considerations for identifying poorly ventilated spaces during the pandemic, which include:

- Identifying areas that feel stuffy;
- Using CO_2 monitors to measure typical concentrations in an area;
- Looking for spaces where there is no ventilation (such as rooms without windows or areas with no air vents); and
- Checking how a mechanical ventilation system is operating (such as whether there is air recirculation, and if so, how much is recirculated).[3]

In naturally ventilated buildings in the UK in summer, good ventilation is often easy, as windows are likely be opened. However, in winter, good ventilation can be harder to achieve but may be more important, as windows can be opened less often and there can be indoor sources of pollution from heating systems. In addition, excessive air flow should be avoided, as this can lead to a loss of comfort for building occupants. A natural ventilation system needs to be adjustable, in the same way that a mechanically ventilated system is, and ideally should be controllable by the occupants.

Possible conflicts in design. There are a few possible confounding issues in building design whereby different drivers will require collaborative solutions. For example, in modern low-energy buildings there can be an increased risk of overheating and associated adverse health effects. But providing additional ventilation may lead to a higher proportion of outdoor pollutants entering the indoor environment. Similarly, opening windows may provide additional ventilation to dilute internal pollutants, but may introduce cold draughts and increase the penetration of ambient noise. This is a typical problem in urban areas, and a common solution is to design apartment buildings to have a hybrid ventilation system, which can operate under different modes depending on the time of day or indoor/outdoor temperature.

Air intakes for a mechanical ventilation system need to be sited away from pollution sources, such as main roads, to reduce air pollution ingress into a building. Ideally, a contextual study of the site to identify any local pollution sources should be carried out as early on in the design stage as possible.

Another confounding issue is the use of mechanical ventilation and energy use. A building using a mechanical ventilation system may have a higher energy demand than one that is naturally ventilated. Higher energy use, in turn, can lead to higher carbon and air pollutant emissions. The use of mechanical ventilation in commercial buildings has been the norm, but it is becoming more common to consider the possibility of using natural ventilation and other more sustainable methods.

One way in which buildings can be designed to reduce energy demand is to consider the solar orientation of the building to reduce solar exposure and reduce internal heat (where overheating may be an issue). Similarly, the use of materials with a higher thermal mass, such as concrete, can help to regulate indoor temperatures. This means that daytime peak temperatures are dampened and a similar temperature is maintained in the building throughout the day and night. This effect is commonly seen in buildings with thick walls, such as mosques or churches. The way a building is designed for heating and cooling purposes can reduce the amount of ventilation needed for cooling in occupied hours and subsequently affect the type of ventilation method proposed during design, and the operation of the ventilation system during the building's operation. As with all good design, a collaborative approach between different disciplines will lead to the best outcome for the project.

OPERATION

How a building's ventilation system is operated can have an effect on indoor pollutant concentrations. The elements to consider include:

- The operation and maintenance of the ventilation system, including opening of windows and doors;
- The cleaning of the mechanical ventilation system; and
- The materials and cleaning chemicals used in the building.

One element that should be considered during operation is the way in which building occupants will behave. For example, how and when building occupants are likely to open windows in a naturally ventilated building can have a significant effect on indoor conditions. A study by Schweiker *et al*. (2020) investigated human behaviour and perception in the indoor environment.[4] They found that occupants were more satisfied if they had perceived control over the indoor environment. The study also highlighted that occupant behaviour in relation to building ventilation is complex and can be influenced by a vast number of factors. For example, window opening by occupants was shown to be affected by indoor/outdoor temperatures, time of day, solar radiation and perceived outdoor air quality.

Understanding and carefully managing a ventilation system can ensure that it is working in the best way possible for the building occupants. During operation it is important to carry out regular maintenance, cleaning and assessment of the ventilation system, to make sure that the system is working as it was designed to.

Air cleaning technologies. When it is not possible to reduce pollutants at source, the use of air cleaning technologies may help. These can be integrated into a mechanical ventilation system or be stand-alone systems. The different types of technologies include:

- Filtration: filters such as high efficiency particulate air (HEPA) filters are used for filtering dust and particulate matter from air. HEPA filters are often integrated into a mechanical ventilation system, and the higher class a filter is, the more it will filter out. This is called the 'filter efficiency', and indicates the fraction of particles the filter will remove from the air. Increased filtration can lead to a drop in pressure in a ventilation system, and an increase in fan use to maintain a good air flow. Therefore a balance is needed between good filtration and energy demand. In addition to the filter itself, some systems use static electricity to aid particle removal.

  ASHRAE notes that the effectiveness of reducing particulate matter depends on:

  - Airflow rate through the filter;
  - The removal efficiency of the filter;
  - The number and size of the particles;
  - The location of the filter bank in a ventilation system; and
  - The ongoing maintenance and cleanliness of the filters and the system itself.[5]

- Gas sorption: this is often used to remove gases and odour from the air by physical adsorption of the gas onto a sorbent material, such as activated charcoal. In the same way that filters can get clogged, sorbent media can become saturated, so regular maintenance and periodic replacement of the media is required.
- Ultraviolet germicidal irradiation (UVGI): ultraviolet energy can help to remove biological aerosols. UVGI lamps generate UV-C energy, which disinfects air flowing past it. The most efficient use of UVGI is when it is integrated into a mechanical ventilation system.

"The Covid-19 pandemic may have accelerated the demand for healthy buildings, but there is still a lot of work to do to really understand and improve indoor environmental conditions in buildings."

Different technologies have different advantages, and the above list is by no means exhaustive. In terms of air cleaning during the Covid-19 pandemic, the Scientific Advisory Group for Emergencies (SAGE) produced a report in November 2020 that provided information on potential applications of air cleaning devices in indoor environments.[6] However, it noted that air cleaning devices are not a substitute for ventilation. A literature review by Peters and Halleran (2020) looked at urban housing and health, with a focus on post-pandemic design. They concluded that buildings should be designed to:

- Have better indoor air quality;
- Use natural ventilation wherever possible;
- Have layouts and space to prevent overcrowding; and
- Support wellbeing.[7]

In summary, how, when and where air is drawn into and extracted from a building can greatly influence the indoor environment. The Covid-19 pandemic may have accelerated the demand for healthy buildings, but there is still a lot of work to do to really understand and improve indoor environmental conditions in buildings. As environmental practitioners we can help to influence the design and operation of buildings to have the best possible outcome for occupants. With appropriate ventilation systems being designed for new buildings, and with good ventilation management practices already in place, we can start to make sure we are equipped for any future pandemics. ES

Emma Gibbons, BSc Hons, CEnv, MIAQM, MIEnvSc, PIEMA, is a PhD student at University College London. Her field of research is indoor air quality, with a focus on the ingress of ambient air pollution into buildings. Prior to her PhD studies, Emma was a senior consultant at Arup, and she has more than 12 years of experience in air quality consultancy. She is a chartered environmentalist and a full member of the IES and the IAQM.

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CASE STUDY

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Monitoring indoor air quality

Peter Walsh presents the findings of research to compare the nitrogen dioxide concentrations inside and outside schools and nurseries.

In the past, discussions around indoor air quality have been limited to ventilation and fresh air, rather than from the broader perspective of pollutants that could cause harm to health. Ventilation performance and fresh air are often measured using carbon dioxide (CO_2) concentrations, temperature and humidity. Poor ventilation and respiration of building occupants results in high CO_2 concentrations, to which the post lunch-time sluggishness of occupants in cramped city offices is often attributed. But indoor air quality is strictly the concentration of any airborne substance potentially harmful to human health.

Sources of indoor air pollutants are often within the building itself, including volatile organic compounds (VOCs) from paints and furnishings, or particulate matter from cleaning and combustion process (e.g. wood fires, cigarette smoking, etc). In cases where the pollution source is inside the building, the operator of the building can often control the pollutant at source, or at least its ventilation.

Poor ambient (outside) air quality is often thought to result in poor indoor air quality. Where indoor air pollutants are from outside the building, then these pollutants are often more difficult to control at source, as they are often emitted from processes outside the control of the building's occupants or managers. Examples include nitrogen dioxide (NO_2) from vehicle emissions and particulate matter from combustion outside the building.

Recently, attention has been drawn to the impact and effects of poor urban air pollution on young people, particularly school children. In 2016, Sadiq Khan, the Major of London, included improving air quality in and around schools as one of his election manifesto promises, and in 2021, a coroner returned the judgement that air pollution was a s ignificant factor in the death of nine-year-old Ella Adoo-Kissi-Debrah.

▲ **Figure 1. Predicted NO_2 concentrations in central London. (© London Atmospheric Emission Inventory)**

AIR QUALITY IN EARLY-YEARS EDUCATION

This case study looks at the influence of ambient air quality on the indoor air quality of 17 central London schools and 20 central London nurseries (see **Figure 1**), and the work was commissioned by the Alpha Schools Plus Group and the Greater London Authority. As part of the Mayor's campaign to tackle poor air quality in London, WSP was commissioned to assess the air quality at 20 central London nursery schools. In a separate commission by the Alpha Schools Plus Group, WSP was asked to assist with determining air quality at some of their central London sites. The results of monitoring pollutants could help measures, actions and mitigation to be put in place to address and reduce the exposure of young pupils to poor air quality.

High concentrations of NO_2 and particulate matter such as $PM_{2.5}$ (particles smaller than 2.5 microns) are known to be a major issue within the London. As part of the monitoring surveys, mapping audits of the schools were undertaken (see **Figure 2**). NO_2 was identified as one of the pollutants most likely to cause health effects in school children in central London, and were chosen as the pollutants to be monitored in both the schools study and the nurseries study.

MONITORING EQUIPMENT

Deploying monitoring equipment within a school environment gives rise to some challenges, such as the security of the instruments, the intrusiveness of having a loud air pump in a classroom, risks around electrical equipment being installed above head height and at risk of dropping onto an unsuspecting pupil, and the quality of data collected. Working closely with our clients, WSP set out some criteria for the selection and deployment of sampling equipment for the detection of NO_2 in schools and nurseries, and these were:

- Robust;
- Quantitative;
- Traceable;
- Established, recognised method;
- Good detection limits (low);
- Discrete (both visually unobtrusive and inconspicuous);
- Quiet;
- Low power demands;
- Inexpensive; and
- Low risk (hazard free).

Low-cost sensors. The development of low-cost sensors and indicative monitoring devices has transformed indoor air quality monitoring. Through electrochemical sensor technology, typical pollutant gases can now be routinely continuously detected by small, low-cost (£400 to £4,000) devices at concentrations below micrograms per cubic metre. Even as recently as 10 years ago, such measurements would have only been possible using large, expensive (£15,000) devices with noisy pumps, unsuitable for quieter indoor environments. However, electrochemical sensors are sensitive to changes in both temperature and humidity, and their signal has a tendency to drift over time.

Passive sampling. Passive sampling techniques are commonly deployed to record ambient air quality, but passive samplers such as the diffusion tube (see **Figure 3**) are well suited to an indoor environment, as they are small (6 cm in length), discrete and inexpensive. However, they only provide an average concentration over the exposed period, typically between two weeks and a month for a diffusion tube and one to several hours for a passive badge sampler.

We arrived at a monitoring strategy that, combined the use of both low-cost sensors and passive sensors against the criteria we had set out, providing the following advantages:

- Quiet and discrete method – small, low power;
- Low risk/hazard free – light and secured above pupil height;
- Adaptable and easy to deploy – rapid set-up, no enclosure, small footprint;
- Combination of robust and high-resolution data – standardised methodology, access to raw data; and
- Inexpensive – low-cost options available.

MONITORING STRATEGY

WSP deployed both low-cost sensors and passive samplers in parallel across all of the schools and nurseries within the survey. Low-cost sensors were deployed for up to 14 days to provide a snapshot of the short-term changes in indoor air quality throughout the day, and to register the changes in concentrations between mid-week and weekend periods. The passive samplers were deployed for an extended period (three months) to allow average NO_2 concentrations to be understood.

At each site, passive samplers were deployed at three indoor locations and three outdoor locations, whereas low-cost sensors were deployed at one indoor location and one outdoor location.

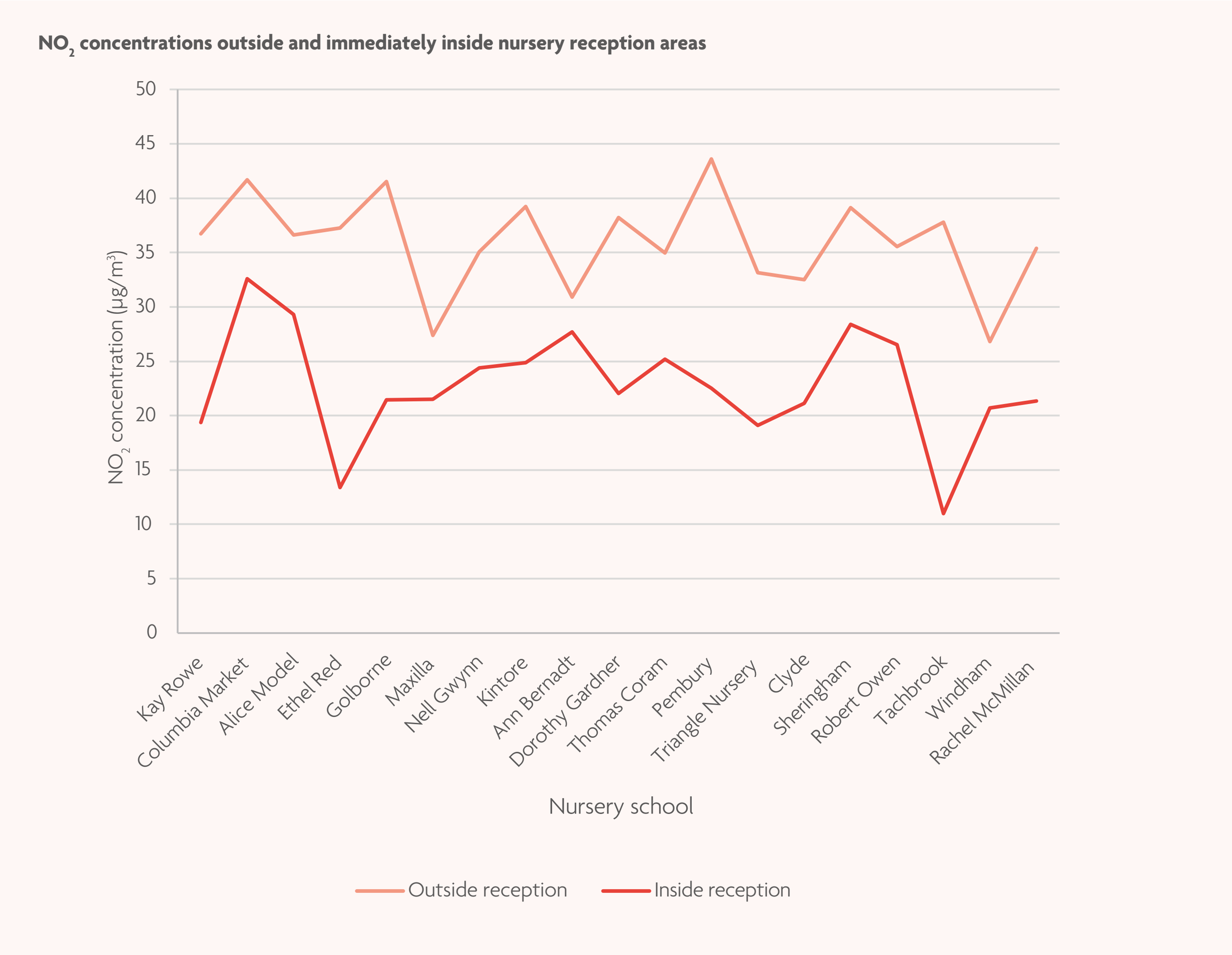
FINDINGS

Nurseries. At all nursery locations, concentrations of NO_2 were found to be considerably lower in indoor air than in the ambient air immediately outside the building; this was also the case at most of the schools monitored. As sources of NO_2 generated inside the schools and nurseries sampled were very limited, the presence of NO_2 within the buildings was concluded to be the result of infiltration of NO_2 from outside into the school and nursery buildings.

Inside the nurseries surveyed, air quality was considered good to very good, so the risk of nursery pupils being exposed to poor air quality while inside nursery classrooms was very low, even though most of the nurseries were located in heavily polluted areas of London. This was due to low infiltration of ambient NO_2 into classrooms – the school building tended to attenuate infiltration.

▲ **Figure 2. Diffusion tube mounted on a lamp-post. (© Gradko)**

▲ **Figure 3. Zephyr indicative low-cost sensor. (© EarthSense)**



▲ **Figure 4. Comparison of NO_2 concentrations outside and inside nursery reception areas (µg/m³).**

Generally indoor NO_2 concentrations appeared to vary according to the building location, building type, use and building fabric. School and nursery buildings that were close to busy roads, and therefore close to vehicles emitting NO_2, were more likely to have a higher concentration of NO_2 immediately outside their school buildings. School and nursery buildings that were set back from the road often had lower ambient NO_2 concentrations immediately outside their buildings.

The potential that NO_2 could infiltrate into nursery reception areas, putting nursery staff at risk of exposure, was assessed. Concentrations of NO_2 outside and immediately inside reception areas were monitored. **Figure 4** shows that although NO_2 concentrations were elevated outside, inside the nursery building, where reception staff were located, concentrations were observed to dramatically decrease. This was confirmation that attenuation of external pollutants occurred not just within classrooms, but also within nursery receptions areas.

As well as the pupils, nursery staff were at low risk of being exposed to poor air quality while working in and around nursery reception areas.

Schools. Of the 17 schools sampled, NO_2 concentrations in all classrooms were recorded as either low or very low for the sampling period (see **Figure 5**). Concentrations of NO_2 were observed to be higher at sample locations closer to the street, lower in school classrooms than school lobbies, and lower in school lobbies than in outside spaces.

INFILTRATION RATES

It was observed that of the schools and nurseries with low infiltration rates of NO_2 (i.e. much lower internal NO_2 concentrations than external concentrations), the majority had well-sealed windows and doors, and entrances were set well away from the roadside. The schools and nurseries with high infiltration rates were observed to be primarily older, draughty buildings, with entrances (lobbies) very close to central London traffic.

▲ **Figure 5. Comparison of NO_2 concentrations outside and inside central London schools (µg/m³).**

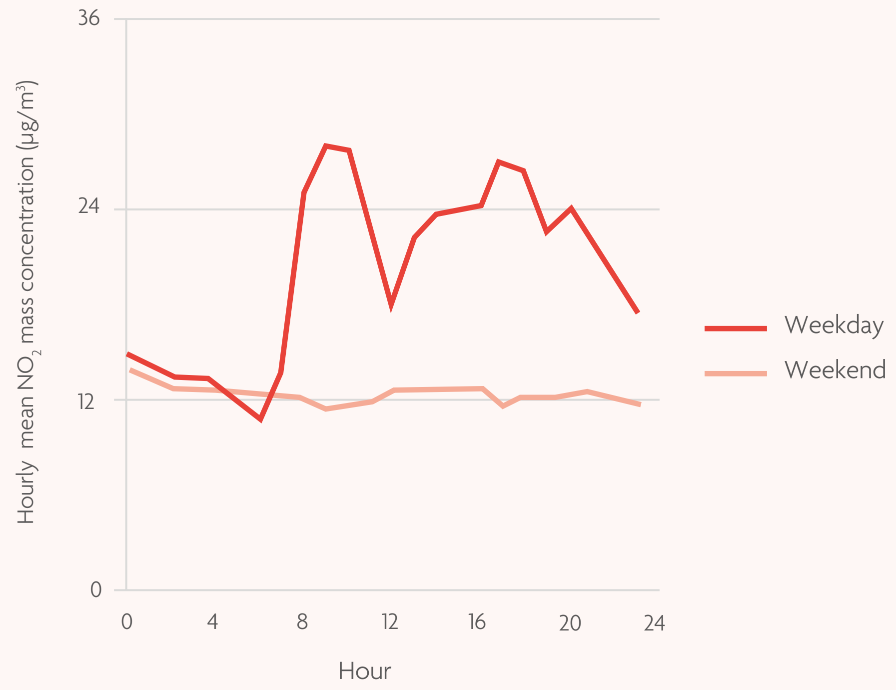
Tachbrook Nursery School – low infiltration. The nursery is located in a housing estate, away from busy roads and traffic, though in a polluted area of Westminster (central London). The nursery is sited within a building from about the 1950s (see **Figure 6**), although its windows and doors have been upgraded and are airtight. The nursery outdoor play space is located away from busy roads and therefore the influence of traffic emissions. Concentrations of NO_2 recorded in indoor air were very low, even though the ambient air NO_2 concentrations were some of the highest recorded in the study.

▲ **Figure 6. Tachbrook Nursery School, which has a low building infiltration rate.**

▲ **Figure 7. Columbia Market Nursery School, which has a high building infiltration rate.**

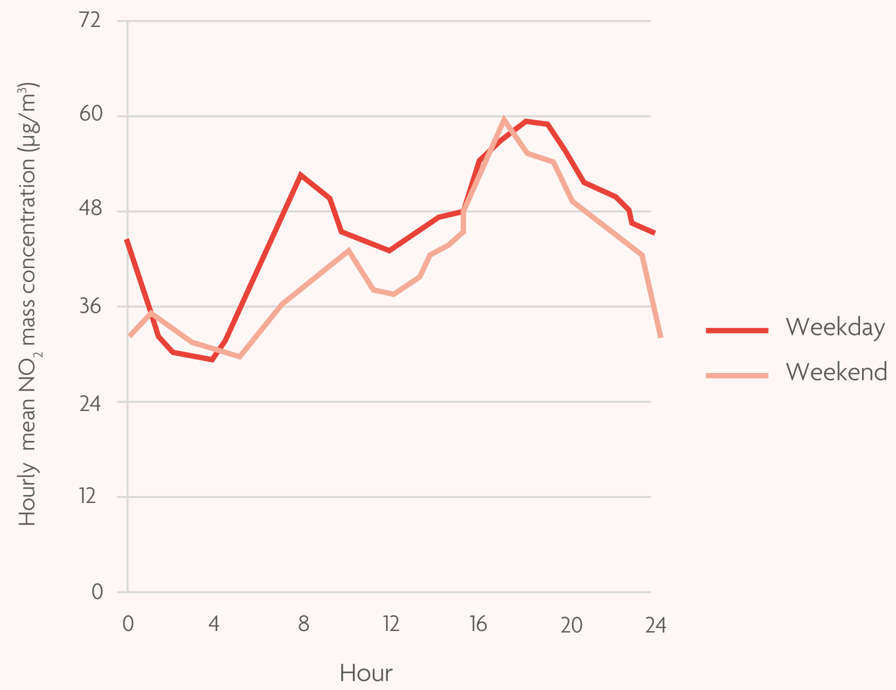
CASE STUDY

Comparison of hourly average NO_2 concentrations during a weekday and at the weekend in a sealed airtight school building



▲ **Figure 8. Low pollution building infiltration rate, measured using an internal monitor.**

Comparison of hourly average NO_2 concentrations during a weekday and at the weekend in a poorly sealed school building



▲ **Figure 9. High pollution building infiltration rate, measured using an internal monitor.**

Columbia Market Nursery School – high infiltration. The nursery is located in a polluted area of Tower Hamlets (east London), and NO_2 concentrations in ambient air were recorded as high at two of the three outside sampling locations. The majority of the nursery building dates from the 1930s, and the degree to which it was airtight was limited (see **Figure 7**). In addition, the staff often leave external nursery classroom doors open for children to free-play between the internal classroom and the outdoor classroom. The combined outcome was that NO_2 concentrations in the nursery building were not as low as in other nurseries sampled.

Infiltration and low-cost sensor data. Low-cost sensor monitoring data illustrates the effectiveness of a sealed airtight building on indoor air quality (see **Figure 8**). Comparing NO_2 hourly average concentrations during a weekday (Monday–Friday) to hourly averages at the weekend in a sealed airtight school building, we can observe the impact of low infiltration during the period when the school building is unused. In this case NO_2 concentrations do not fluctuate during the day at the weekend as they do over a weekday, as doors and windows are not being opened, and polluted air is unable to enter the school building. In a poorly sealed school building (see **Figure 9**) the changes in NO_2 hourly average concentration are very similar for weekdays and the weekend, due to the high infiltration rate of external polluted air and, therefore, the relatively lower importance of door and window opening.

REDUCING INFILTRATION OF POLLUTED AIR

From the central London school and nursery classrooms surveyed, the reassuring conclusion was that concentrations of NO_2 were generally low to very low. In addition, the risk of nursery reception staff being exposed to externally polluted air was observed to be low.

However, the extent to which ambient, polluted air can impact indoor air quality was observed to be as much related to the effectiveness of the building airtightness as to the concentration of external pollution. This is a lesson for building designers, architects and facility managers as much as for air quality scientists. Ensuring that there is low infiltration of polluted air into nurseries and schools could end up protecting the health of the buildings users, be they reception staff or young pupils. ES

Peter Walsh is a Technical Director within WSPs Air Quality Team, and has more than 28 years of experience in environmental monitoring, research, regulation and assessments. Peter specialises in air quality monitoring, including indoor air quality monitoring, and has a particular interest in new monitoring techniques, novel sensors and new applications of existing monitoring methods.

The inequality of indoor air quality legislation and assessment criteria

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ANALYSIS

Oliver Puddle highlights how air quality legislation and assessment criteria vary depending on whether you are outside or indoors.

The House of Lords is currently reviewing the Clean Air (Human Rights) Bill.[1] But who will ultimately be responsible for ensuring we have access to clean air when we spend around 90 per cent of our time indoors,[2] in our workplaces, commercial and recreational premises and our homes? You may be surprised to learn that the air you breathe throughout your day is not always regulated.

UK AMBIENT AIR QUALITY LEGISLATION

The next time you step outside your front door, take a deep breath of fresh air. How 'fresh' the air you are breathing will largely depend on where you live, and indeed whether or not you have actually stepped outside the building you live in. For now, let us assume the air you have inhaled is outdoor/ambient air. If you live in the UK, that air is regulated under European legislation (2008/50/EC),[3] which has set legally binding concentration limits for pollutants that impact human health, especially those associated with emissions from transport and industry. These include nitrogen dioxide (NO_2) and particulate matter (PM) with an aerodynamic diameter of less than 10 µm (PM_{10}) and 2.5 µm ($PM_{2.5}$). This European legislation was made law in England through the Air Quality Standards (AQS) Regulations,[4] which also incorporated the fourth air quality daughter directive (2004/107/EC)[5] that sets concentration targets for specific heavy metals and polycyclic aromatic hydrocarbons (PAHs). The devolved administrations of Northern Ireland, Scotland and Wales have their own equivalent regulations. After the UK left the European Union (EU) on 31 January 2020, the current framework of air quality legislation was made into UK (EU retained) law through the European Union (Withdrawal) Act 2018.[6]

In the UK, the Secretary of State for Environment, Food and Rural Affairs is responsible for meeting the air quality standards limit values and the Department for Environment, Food and Rural Affairs (Defra) produces air quality plans and co-ordinates assessment. Under the Environment Act 1995,[7] the UK government and the devolved administrations are required to produce a national air quality strategy. This strategy sets out the UK's air quality objectives (AQO). Part IV of the Environment Act 1995 requires local authorities to review air quality in their areas of jurisdiction and designate

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air quality management areas (AQMAs) if pollutant levels breach air quality objectives and improvements are necessary. An air quality action plan setting out measures to reduce the pollutant/s in question must be put in place. These local authority measures typically include the requirement of air quality assessments and management plans for developments and often set planning conditions that require specific pollutants to be monitored and where possible mitigated.

Air quality standards are pollutant concentrations recorded over a given time period that are considered to be acceptable based on what is scientifically known about the effects on human health and the environment, and, to a lesser extent, on what is achievable in practical terms. The air quality standards limit values are set for individual pollutants and specify a concentration value and an averaging time (e.g. 24-hour and annual mean µg/m^3 values), and in some cases, the number of times each year that the concentration may be exceeded. Air quality objectives also specify target dates by which the air quality standards should not be exceeded.

By rights then, the pollutants in the outdoor air you are breathing should be at lower concentrations than their corresponding air quality objectives – although in practice they often are not, as recently highlighted in the tragic case of Ella Adoo-Kissi-Debrah.[8]

UK WORKPLACE AIR QUALITY LEGISLATION

Let us now assume you have commuted to work and have just stepped into your workplace. Again, take a deep breath to prepare yourself for a busy day ahead. The air you breathe in your workplace is regulated by the UK Health and Safety Executive (HSE) under the Control of Substances Hazardous to Health (COSHH) regulations.[9] Exposure to some substances, such as lead and asbestos, is regulated separately[10,11] COSHH Regulation 6(1) states that an employer 'should carry out a suitable and sufficient assessment of the risks to the health of your employees and any other person who may be affected by the work, if they are exposed to substances hazardous to health'. This implies that any visitors (e.g. members of the public) to a workplace are included in the remit of the regulations.

COSHH Regulation 10 states that monitoring is required 'when measurement is needed to ensure a WEL [workplace exposure limit] or any self-imposed working standard is not exceeded'. The HSE routinely inspect workplaces, sometimes focusing their attention on specific sectors – there was a Construction Sector Inspection Initiative during October 2020. Where appropriate, they can take enforcement action if they suspect any regulations are being flouted. For example, employers can be issued with improvement notices if HSE inspectors believe any occupational exposure risks have not been suitably assessed.

HSE document EH40[12] sets out specific workplace exposure limits (WELs) and short-term exposure limits (STELs) for around 500 substances, including dusts, gases and volatile organic compounds (VOCs). That number is significantly more than the pollutants regulated in ambient air and includes some with an air quality objective (such as NO_2). WELs are reported as 8-hour time-weighted average

▼ **Table 1. Comparison of pollutant concentrations for ambient air and occupational exposure regulatory limits**

Pollutant	Ambient air quality regulatory limits	Occupational exposure regulatory limits
	UK air quality objectives (µg/m^3) (averaging time)	EH40 (µg/m^3) 8-hour TWA WEL and 15-minute STEL
PM_{10}	40 (annual mean) 50 (24-hour mean)	No equivalent
$PM_{2.5}$	25 (annual mean)	No equivalent; respirable (PM_4) dust WEL: 4,000
Nitrogen dioxide (NO_2)	40 (annual mean) 200 (1-hour mean)	WEL: 960 STEL: 1,910
Ozone (O_3)	100 (8-hour mean)	STEL: 400
Sulphur dioxide (SO_2)	125 (24-hour mean) 350 (1-hour mean) 266 (15-minute mean)	WEL: 1,300 STEL: 2,700
Polycyclic aromatic hydrocarbons (PAHs)	0.25 ng/m^3 (annual average)	No equivalent
Benzene	16.25 (running annual mean) 5 (annual average)	WEL: 3,250
1,3-butadiene	2.25 (running annual mean)	WEL: 2,200
Carbon monoxide (CO)	10 (max daily running 8-hour mean)	WEL: 23,000 STEL: 117,000
Lead	0.5 (annual mean)	No equivalent; CLAW[10] occupational exposure limits (OEL) 150

(TWA) concentration values in mg/m^3 or parts per million (ppm); some substances have 15-minute STEL values in the same units. WELs are generally based on indicative occupational exposure limit values (IOELVs), which are health-based limits set under the Chemical Agents Directive (98/24/EC).[13] Occupational exposure regulatory limits are often considerably higher than corresponding ambient air quality regulatory limits: NO_2, for example, has a 1-hour mean ambient air limit value of 200 µg/m^3, whereas the occupational exposure regulatory limit (8-hour WEL) is 960 µg/m^3. **Table 1** provides a comparison of ambient air quality regulatory limits and occupational exposure regulatory limits. It would seem that at work we are expected to tolerate higher levels of pollutants.

By definition WELs and other occupational exposure limits (OELs) only apply to occupational exposure, and EH40 states that 'the limits cannot be adapted readily to evaluate or control non-occupational exposure' and that 'WELs are approved only for application to people at work'. While COSHH may apply to all those working in or visiting a workplace, its supporting EH40 substance assessment criteria does not. All exposure limits are also often considered to apply to healthy adults[14] in industrial settings who work 8-hour shifts in a typical 5-day week. These exposure limits cannot be assumed to offer the same level of protection to more vulnerable demographics such as pregnant women, for example, or people who spend extended periods in workplaces.

ANALYSIS

▼ Table 2. WHO indoor air quality guidelines

Pollutant	WHO guideline concentration (µg/m³) (averaging time)
Benzene	No safe level of exposure can be recommended
Carbon monoxide (CO)	100,000 (15 minutes*) 35,000 (1 hour) 10,000 (8 hours) 7,000 (24 hours**)
Formaldehyde	100 (30-minute average)
Naphthalene	10 (annual average)
Nitrogen dioxide (NO_2)	200 µg/m³ (1-hour average) 40 µg/m³ (annual average)
Polycyclic aromatic hydrocarbons (PAHs)	No threshold determined and all indoor exposures are considered relevant to health.
Radon	100 to <300 Bq/m³ (annual reference level)
Trichloroethylene	No safe level of exposure can be recommended
Tetrachloroethylene	250 (annual average)

* Assuming light exercise and that such exposure does not occur more than once per day.
** Assuming that the person is awake and alert, but not exercising. It is recognised that someone would not be expected to be awake and alert for the whole 24-hour period.

So, what if your place of work is a non-industrial setting such as an office or a shop? What if you are pregnant or have compromised health in any place of work? WELs and STELs are unlikely to be appropriate assessment criteria for you. If you work in a school, WELs and STELs might be appropriate to assess teaching and support staff in design and technology (e.g. woodworking) classes but not necessarily in other classrooms or offices.

INDOOR AIR QUALITY LEGISLATION

Let us now assume that you have completed your day's work and are now in a different indoor location. Outside the remit of COSHH (EH40 assessment criteria only apply to people at work) there is no regulatory indoor air quality equivalent to air quality standards. Therefore, the air you breath in an indoor environment that is not your place of work is essentially unregulated. For example, you could be:

- Visiting a relative in hospital or a care home and exposed to pollutants in fumes from cleaning products (incidentally, long-term patients and residents of care homes essentially live in a workplace and are frequently exposed to such pollutants);
- Dining in a restaurant and exposed to cooking fumes that include particulate matter, carbon monoxide (CO) and VOCs;
- Joining others in a nightclub and exposed to particulate matter from smoke machines and elevated CO_2 levels;
- Joining the congregation at a place of worship and exposed to incense smoke and burning candle fumes (including VOCs); and

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- Visiting any building for non-occupational purposes and exposed to pollutants migrating from external sources.

Clearly, harmful pollutants have the same effect on our health irrespective of where we are exposed to them. They are no less harmful in these non-occupational indoor settings than they are in regulated ambient and 'industrial' workplace settings. Such non-occupational indoor settings represent a grey area in regulatory terms, although some rudimentary statutory guidance does exist. The UK Building Regulations Approved Document F1 (ADF1) Means of Ventilation,[15] sets out regulations in England for building ventilation requirements to maintain indoor air quality. 'Appendix A: Performance-based ventilation', sets maximum acceptable indoor levels for NO_2, CO, total volatile organic compounds (TVOC), ozone (O_3) and radon, most of which are based on World Health Organisation (WHO) guidelines.[16] Building Bulletin 101[17] provides guidelines on ventilation and indoor air quality in schools and references ADF1, WHO, AQS, COSHH and other regulations but states that 'best practice is to follow the latest WHO indoor air quality guidelines'.

INDOOR AIR QUALITY GUIDELINES

Despite the lack of legislation, there are universally applicable indoor air quality guidelines. The WHO Air Quality Guidelines for Europe[18] were published

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in 1987 and updated in both 2000 and 2005 to consider more recent data and developments in risk assessment methodology. The 2000 second edition[19] has other guidelines that remain current, while the most recent 2005[20] version includes revised guideline values for selected pollutants (PM_{10}, $PM_{2.5}$, O_3, NO_2 and sulphur dioxide [SO_2]). It should be noted that these WHO guideline values 'do not differentiate between indoor and outdoor air exposure'.

In 2010 the WHO also published guidance specifically for the protection of public health from the risks associated with a number of pollutants commonly found in indoor air.[16] Benzene, CO, formaldehyde, naphthalene, NO_2, PAHs, radon, trichloroethylene and tetrachloroethylene were included (see **Table 2**) as they are known to be hazardous to health and were all identified as having potential indoor sources, often in concentrations of specific health concern. These guidelines were prepared to provide a scientific basis for legally binding standards for use by public health professionals and specialist authorities involved in the design and use of buildings and building materials; some have been adopted in the Building Regulations.

The most recent indoor air quality guidelines for the UK were published by Public Health England (PHE) in 2019.[21] These were based on a comprehensive literature review of recent scientific evidence about the occurrence of VOCs in residential and public buildings and their toxicity. Individual VOCs were identified and were further investigated to assess their relevance according to the limits of exposure and their prevalence in indoor environments. The VOCs included in the Public Health England guidelines are acetaldehyde, a-pinene, benzene, d-limonene, formaldehyde, naphthalene, styrene, tetrachloroethylene, toluene, trichloroethylene and mixed xylenes, which can be emitted from construction products, building materials and cleaning and personal hygiene products.

While both the WHO and PHE guidelines apply in all indoor environments, they are only guidelines and not enforceable; the pollutants they include are also limited in number in comparison to EH40. The limited number of pollutants with indoor air quality criteria, the inconsistency in guideline concentration values and averaging times, and the gaps in regulation led the Institute of Air Quality Management (IAQM) to work with stakeholders and other industry groups to formulate comprehensive indoor air quality assessment guidance, due to be published later this year.

It should be noted that there are also a growing number of voluntary building certification schemes that include indoor air quality performance criteria (e.g. BREEAM,[22] WELL[23] and LEED[24]), and these are largely based on WHO guidelines. The aim of such schemes is principally to promote building energy efficiency, environmental performance and occupant wellbeing.

RESIDENTIAL INDOOR AIR QUALITY

Back from work, you close your front door and take a deep breath and perhaps sigh with relief that you are home. You might light a cigarette or take a draw from a vape, light some candles or incense, light a fire, do a bit of DIY sanding or fry up some sausages, safe in the knowledge that, while these activities will very likely release harmful pollutants with health-based limit values, they are unlikely to ever be regulated in our homes.

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Oliver would like to thank Gordon Allison (DustScanAQ) and Peter Walsh (WSP) for reviewing and contributing to this article.

ES

Oliver Puddle is a Chartered Scientist and Principal Consultant at DustScanAQ. He has specialised in indoor air quality and occupational exposure assessment for more than 6 years. He is also a committee member of the IES and a member of the IAQM Indoor Air Quality sub-group.

OliverP@dustscan.co.uk

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CASE STUDY

IAQM's indoor air quality guidance

Carl Hawkings summarises the IAQM's guidance on the assessment, monitoring, modelling and mitigation of indoor air quality.

An Institute of Air Quality Management (IAQM) survey of its members in 2019 identified that 40 per cent were working on indoor air quality in some capacity and a further 22 per cent thought that indoor air quality would become part of their work in the future. The importance of this area of work to members led the IAQM to extend its membership to those working primarily in this area.

An indoor air quality subcommittee was established in October 2019, comprising experts in the field and members of the IAQM committee experienced in producing guidance for members to use in their day-to-day work. The subcommittee also organised IAQM's first indoor air quality conference in 2021.

The lack of professional guidance for the assessment of indoor air quality was identified early on and work started on drafting IAQM's guidance at the beginning of 2020. From an early stage, IAQM worked closely with the Chartered Institution of Building Services Engineers

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(CIBSE) Air Quality Working Group, some of whose members were also members of the IAQM subcommittee. The guidance is supported by CIBSE, with contributions from them on mitigation measures and case studies.

A full draft of the guidance was produced by early 2021 and sent to external reviewers (including academics and government specialists). Following consideration of their very useful and insightful comments, a consultation draft is now available to IAQM members and non-members with expertise in indoor air quality.[1]

DRAFTING THE GUIDANCE

The subcommittee had several discussions on the scope of the guidance, including the below.

All indoor environments? (e.g. workplaces, airports, trains, care homes, houses, schools, cars, buses, domestic kitchens). Worker exposure limits (WELs) legally apply to all workplaces.[2] However, the WELs were originally designed to apply to healthy, working-age adults in industrial locations and may provide less protection than other guidelines, such as those from the World Health Organization (WHO), which set out to protect the health of the general population. The boundary between the work of industrial hygiene specialists and indoor air quality specialists is blurred and difficult to precisely define. The subcommittee agreed that the indoor air quality (IAQ) guidance would be applicable for all new and existing buildings but should not be used to override legally applicable and enforceable considerations. The general assessment approach may also be applicable to the assessment of air quality in vehicles.

All aspects of indoor air quality? (e.g. comfort aspects [temperature, relative humidity], pathogens [viruses, bacteria], all gaseous pollutants and particulate matter). It was decided to focus the guidance on gaseous pollutants and particulate matter relating to health impacts (not dust nuisance). While other issues affecting the quality of the indoor environment are briefly discussed, it was agreed that the guidance would not provide advice on comfort and pathogens, especially related to areas already well covered in the law (e.g. legionella).

Many locations indoors are a mix of both occupational and public spaces (e.g. care homes, taxis, restaurants), where the health of workers is regulated by legislation but that of others is not. Some guidance and legislation on air quality relate specifically to indoor *or* outdoor air; some relate to *both* indoor and outdoor air. Some government guidance (e.g. for schools[3]) does cover non-workplace exposure, i.e. of the children and visitors.

The overarching principle of the IAQ guidance is to address the gaps that exist and not to overlap with air quality legislation (which relates to outdoor exposure of the public) or occupational legislation (which is largely related to workers but does touch on exposure of the general public, as employers have a duty of care to protect visitors to places under their control).

Derive a specific methodology to assess indoor air quality? The subcommittee thought this a good idea and followed a similar approach to existing IAQM guidance. A method was drafted, revised and tested against a several case studies (which are in Appendix E of the IAQ guidance[4]). It was quite exciting to have a blank canvas and to be able to think about different ways to approach the problem. Credit goes to Kieran Laxen for developing a useful and practical starting point for the subcommittee to develop.

Other scope considerations. It was then decided, given that many IAQM members may be new to indoor air quality, that the IAQ guidance should summarise indoor air quality monitoring methods, assessment criteria, modelling and mitigation measures.

IAQM'S IAQ GUIDANCE

The IAQ guidance has seven chapters, as set out in **Box 1**. It also has a number of appendices, including how to convert between units of concentration, case studies, monitoring equipment, testing protocols and more. There is also an extensive bibliography/reading list with more than 80 references, which was greatly enhanced by our external reviewers. The main guidance has been kept intentionally short (about 30 pages) so that it can be read cover to cover.

ASSESSING INDOOR AIR QUALITY

Because IAQM has developed a new approach, the rest of this article is dedicated to a summary of the methodology for assessing indoor air quality. Anyone with knowledge of IAQ is encouraged to test the method and comment to IAQM as part of the current consultation (closing 19 July 2021). Once published, it will hopefully become the default method for non-occupational exposure to IAQ (if the widespread acceptance of other IAQM guidance is any indication). Now is your chance to ask for changes if it does not work for you!

It was largely developed with new-build or major refurbishments in mind, although the method is also applicable to other situations, such as in response to complaints from occupants of existing buildings. The method applies to people, but also to inanimate objects such as computers in data centres, food preparation areas in kitchens or microelectronics in clean rooms.

BOX 1. IAQ GUIDANCE – SUMMARY

1. Introduction: sets out the scope and purpose of the guidance, the context, why indoor air quality is important and the purposes of an indoor air quality assessment.

2. Background: takes the reader through the main indoor air quality pollutants (i.e. nitrogen dioxide [NO_2], particulate matter, radon, volatile organic compounds [VOCs], aldehydes, formaldehyde, acrolein, terpenes, ozone [O_3], carbon monoxide [CO] and carbon dioxide [CO_2]) and their health effects and chemistry; the important factors relating to exposure; and interactions with other indoor conditions (ventilation rates, humidity, temperature etc).

3. Assessment criteria: runs through the organisations and references where criteria can be found, summarises them and introduces an appropriate hierarchy if there are more than one criterion. It also discusses what to do if no published criteria exist for the pollutant under consideration.

4. Assessment approach: presents the source–pathway–receptor model as it applies to indoor air quality and details a methodology that can be used to assess indoor air quality in a way that demonstrates a logical and step-wise approach. This gives the professional an opportunity to document their judgement and will hopefully help indoor air quality assessments to be more standardised.

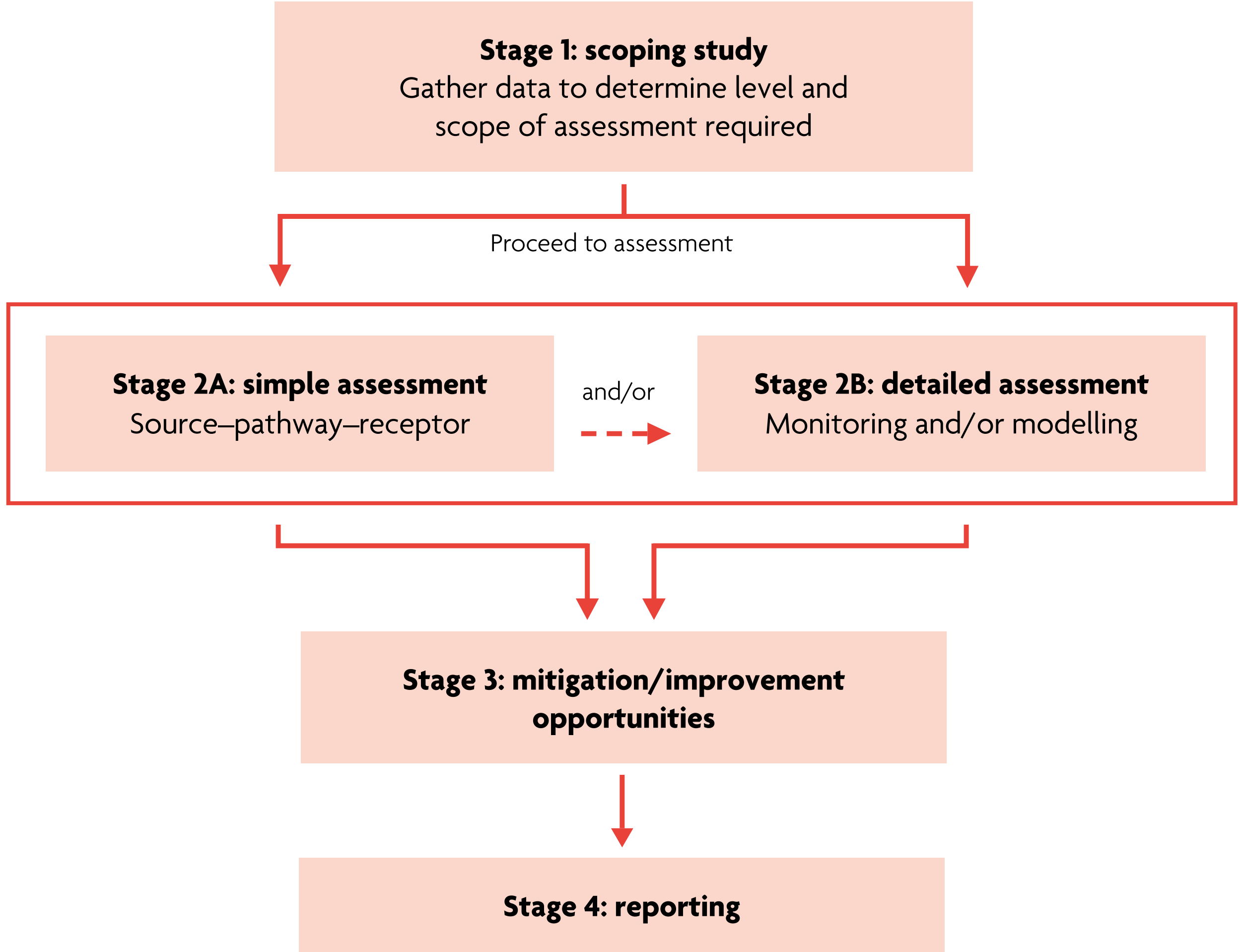
5. Monitoring: covers the how/what/when/where of indoor air quality pollutant sampling.

6. Modelling indoor air quality: gives a brief introduction to the models available, and their advantages and disadvantages.

7. Improvement measures: introduces a hierarchy of improvement measures, starting with removal of pollutant sources and ending with removal of receptors. Discusses examples of how to improve indoor air quality and how to implement them.

The source–pathway–receptor concept is applied; if one or more of these three elements is not present then that is where the assessment stops (**Figure 1** shows how to determine whether an indoor air quality assessment is required). Once it has been determined that an indoor air quality assessment is required, a four-stage process is applied and it is stressed that cooperation between the wider project team (architects, building services engineers and designers) is essential.

Stage 1: scoping study. This involves collation and review of all available information, including a walkthrough of an existing building. The aim is to identify the pollutants of concern in the specific context of the building under assessment, and the level of assessment required (i.e. no further assessment, simple assessment or detailed assessment).



▲ **Figure 1. The stages of an indoor air quality assessment.**

Stage 2: assessment. This is divided into two:

Stage 2A: simple assessment/source–pathway–receptor review. Assesses the risk to receptors that harm will arise from exposure to a pollutant.
Stage 2A involves four steps:

a) The magnitude of the hazard arising from the ingress of outdoor pollution, which is ranked on a scale of 0 to 5 based on a combination of the quality of outdoor air in relation to air quality guidelines and potential pathways (Table 4.1 in the IAQ guidance);

b) The magnitude of the hazard arising from indoor sources of pollution, ranked on a scale of 1 to 5 based on the type of emission source and pollutant and potential pathways (Table 4.2 in the IAQ guidance);

c) The magnitude of the exposure, taking into account (a) and (b), the pathway(s), duration, the response to exposure being chronic or acute, the frequency of exposure and receptor(s). This is ranked on a four-point scale (low, medium, high, very high) (Table 4.3 in the IAQ guidance); and

d) A risk assessment using the highest score obtained from (a) and (b) in combination with (c) to obtain an overall risk category on a four-point scale (negligible, low, medium, high).

The outcome of (d) determines what action to take next: negligible and low risks do not require a Stage 2B: detailed assessment, but the higher categories do. There are supplementary accompanying outcomes to distinguish the response to the four categories of risk (see Box 4.2 in the IAQ guidance for more detail).

Stage 2B: detailed assessment. This usually follows on from stage 2A: simple assessment, but the need for a stage 2B: detailed assessment may be determined at stage 1: scoping, and usually requires monitoring and/or modelling, techniques for which are covered in the guidance.

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Stage 3: mitigation/improvement opportunities. This is the final stage of assessment (unless there is negligible risk of harm to a receptor) and aims to identify suitable and effective mitigations and improvements that will reduce the risk to receptors. This is then all written up in **Stage 4: reporting.**

IAQM hope you will find the guidance useful and take the time to test it for us. IAQM are keen to receive feedback on it and will occasionally update the guidance as appropriate. **ES**

Carl Hawkings worked in the air quality and impact assessment teams at ERM for 15 years and then joined ADM Ltd, where he has worked in many sectors, including oil and gas, cement, incineration, foodstuffs, power and transport infrastructure. Most of his work in the past decade has been managing environmental impact assessments overseas, but he was acting head of the air quality team at ARUP for a while. He has been a Committee Member of IAQM for nearly 3 years and has worked on a variety of IAQM working groups and sub-committees, including the indoor air quality working group.

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New members and re-grades

Member is for those individuals who have substantial academic and work experience within environmental science.

Hugh Addlesee – Principal Environmental Consultant
Richard Alexander – Senior Data Scientist
Daniel Arnold – Environmental Advisor
James Ashby – Scientific Team Leader
Jehan Baban – Founder and CEO
Jonas Beaugas – Senior Air Quality & Noise Consultant
Hope Bootle – Senior Sustainability Consultant & Building Life Cycle Specialist
Fergus Boughton – Senior Air Quality Consultant
Rachel Boyle – Engineer
Rachel Buchanan – Development Project Manager
Alexander Bull – Principal
Carl Capewell – Freelance Ecologist
Deborah Carpenter – Environmental Consultant
Robert Cram – Board Advisor/HSE Consultant
Michael Craske – Environmental Consultant
Gareth Cunliffe – Managing Director
Matthew Davies – Owner
Karen Dineen – Scientist & Planner
Cat Dixon – Environmental Consultant
Sunanda Dola – Senior Lecturer
Guy Dowdeswell – Principal Environmental Consultant/Engineer
Jack Faber – Environmental Consultant
Michael Fews – Telecoms Advisor
Elena Fidelibus – Geo-environmental Consultant
Denis Fischbacher-Smith – Professor of Risk & Resilience
Bhooshan Garge – Environmental & Sustainability Manager
Thomas Goodfellow – Engineering Hydrogeologist
Andrew Green – Senior Consultant
Claire Griffiths – Principal Environmental Consultant
Russell Grinham – Environmental Interface Manager
Grant Harrington – Professional Environmental Consultant
William Hartas – Environmental Scientist
Simon Hay – Senior Environmental Consultant
Nikolas Hill – Associate Director, Knowledge Leader
Sarah Irons – Director
Mervyn Keegan – Director
Tom Keighley – Environmental Consultant
Darcy Kitson-Boyce – Associate
Gowthaman Krishnasamy Govindraj – Environmental Specialist
Vinaben Kukadia – Research Development Manager
Ka Wing Leung – Consultant
Alan McDonald – Senior Specialist Scientist
Jane McEwen – Technical Director
Stephanie McGovern – Associate Director
Orlaith McVeigh – Environmental Scientist
Syed Azam Moinuddin – Chief Executive Officer
Charlotte Newman – Senior Consultant
Russell Old – Senior Geo-environmental Consultant
Aisling O'Neill – Project Environmental Scientist
Bryan Paul – Environmental Executive
Barry Plane – Principal Environmental Consultant
Catheryn Price – Senior Consultant
Daniel Quinn – Senior Consultant
Javanshir Rasulov – Senior Consultant/Head of Indoor Air Quality
Katie Rowney – Senior Environmental Consultant
Angel Salcedo – Environmental Engineer/Consultant
Hazel Salkeld – Geo-environmental Engineer
Lucia Sellars – Environmental Scientist
Lee Shelton – Senior Air Quality Consultant
Karin Skelton – Project Manager
Sara Smith – Learning & Development Coordinator
Jim Stewart-Evans – Principal Environmental Public Health Scientist
Karen Straw – Environment Manager
Sarah Strickland – Principal Consultant
Sia Tanhai – Environmental Consultant
Adrian Thiedeman – Director
Nena Uraih – Project Manager UK Nuclear
William Warnock – Geo-environmental Consultant
Richard Watts – Senior Consulting Engineer
Malcolm Wilkinson – Geopark Coordinator/Freelance Environmental Consultant
Cerys Williams – Senior Environmental Protection Officer
Adam Yusaf – Senior Environmental Consultant
Lantian Zhang – Senior Air Quality Consultant

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Patrick Amoatey – Research Assistant
Alan Archer – Graduate
Nancy Baines – Healthy Waters Specialist
Sam Baldwin – Graduate Air Quality Consultant
Jake Bayne – Managing Director
Yasmeeyn Bhatti – Graduate
George Bratchel – Environmental Consultant
Todd Brumwell – EIA Advisor
Olivia Cairns – Environmental Graduate Researcher
Emily Cooke – Environmental Engineer
Chante Darien-Campbell – Air Quality Consultant
Frank Dawson – Graduate
Christopher Doyle – Ecologist
Kelly Drake – Environmental Scientist
Lorna Garner – Graduate
Jonathan Griffiths – Geo-environmental Consultant
Annie Harding – Geo-environmental Consultant
Dale Hodder – Environmental Scientist
Brittany Huggins – Graduate
Samah Ibrahim – Manager
Megan Jones – Geo-environmental Consultant
Adam Luff – Graduate
Constance McKay – Renewable Developer
Kenny McLaren – Geo-environmental Scientist
Sarah Meek – PhD student in Marine Ecology
Sophie Morris – Environmental Improvement Officer
Emily Murray – Geo-technical & Geo-environmental Engineer
Sophia Norfolk – Technical Officer - Air Quality & Environmental Noise
Oluwadamilola Omoleye – Graduate
Anis Shahrim – Graduate
Ashish Sharma – PhD Researcher
Hazel Swinfen – Graduate Air Quality Consultant
Laura Emeline Kiat-Niouk Tsang Mang Kin – Graduate
Eirini Georgia Tsermentseli – Graduate Air Quality Scientist
Elisa Uginet – Graduate Air Quality Consultant
Georgie Watson – Environmental Scientist
Connor Webster – Geo-environmental Scientist
Muhammad Zeeshan Munawar – Environmental Engineer

Affiliate is for individuals with an interest in environmental issues but who don't work in the field, or for students on non-accredited programmes.

Andy Carling – P&E Sales Technician
Julia Evans – Graduate
Catherine Lindsay – Student
Hamish Mackay Miller – Semi-retired Community Magazine Publisher
Mahmud Mustafa – Part-time Lecturer
Helen Pearce – PhD Student
Lee Rawson-Gill – Environmental Consultant
Alex Scoular – Student
Leah Silabon-Swinney – Student
Martha Taylor – Graduate
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FEATURE

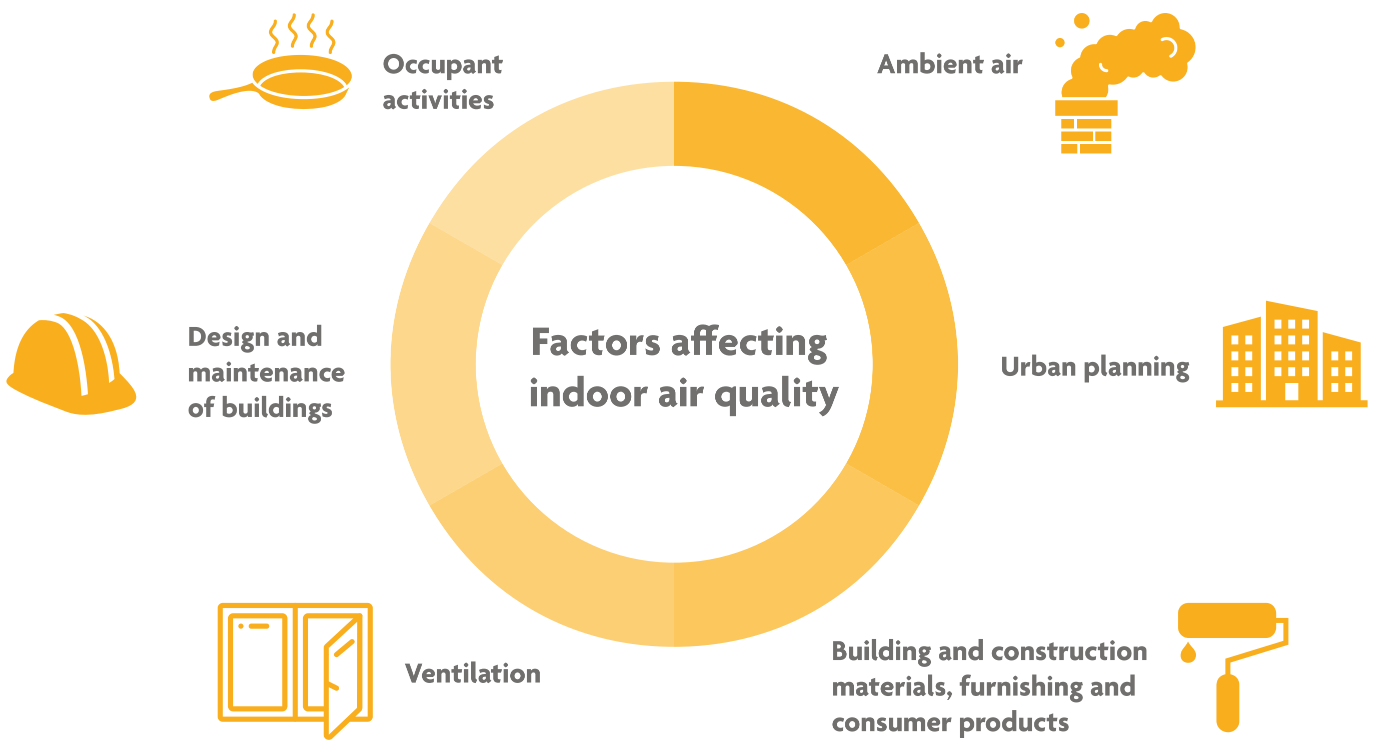
Indoor air quality and health

Sani Dimitroulopoulou gives an inside view of Public Health England's work.

People spend about 90 per cent of their time indoors, much of which is at home,[1] and therefore the indoor environment plays a key role in human health and wellbeing, from the young to the elderly. A multitude of indoor factors can affect indoor environmental quality, in other words indoor air quality, thermal comfort, ventilation, noise and lighting. Together or separately, these may all have a negative effect on occupant health and wellbeing.

Figure 1 illustrates the factors affecting indoor air quality. The ingress of ambient air polluted with emissions from traffic and industrial activities is one of the main factors, especially in the absence of indoor sources. Urban planning also plays a significant role, by defining the urban form and therefore dispersion in urban areas and the concentrations of the pollutants on building façades, which eventually penetrate indoors. Building structures are designed to provide a shelter against ambient air but cracks and gaps in the building envelope provide for the unintended ingress of air pollutants into buildings. Thus, building design and maintenance is also crucial for providing good indoor air and environmental quality.

Ventilation plays a central role in improving and maintaining good indoor air quality; however, it is not a panacea. In terms of interventions, the hierarchy is first to control emissions of air pollutants from indoor, outdoor and ground sources, including those generated by occupant activities, and then to provide adequate ventilation to maintain good indoor air quality.



▲ **Figure 1. Factors affecting indoor air quality.**

COMMON INDOOR AIR POLLUTANTS

Apart from the well-studied radon and asbestos, common indoor air pollutants, include:

- Carbon monoxide (CO), nitrogen dioxide (NO_2), particulate matter and polycyclic aromatic hydrocarbons (PAHs) generated from combustion processes (e.g. cooking, smoking, wood burning);
- Volatile and semi-volatile organic compounds (VOCs and SVOCs), including formaldehyde, emitted from building and construction materials, furnishings and consumer products; and
- Biological contaminants that are, or are produced by, living things, such as bacteria, viruses, animal dander and cat saliva, house dust, mites, and are often found in areas that provide food and moisture or water.[2,3]

Indoor air quality matters because of the health effects associated with exposure to indoor air pollutants. Recent evidence reviews published in 2020, both by the National Institute for Health and Care Excellence[4] and the Royal College of Paediatrics and Child Health[5] in collaboration with the Royal College of Physicians (RCP), highlighted the health risks associated with poor indoor air quality at home and at school. Indoor air pollutants generated from indoor sources can trigger or exacerbate asthma, irritation of the eyes, nose and throat, and other respiratory or cardiovascular conditions; they may even have carcinogenic effects. The annual burden of disease associated with poor indoor air quality has been estimated to correspond to a loss of over 2 million healthy life years in the European Union.[6] This burden is not only associated with indoor sources of pollution, but also with the ingress of polluted outdoor air used to ventilate indoor spaces.

There is growing evidence that climate change has the potential to significantly affect public health, due to mitigation policies in the housing sector. The UK introduced legislation that requires net-zero greenhouse gas emissions to be achieved by 2050.[7] The government's Clean Growth Strategy[8] aims to improve the energy efficiency of homes, which is a key objective to help reach the net-zero target.

The impact of climate change on the indoor environment and health has been investigated over the last decade.[9,10] Increasing the airtightness of dwellings in pursuit of energy efficiency may have unintended consequences, such as increasing the concentrations

of pollutants derived from indoor or ground sources and biological contamination, on top of the ingress of outdoor air indoors. Consideration of both the indoor environment and the outdoor is therefore crucial for public health protection.

PHE'S CONTRIBUTION TO GOVERNMENT WORK

Indoor air quality is an interdisciplinary field, similar to outdoor air. The UK government does not directly regulate indoor air quality but does provide guidance and other advice, which have an impact on indoor air. Relevant examples are presented in **Table 1**, which includes Public Health England (PHE)'s contribution to these activities. The Department of Health and Social Care (DHSC) intend to take responsibility for cross-government coordination of indoor air quality, with PHE supporting the indoor air quality programme.

Local authorities have a vital role to play, as they are responsible for preparing local plans, granting planning permission and working with developers. The key role of environmental health officers was emphasised in the National Institute for Health and Care Excellence (NICE) guidelines on indoor air quality at home.[4] Directors of public health, having the role of the principal adviser on all health matters to elected members and officers in the local authorities, could play a vital role in promoting and providing healthy homes with good indoor air quality.

PHE ACTIVITIES

The primary role of PHE is to develop the evidence/knowledge on the health impacts of indoor air quality as well as to identify potential interventions to inform those who are in a position to take action (including the public) and thereby improve indoor air quality. PHE has contributed to, and continues to contribute to, the work of government departments (see **Table 1**).

As the UK's primary experts on radiation protection, PHE represents a significant nationwide resource for the public, industry, education, research and medicine and is the primary resource for advice about radon in the UK.[18] PHE is recognised by the Health and Safety Executive as a Radiation Protection Adviser Body under IRR17 (Ionising Radiation Regulations 2017). PHE expertise is also acknowledged worldwide with contributions to international bodies such as the International Commission on Radiological Protection (ICRP) and the International Atomic Energy Agency (IAEA).

Table 1. Examples of government departments' responsibilities that influence indoor air quality and PHE's contribution

Government department	Examples of responsibilities relevant to indoor air quality	PHE's contribution
Ministry of Housing Communities and Local Government (MHCLG)	Housing Health and Safety Rating System (HHSRS[11]; currently under review)	PHE sits on the Project Board for the revision of HHSRS, providing expert advice, as requested.
MHCLG – The Building Regulations	Building Regulations, Energy Efficiency and Sustainability Review 2020[12] Part F – Ventilation (ADF, 2010) Part L – Conservation on fuel and power (ADL, 2013) (Parts F and L are currently under review.) Part C – Site preparation and resistance to contaminants and moisture (ADC, 2013)	PHE sat on the Advisory Board for the revision of the Building Regulations (Part L and Part F) for non-domestic buildings and dwellings, as well as overheating in new residential buildings and the development of the Future Buildings Standard.
Department for Education (DfE)	Building Bulleting BB101 – Guidance on ventilation, thermal comfort and indoor air quality in schools[13] Non-statutory guidance in support of the Building Regulations ADF and ADL	PHE was on the Advisory Group for the revision of BB101. Following PHE's recommendation, BB101 mentions, for the first time in a government document, the health-based indoor air quality guidelines by the WHO (2010).
Department for Environment, Food & Rural Affairs (Defra)	Clean Air Strategy (2019)[14]	PHE quantified the health impacts of air pollution, including its cost to the NHS and social care.
	Development of the Chemicals Strategy	PHE is engaged in the development of the strategy, by providing currently input to the scope of the strategy.
	Air Quality Expert Group's (AQEG)[15] report on indoor air quality	PHE is co-author to the AQEG report.
Cross Government Group on Gas Safety and Carbon Monoxide Awareness (COCGG)	Annual Report on carbon monoxide[16]	PHE regularly participates in the meetings of the Cross Government Group and contributes to the annual report.
PHE	Indoor air quality guidelines for selected VOCs[17]	PHE developed, for the first time in the UK, indoor air quality guidelines for selected VOCs, which will be included in the revised Building Regulations (Approved Document F) as ventilation standards.[12]

FEATURE

OTHER ORGANISATIONS

PHE also works closely with various organisations on their projects to provide scientific input, using expert knowledge and experience on indoor air quality in relation to public health. The following projects and outputs are indicative of PHE's collaboration in this area:

- The development of the NICE guidelines on indoor air quality at home,[4] which are PHE co-badged as well as the ongoing work on the development of a standard. The guidelines are addressed to local authorities, health care professionals, and the building and construction industry. Their focus is on structural interventions (in terms of ventilation and materials used in new and existing homes) as well as behavioural interventions aiming to change people's knowledge, attitude and behaviour in relation to a range of actions to reduce their exposure to indoor air pollution at home;

- PHE was co-author of the evidence-based systematic review by the Royal Colleges: *Health Effects of Indoor Air Quality on Children and Young People*;[5]

- The revision of the TM40 Guidance, *Health and wellbeing in building services*, by the Chartered Institute for Building Services Engineers (CIBSE); it aims to inform and educate building service designers and managers of the health implications of the services for which they are responsible. PHE's contribution was on indoor environmental quality issues, namely, indoor air quality, ventilation, radon, noise and lighting;[19] and

- The World Health Organization (WHO)'s project on assessing the combined exposure of children at schools to chemicals. PHE contributed to the publication on the identification of methods for sampling and analysis of chemical pollutants in indoor air,[20,21] as part of the development of a screening tool for the assessment of health risks from combined exposure to multiple chemicals in indoor air.

PHE is working to develop evidence on the factors affecting indoor air quality and related interventions. Recent work includes a review on exposure to air pollution from indoor solid fuel combustion and respiratory outcomes in children in developed countries,[22] as well as a review on the impact of portable air purifiers on indoor air quality and health.[23]

PHE is developing understanding of the factors affecting personal exposure, especially of vulnerable populations, considering both indoor and outdoor air and addressing inequalities, by co-funding and co-supervising PhD projects. Ferguson *et al.* (2020, 2021) linked systemic inequalities (i.e. low-income households) to high indoor air pollution, identifying that the key factors were:

- Housing location and ambient outdoor levels of pollution;
- Housing characteristics including ventilation properties and internal sources of pollution;
- Occupant behaviours;
- Time spent indoors; and
- Underlying health conditions.[24,25]

BOX 1. OVERVIEW OF THE UKRI NETWORKS

Indoor/Outdoor Bioaerosols Interface and Relationships Network (BioAirNet; led by Frederic Coulon, Cranfield University)

The aim of BioAirNet is to act as the leading voice for the UK bioPM (biological particulate matter) science community by taking a transdisciplinary approach to understand the complexity and connectivity among people, bioPM exposure and the indoor–outdoor continuum.

Breathing City: Future Urban Ventilation Network (FUVN; led by Catherine Noakes, University of Leeds)

The aim of Breathing City is to define a new integrated health evidenced approach to urban building design and technology innovation for vulnerable groups, by understanding how airflows transport pollutants in indoor and urban environments. IAQM is a partner of this network.

The health and equity impacts of climate change mitigation measures on indoor and outdoor air pollution exposure (HEICCAM; led by Ruth Doherty, University of Edinburgh)

The aim of HEICCAM is to strengthen evidence to optimise the health and equity impacts of changes in air pollution at the indoor–outdoor interface as we transition to a low-carbon future.

Transition Network: Optimising air quality and health benefits associated with a low-emission transport and mobility revolution in the UK; led by Suzanne Bartington, University of Birmingham)

The aim of the Transition Network is to identify, prioritise and tackle indoor and outdoor air quality challenges linked to the UK low-emission mobility revolution, bringing together academics, researchers, policymakers, business, civil society and the wider general public.

Network on Air Pollution Solutions for Vulnerable Groups (CleanAir4V; led by Christian Pfrang, University of Birmingham)

The aim of CleanAir4V is to develop innovative and cost-effective behaviour and technology interventions to reduce further air pollution exposure and improve the health of vulnerable groups and implement these interventions through policy advice, planning and business innovation.

Tackling air pollution at school (TAPAS; led by Paul Linden, University of Cambridge)

The aim of TAPAS is to bring together interdisciplinary expertise to develop the research base to design and operate healthy schools in the environment of the future.

PHE also participates in the National Institute for Health Research (NIHR) Health Protection Research Units (HPRU) on Environmental Exposures and Health, led by Imperial College London and by the University of Leicester. Among other projects, PHE leads on the development of a modelling tool to assess exposure to VOCs and SVOCs in homes.

Finally, PHE participates in the UK Research and Innovation (UKRI) multidisciplinary research networks that will address future air quality challenges at the indoor–outdoor interface, either as a coinvestigator or partner/advisor. This provides PHE with a great overview of all the networks. **Box 1** provides an overview of the six funded networks.

Interest in indoor air quality continues to grow, so it should be expected more developments in this area, both from the policy perspective and from the research community. ES

Dr Sani Dimitroulopoulou is a Principal Environmental Public Health Scientist on Indoor Environments, at Air Quality and Public Health, PHE. She is also an Honorary Senior Lecturer at The Bartlett, UCL's Faculty of the Built Environment. She works closely with colleagues from government departments (e.g. the Department for Education [DfE], MHCLG, Defra, the Department for Business, Energy and Industrial Strategy [BEIS]) and organisations (e.g. WHO, NICE, CIBSE, RCP/RCPCH) to provide expert advice on indoor air quality and health.

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FEATURE

Collaborating on assessment, design and management

Chris Rush emphasises that for the best indoor air quality coordinated input is needed at all stages of a building project.

The quality of the environment inside the buildings in which we live, play and work is governed by a host of interacting factors. The air is one part of the broader indoor environmental quality (IEQ) package and is influenced by a range of disciplines throughout the design process and then during the operation of the building. Architects, building services engineers, building managers and air quality consultants are some of the people who have a role to play in how the quality of the air we breathe in these indoor spaces is taken into account in the design and subsequent operation of a building.

FEATURE

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OVERVIEW OF THE CURRENT PROCESS

Recently, indoor air quality services have seen a surge in interest, fuelled by the health and wellbeing agenda and, more recently, the Covid-19 pandemic. The consultation on the Future Homes Standard[1] that included changes to Approved Document F1 of the Building Regulations[2] is one example of how indoor air quality is being given greater consideration in the design process. In parallel to this, there is growing recognition of the benefits of moving beyond compliance to voluntary accreditations, such as the WELL Standard.[3] In some cases, developers have assembled bespoke criteria for indoor air quality that will be of most benefit to their end users – employees, tenants or buyers, for example.

The increased focus on indoor air quality across various disciplines is evidenced in the new guidance and notes that are being released, such as the Technical Memorandum series on operational performance from the Chartered Institution of Building Services Engineers (CIBSE)[4,5] The requirement for expertise of disciplines from professional bodies such as CIBSE in working towards this common goal of improved indoor air quality means that an interdisciplinary approach is absolutely essential.

Reaching this goal is further complicated as the amount and type of specific expertise required varies with the stage of a project. For example, detailed input will be required from a competent and suitably experienced air quality professional (the air quality expert) at the start of a project, so as to identify and understand the air quality climate. Input from mechanical building services engineers is required to a greater extent during the subsequent detailed design stages when specification of filtration and how it integrates with other design considerations is required. Over the life of a project, the input for indoor air quality can be split into two high-level areas: identifying and understanding the issues, followed by adapting to and mitigating them.

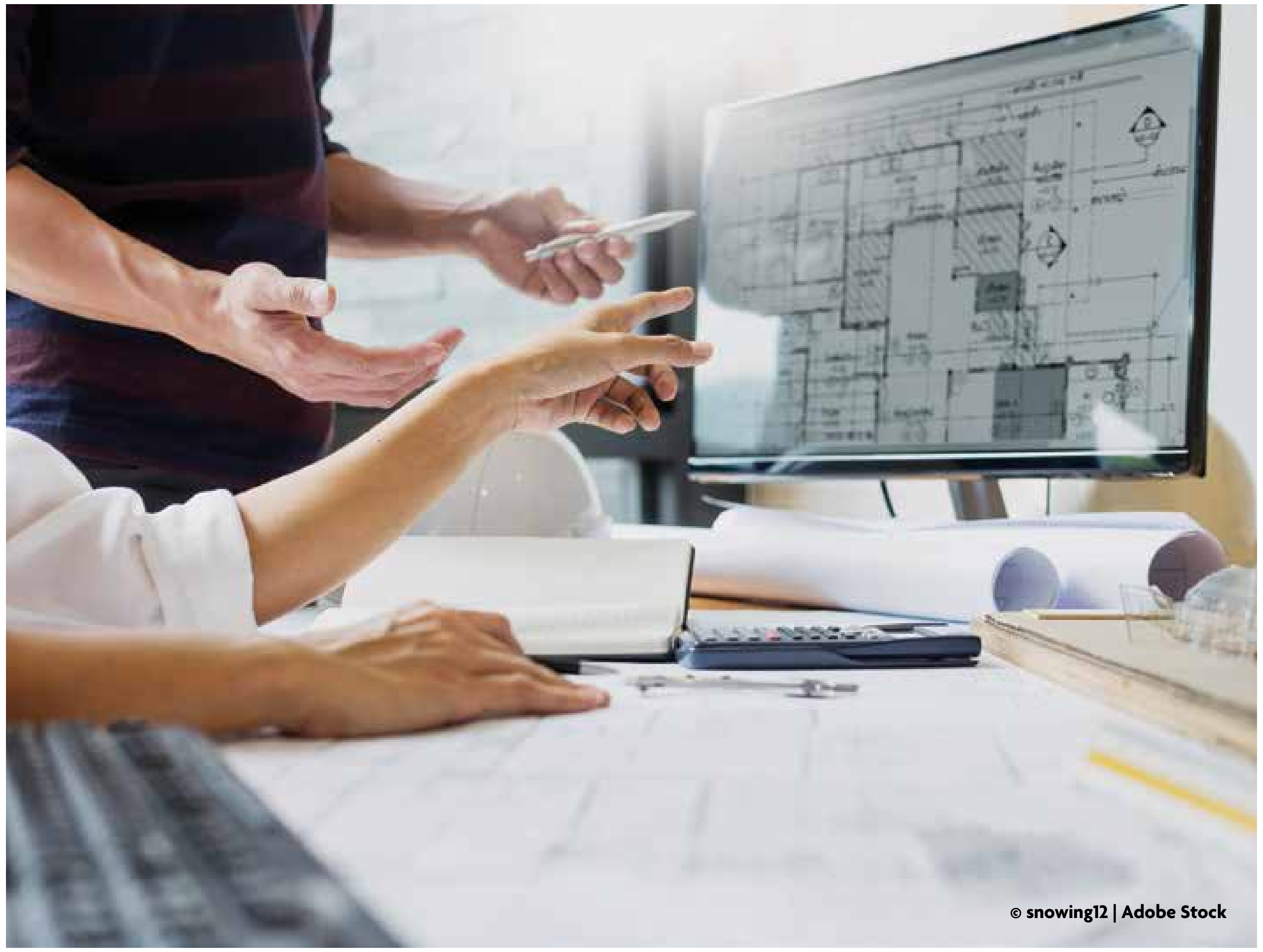
IDENTIFICATION AND UNDERSTANDING

Having a firm grasp of the issue at hand and the science of air quality is the first step in moving towards a building with the desired indoor air quality. This means that identifying and understanding both the outdoor and indoor air quality in terms of the sources of pollution as well as the pollutants' chemistry and behaviour in the environments is necessary in order to inform other professionals in the group, such as the architect and the building services engineer. This allows for effective design and subsequent operation.

To realise the full potential of air quality technical expertise, it cannot be provided in isolation. Having an appreciation of the wider policy setting, existing and upcoming guidance, legislation and regulation involved in applying this science to real-world situations and how this integrates with other disciplines is critical. The role of the air quality expert at this stage is pivotal – as well as providing the understanding of the science and its application, the air quality expert can help support the project team on how air quality guidance and policy should be applied and at which stage. Setting out options and providing a roadmap by which the building design can develop with air quality as a principal consideration is a key deliverable at this stage, and it can take the form of a project-specific air quality plan.

ADAPTATION AND MITIGATION

Buildings play a role in influencing the outdoor and indoor air quality from the design stage: the ventilation strategy includes intake locations, filtration options, air change rates etc, along with fit out and furniture specification. The role of architects and building services engineers at this stage is key in harnessing the information around the poor air quality and actioning it appropriately as part of the design. Effectively adapting the building design and applying mitigation as appropriate to address and account for the prevailing and projected quality of the air sits largely



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with the mechanical engineers and architect, and they will have been and should continue to be guided by the air quality expert.

As with the identification and understanding stage, to realise the full potential that indoor air quality can offer, adaptation and mitigation should not be progressed in isolation – and the role of the air quality expert is to support the mechanical engineer and architect in the interpretation of the impacts of design decision on air quality.

Beyond design and moving forward into the operation of a building, the principal parties responsible for indoor air quality must ensure that any embedded mitigation and the long-term responsibility transfers to the building managers and users of the building. The maintenance of the existing building services and operations must remain consistent with design parameters to ensure the long-term integrity of indoor air quality for all end users and occupants.

This is a rapidly evolving field, so during the operational phase, accreditation bodies (such as WELL) and building performance engineers help to maintain compliance with the design as well as highlighting opportunities for improvements, taking into account any recent guidance and knowledge. This expertise again helps to bolster the building management organisations and building users to ensure indoor air quality is maintained.

As part of any design and operation there is also a need for collaboration with other parties beyond those mentioned previously – such as sustainability consultants with regards to design considerations to avoid overheating and excessive energy usage. In addition to the more established parties as part of the standard design and operation team for a building, input from experts in the field of virology may be one area from which we will see growing input to improve indoor air quality as the ongoing effects of the Covid-19 pandemic continue to be felt.

THE IMPORTANCE OF COLLABORATION

The complexity of the indoor environment, with different disciplines interacting, collaborating and influencing indoor air quality outcomes, means that air quality experts are integral at the identification and understanding stage, so that the various other disciplines can build and develop designs on an informed footing.

Continued dialogue throughout the adaptation and mitigation process is key, to allow for the benefits of indoor air quality to be carried through the project and be truly realised by the end user. Having a solid scientific basis on which to build is critical and means that this expertise acts as an identifiable point of reference for a project team to help navigate the growing complexities and opportunities in this evolving topic in the later design stages. This allows for a truly robust design and operation. To fully realise the opportunity that indoor air quality offers in terms of the value to the individual user, collaboration and engagement by all parties is required throughout the processes of design, build and beyond. ES

Chris Rush is the Air Quality Group Lead at Hoare Lea, a committee member of the IAQM and a member of the CIBSE Air Quality Working Group. He is a Chartered Environmentalist and has an MSc in air pollution management and control. His diverse experience includes air quality works from initial feasibility through planning to construction and operation. He is involved in the testing and assessment of indoor air quality and furthering understanding of how building design contributes to indoor air quality in the detailed design stages and operation.

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Benzene and polycyclic aromatic hydrocarbons

Kanan Purkayastha argues for systematic human health risk assessment of inhalation exposure to these pollutants.

TECHNICAL

People are spending an increasing amount of time indoors. Some global data suggest that people now spend 80 per cent of their lifetime indoors,[1,2] and a study showed that on average people in the UK spend around 77 per cent of their time indoors.[3] We are exposed to pollutants generated outdoors that penetrate to the indoor environment and also to pollutants produced indoors – those resulting from space heating, cooking and other indoor activities, or emitted from products used indoors. So, indoor air quality is important from a public health perspective.

Benzene and its related compounds toluene and xylene are a subset of volatile organic compounds (VOCs); they represent an important group of indoor air pollutants. Indoor air is also contaminated by polycyclic aromatic hydrocarbons (PAHs), which not only come in with outdoor air, but are also produced indoors.[4]

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BENZENE

Benzene (C_6H_6) is a clear, colourless, volatile, highly flammable liquid with a characteristic odour. It evaporates rapidly at room temperature and therefore exists in air predominantly as a vapour, with residence times varying between one day and two weeks, depending on the environment, the climate and the concentration of other pollutants. So inhalation accounts for more than 95–99 per cent of the benzene exposure of the general population, whereas intake with food and water is minimal.[5]

Indoor sources of benzene include building materials and furniture, attached garages, heating and cooking systems and stored solvents. Various human activities, such as the use of materials in construction, remodelling and decorating, are major contributors to indoor benzene concentrations. Certain furnishing materials, nylon carpets and polymeric materials such as vinyl, PVC and rubber floorings may contain trace levels of benzene. It is also present in particleboard furniture, plywood, fibre glass, flooring adhesives, paints, wood panelling, caulking and paint remover.[4]

Tobacco smoke is considered one of the main indoor sources of benzene – emissions from cigarette smoking are 430–590 µg per cigarette. An increase in benzene concentrations of at least 30–70 per cent is expected when environmental tobacco smoke is present indoors, with increases to 16 µg/m^3 (300 per cent) at times.[4] In some developing countries, the problem of indoor pollution from domestic cooking is very high because of poor ventilation and the extensive use of low-efficiency stoves and biofuels. Benzene concentrations of 44–167 µg/m^3 have been found to be associated with the use of kerosene stoves.[6] Indoor concentrations are also affected by climatic conditions and outdoor levels owing to the exchange of indoor and outdoor air. Outdoor benzene concentrations are mainly due to traffic sources, petrol stations and industries such as coal, oil, natural gas, chemicals and steel, and are affected by season and meteorology.[7]

The World Health Organization (WHO) report on guidelines for indoor air quality[4] mentions that benzene is a genotoxic carcinogen in humans. The risk of toxicity from inhaled benzene would be the same whether the exposure were indoors or outdoors. Thus, the guidelines

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for benzene for indoor air should not differ from ambient (outdoor) air guidelines.

POLYCYCLIC AROMATIC HYDROCARBONS

PAHs are a large group of organic compounds with two or more fused benzene rings. Low-molecular-weight PAHs (two and three rings) occur in the atmosphere predominantly in the vapour phase, whereas multi-ringed PAHs (five rings or more) are largely bound to particles. Particle-bound PAHs are considered to be very hazardous to human health. In the atmosphere, PAHs may be subject to direct photolysis, although adsorption to particulates can retard this process.[8] In view of the difficulties in developing guidelines for PAH mixtures, one of them, benzo[*a*]pyrene (B[*a*]P), is often used as a marker for total exposure to carcinogenic PAHs, as the contribution of B[*a*]P to the total carcinogenic potential is high.[4]

Indoor sources of PAHs include emissions from smoking, cooking, domestic heating with fuel stoves and open fireplaces, and incense and candle burning. Globally, cooking and heating with solid fuels such as dung, wood, agricultural residues or coal, especially in unvented or flueless stoves, are likely to be the largest source of indoor air pollution, owing to the high level of use in developing countries.[4] These sources mainly produce two- or three-ring PAHs. Outdoor air may contribute significantly to the indoor PAHs, especially those with four or more rings.[4] Emissions from traffic have been found to be the main outdoor source for the indoor PAH concentrations at urban and suburban locations in many industrialised countries.

Humans are exposed to PAH through inhalation of air and resuspended soil and dust, consumption of food and water, and dermal contact with soil and dust.[9] However, while soil contact generally occurs outdoors and food and water consumption is usually indoors, inhalation occurs both indoors and outdoors. As people spend most of their lifetime indoors, indoor air would be the most relevant source contributing to the inhalation route.[4]

HUMAN HEALTH RISK: NON CARCINOGENIC

Non-carcinogenic health risk (NCHR) assessment for indoor air quality can be evaluated in terms of the threshold mechanisms of toxic effects. Risk can be quantified by calculating a hazard index (HI).[10]

$HI = C_{exp}/RfC$

where C_{exp} is the inhalation exposure level of a given air toxic species and RfC is the threshold dose of a species. HI = <1 implies that such an exposure is unlikely to be a risk of toxicity or a health hazard.[10]

It is necessary to compare the indoor concentrations of benzene to the reference concentration or threshold dose; the reference concentration is the maximum acceptable dose of a toxic substance and the threshold dose follows a margin-of-safety approach. RfCs for chronic inhalation exposure vary from country to country: the RfC for benzene is 110 µg/m³ in China and 30 µg/m³ in the USA.[11] However, WHO suggests that there is no known exposure threshold for the risks of benzene exposure.[4] Therefore, it is important to reduce indoor exposure levels to the lowest possible.

HEALTH RISK ASSESSMENT: CARCINOGENIC

Carcinogenic health risk (CHR) by inhalation exposure to benzene and B[*a*]P can originate from both outdoor and indoor microenvironments, which include, but are not limited to home, workplace and transport. For a health risk assessment, personal concentrations of the species in the indoor environment are necessary, and these can be determined by two methods. The first is personal exposure measurement, which requires access to the individual – this brings with it ethical issues of collecting data from an individual.

The second method is computational modelling to simulate human activity and the indoor air pollution of the species under investigation using the Monte Carlo (MC) method.[12] For example, the model population would be males and females of a certain age group who live and work in a building. The distribution of indoor personal concentrations of benzene and B[*a*]P can be developed with the MC simulation technique using MATLAB software (for example) for 10,000 trials. The next steps would be to calculate the cancer risks associated with the developed exposure to benzene and B[*a*]P using the MC simulation as mentioned above, and then the cancer risks would be compared risk to levels of risk reported in the literature. The indoor personal exposure (E) to benzene and B[*a*]P can be calculated using the following equation:

$$E = \sum_{i=1}^{N} (C_{i,home} \times T_{i,home} + C_{i,office} \times T_{i,office}) / T$$

where C_i is the concentration of benzene or B[*a*]P for ith person at home or at work; T_i is the time that ith person spends at home or at work; and T is the total exposure time in all environments (indoor and outdoor).

The cancer risk can be estimated by multiplying the personal concentration (E) calculated above by the inhalation cancer risk value, which represents the excess number of cases per million people expected to develop cancer following lifetime exposure (70 years) to 1 µg/m³ of a given species.[10] According to WHO, the corresponding concentrations for lifetime exposure to B[*a*]P producing excess lifetime cancer risks of 1/10,000, 1/100,000 and 1/1,000,000 are approximately 1.2, 0.12 and 0.012 ng/m³, respectively.[4]

FURTHER WORK

The issue of indoor air pollution has been largely overshadowed by the attention focused on outdoor air pollution related to industrial and transport emissions. There is a need for more information about levels of exposure to indoor air pollutants, as well as the risks posed by long-term exposure. For example, there are large knowledge gaps in the association between indoor exposure to benzene or PAHs and public health risk. Any measurement and modelling uncertainty should be taken into account in any risk assessment. Any cumulative risk assessment needs to consider the detailed characterisation of sources of pollutants.

There are also emerging pollutants, such as the carbon nanotubes used in lubricants and the polyurethane used in home furnishings, that require more attention. The creation of a database relevant to the UK for indoor air quality reference concentrations could play an important part in human health risk assessment through inhalation exposure in indoor air. There is clearly a research need for such a database.

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ES

Dr Kanan Purkayastha, PhD, MSc, MSc, CSci, CChem, MIAQM, FIEnvSc, Fellow RSS, FRSA, spent the last 38 years of his professional career in industry, academia and government organisations. His PhD from the University of Bristol was on theoretical and atmospheric chemistry, with special focus on OH reactivity and urban air pollution study. Recently he taught chemistry and environmental sciences for the University of the West of England's environmental health degree programme at University Centre Weston. His concurrent activities involved working for different local government organisations and as a climate reality leader for climate reality project chaired by Al Gore; he also wrote scientific columns for many newspapers and magazines.

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FEATURE

Outdoor air pollution: its ingress and impact on indoor environments

Vina Kukadia provides an overview of the complex subject of outdoor–indoor air quality.

Fresh air for the ventilation of buildings is essential in order to provide acceptable indoor environments in terms of occupant respiration, good indoor air quality, thermal comfort and for preventing condensation within the structure and hence mould growth. To achieve this, the UK Building Regulations stipulate minimum ventilation requirements: for example, for office buildings, the Approved Document Part F of the Building Regulations for England specifies a minimum fresh air requirement of 10 L/s/person.[1] This is based on the assumption that outdoor air is 'fresh' – largely free from contaminants and nuisance substances.

However, in practice, urban and city buildings are often exposed to contaminated air from common outdoor pollutant sources,[2,3] including: traffic; combustion plant (e.g., boiler flues, combined heat and power and diesel-powered standby generators); industrial processes (e.g. incinerators and fume cupboards); ventilation discharges; and construction and demolition activities.[4] In addition, other potential outdoor sources include fires, vaporisation of spillages from chemical storage tanks and ammonia chillers, and chemical, biological and radiological releases.[5] In the UK, news reports state that in many areas air quality standards for nitrogen dioxide (NO_2) and fine particles are regularly breached and that they adversely impact health.[6,7,8] The European Court of Justice also recently stated that the UK has 'systematically and persistently' breached air pollution limits for over a decade, and that 'levels of nitrogen dioxide, mostly from diesel vehicles, remain illegally high in 75% of urban areas, including Greater London and Greater Manchester'.[9]

Despite ongoing substantial financial investment in air pollution emission controls through, for example, the Clean Air Fund,[10] the Mayor's Air Quality Fund[11] and considerable efforts to implement various innovative and targeted measures to reduce air pollution levels throughout the UK, it could be many years before there are measurable improvements in outdoor air quality. Thus, since people spend typically 90 per cent or more of their time indoors,[12] the contribution of indoor exposure to the outdoor pollutants (as well as those generated indoors) is a major part of their overall pollutant exposure. The challenge, therefore, is to design buildings to reduce pollutant ingress, while at the same time providing optimum ventilation with good-quality outdoor air, resulting in improved indoor air quality for occupant respiration, health, comfort, wellbeing and productivity.

Here, a brief overview is given of the factors that affect air pollutant ingress, some results from building monitoring studies, typical case studies of how inappropriate design of buildings can adversely impact indoor air quality, and a brief summary of current guidance.

FACTORS AFFECTING INGRESS OF POLLUTANTS

Numerous factors affect pollutant ingress into buildings and the resulting indoor air quality, including:[3,5]

- Pollutant source, concentration and location;
- Local topography and surrounding structures;
- Meteorological conditions, such as wind speed and direction;
- Local pollutant dispersion processes;
- Building airtightness and ventilation strategy;
- Pollutant physical properties and depletion mechanisms; and
- Occupant behaviour and activity.

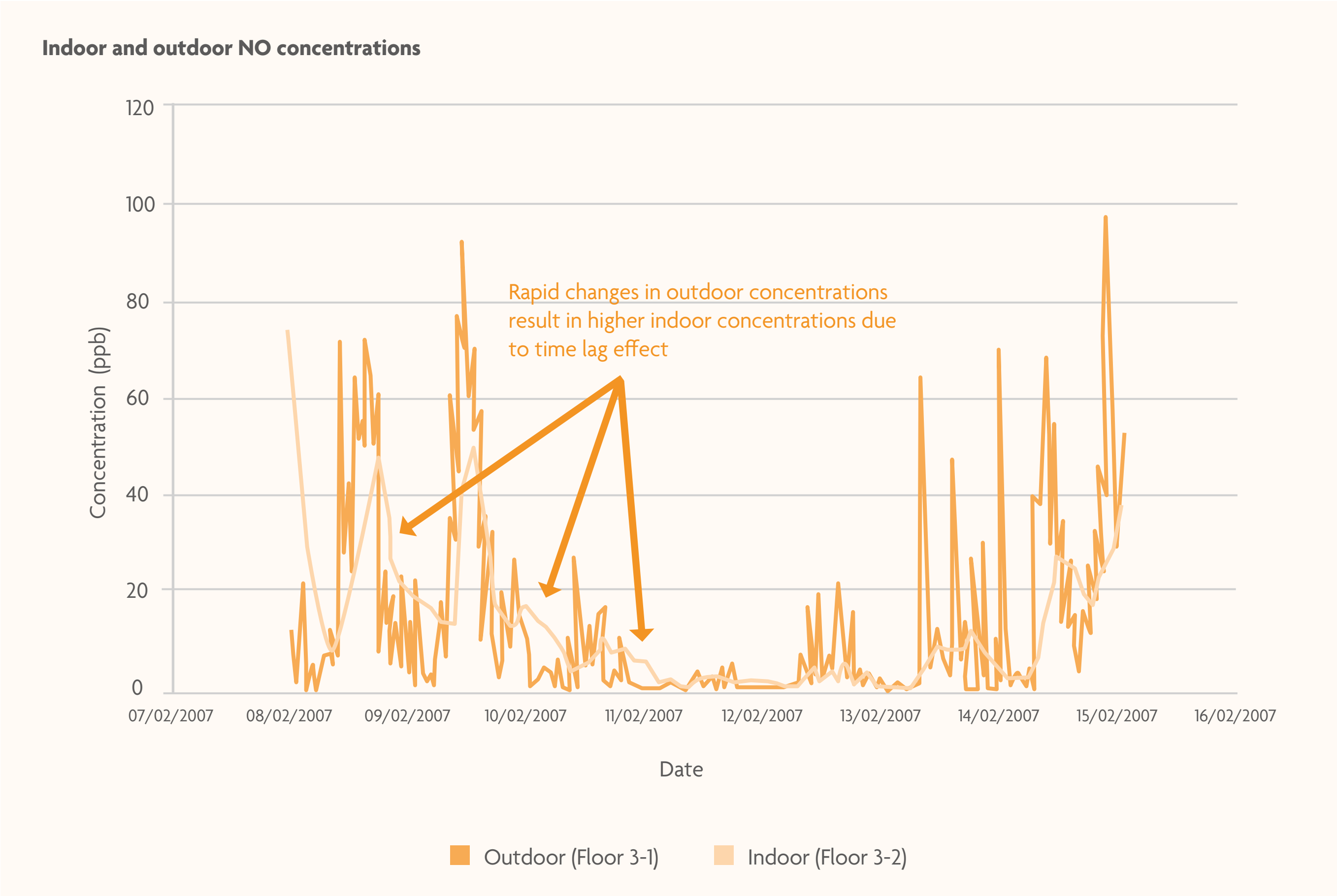
The whole process of outdoor pollutants dispersing through the atmosphere and ingressing through the building fabric and ventilation system, then their subsequent behaviour within buildings and impact on indoor air quality is very complex. Though there has been some *ad hoc* research over the past 25 years[2,3,5,13–18] there is still a lack of adequate research and hence detailed understanding of outdoor–indoor pollutant interactions and guidance for reducing the ingress of outdoor pollutants. This has often led to inappropriately designed buildings, with, for example, cross-contamination issues between ventilation exhausts and inlets, resulting in poor indoor air quality.[2]

IMPACT OF OUTDOOR POLLUTANTS INDOORS

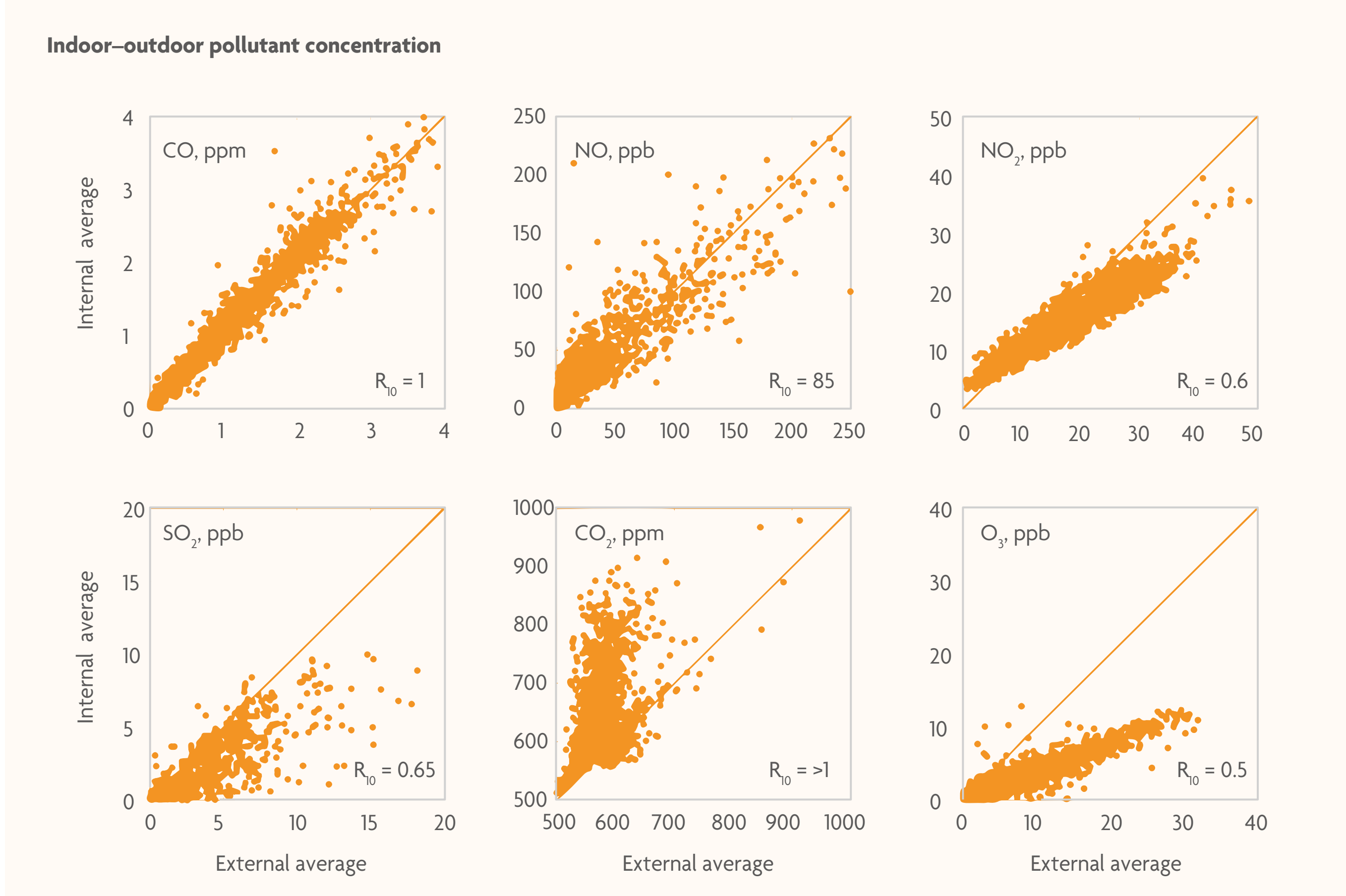
Figure 1 shows typical results obtained from one of the most comprehensive indoor–outdoor building monitoring studies carried out to date; the location was a large urban office/workshop building monitored over 12 months in central London.[17] The study is representative of many other smaller ones carried out over the years and shows that outdoor pollutant concentrations, such as nitric oxide (NO) fluctuate rapidly and are, on average, greater than those measured indoors. Further, indoor concentrations generally follow the trends of those present outdoors, with some damping effect and a time lag that is primarily dependent on the building ventilation rate and is typically of the order of 30 minutes to an hour. Rapid decreases in outdoor concentrations often result in indoor concentrations that are higher than those outdoors due to this time lag. For indoor concentrations, the high peaks in the external concentrations are attenuated by the building fabric and the transient peak concentrations measured externally are reduced.

Figure 2 shows results from monitoring studies carried out over six months in a building located in Manchester next to the busy A57 (M) flyover and the A6 motorway.[13] It can be seen that for the reactive pollutants NO_2, sulphur dioxide (SO_2) and ozone (O_3), the indoor–outdoor concentration ratios (R_{IO}) are <1. As expected, for carbon dioxide (CO_2) R_{IO} >1 as this is related to the number of occupants in the space; the greater the number of people, the greater will be the indoor CO_2 concentration. For the unreactive pollutants, carbon monoxide (CO) and NO, R_{IO} was close to 1. These results indicate that despite the attenuating effect of the building fabric, the resulting indoor pollutant concentrations can still typically be 50–100 per cent of those experienced outdoors, indicating that they need to be carefully considered when designing buildings for good indoor air quality.

Figure 3 shows NO_2 concentrations measured outside and inside offices in naturally ventilated and mechanically ventilated buildings next to each other on a major busy road in Birmingham.[2] As expected, external NO_2 concentrations were higher than those indoors, with the latter following the external NO_2 trends. The high concentration peaks in the outdoor environment were attenuated by the building fabric and, therefore, not seen indoors. The most prominent feature was the exceptionally high level of NO_2 concentrations in the mechanically ventilated building from about 06:00 to 12:30, the period between the start-up and shut-down of the building's ventilation system. This result was due to NO_2 discharges from boiler plant nearby being drawn into the air handling unit (AHU) at the high level of the mechanically ventilated building.

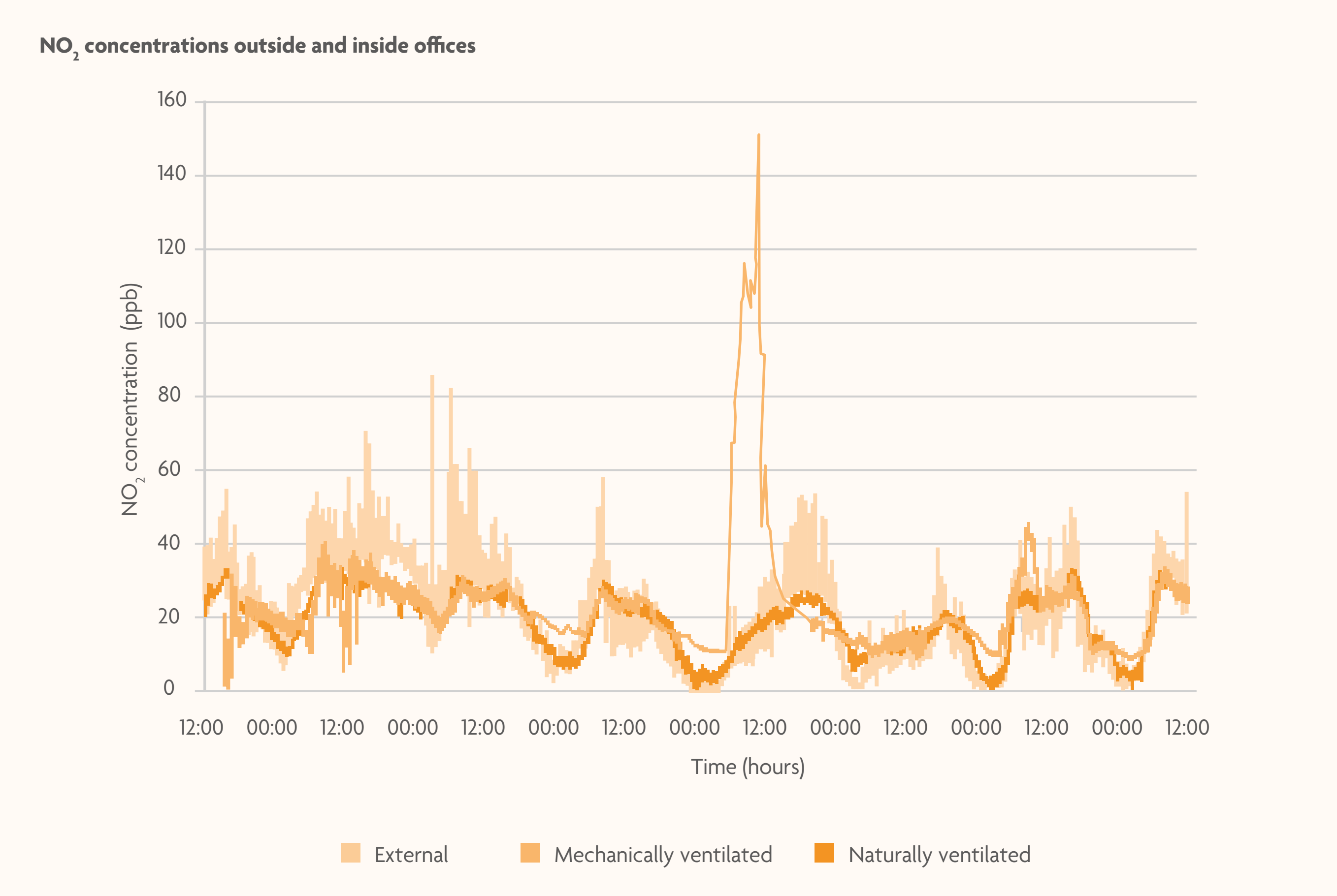


▲ **Figure 1. Changes in indoor and outdoor NO concentrations for a large urban office/workshop building in central London.[17]**



▲ **Figure 2. Indoor–outdoor pollutant concentration ratios measured in a building in Manchester.[13]**

FEATURE



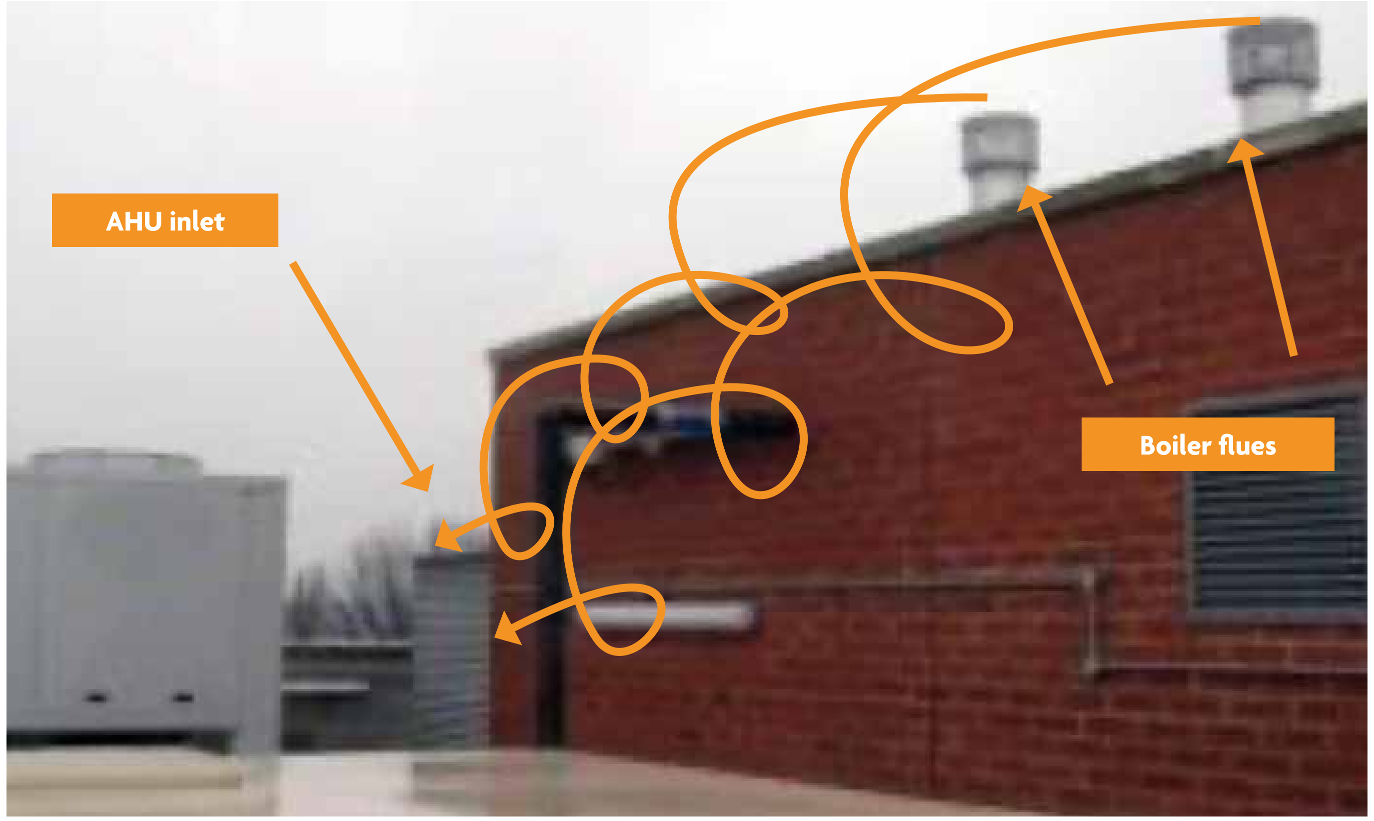
▲ **Figure 3. Changes in NO_2 concentrations in adjacent naturally and mechanically ventilated buildings located on a major road in Birmingham.[2]**

Figure 4 shows a typical example of inappropriately sited gas boiler flues in relation to the AHU.[19] Under certain wind conditions, pollutant discharges from the flues downwashed and ingressed into the building via the AHU, thus affecting the indoor air quality. These findings show the real importance of locating ventilation inlets strategically away from high-level pollutant sources.

Figure 5 shows another example of an inappropriately designed discharge, this time from a standby diesel generator servicing a hospital. Its pollutants discharge horizontally at about 3 m above the ground. These adversely affected pedestrians nearby and also ingressed into the adjacent hospital buildings through open doors and windows, and hence impacted hospital staff, patients and their visitors. In this case, vertical discharge stacks were required that were tall enough to ensure discharges cleared the surrounding buildings and prevented ingress.[20]

Figure 6 (a) shows a day-care centre located on a busy high street in London; its facades are sealed and windows unopenable to prevent ingress of traffic pollution. **Figure 6 (b)** shows ventilation inlets, used to provide fresh air for the building, located in the courtyard on the other side of the centre.[3] However, the courtyard was later converted into a car park, which completely defeated the original objective of the ventilation strategy. During the morning and evening peak times, when the cars arrived and left the car park, studies showed that car exhaust fumes entered the building through these inlets. Wind tunnel studies have shown that as aspect ratios of courtyards increase (the ratio of building height to the horizontal distance between buildings), the pollutant concentration also increases and dispersing pollutants out of courtyards is difficult.[21] Hence, ventilation inlets located in courtyards and enclosed spaces are not generally recommended.

These case studies, therefore, show that local outdoor pollutant sources of all types and at all heights and locations need to be considered and ventilation inlets need to be sited with care. Guidance by Kukadia and Hall (2011),[3] based on information at the time that it was produced, gives a step-by-step approach to designing buildings, taking into account all relevant local sources of air pollution to reduce their ingress and hence achieve buildings with better indoor air quality.

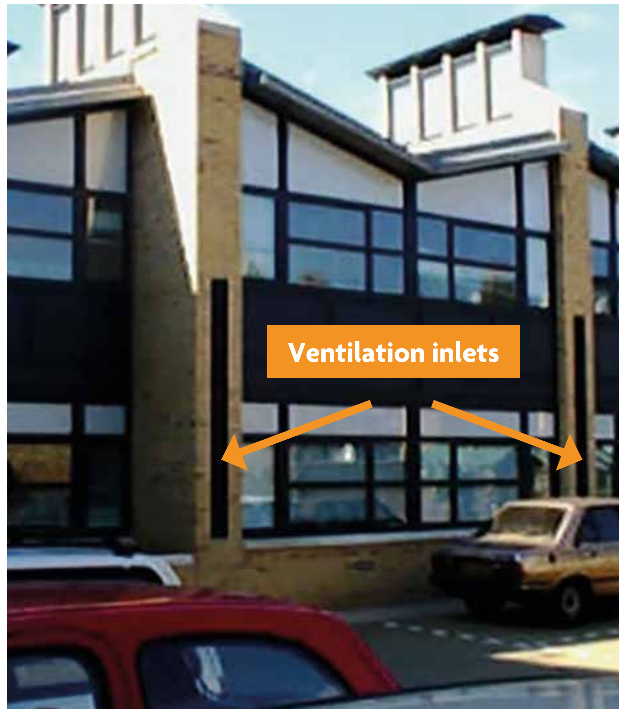


▲ **Figure 4. Discharges from boiler flues at low height ingressing into the building AHU.[19] (© BRE)**

▲ **Figure 5. Emissions from a hospital's back-up diesel generator discharging horizontally.[19] (Low-resolution screenshot of video footage; © BRE)**

FEATURE

▲ **Figure 6 (a). Day-care centre with sealed facades, located on a busy high street in London.[3] (© BRE)**



▲ **Figure 6 (b). Ventilation inlets in the courtyard converted in to a carpark.[3] (© BRE)**

CURRENT GUIDANCE

Current guidance on reducing the ingress of outdoor pollution covers the following main strategies.[1,3,4,5,22,23]

Increasing building airtightness. Adventitious gaps and cracks in the building envelope contribute to the air permeability of the building and the subsequent uncontrolled infiltration of outdoor polluted air. The Approved Document Part L of the Building Regulations in England requires that the air permeability should not exceed a limiting or worst-allowable value of $10\ m^3/(h\cdot m^2)$ at 50 Pa.[24] Therefore, sealing the building envelope and increasing its airtightness will help to reduce air pollution ingress.

Ventilation air inlet position and control. Current guidance recommends:

- Siting ventilation inlets away from the direct impact of local pollutant sources, including roads and ventilation exhausts;
- Ventilation inlets being sited in courtyards and enclosed spaces only if there are no pollutant discharges into them; and
- Closing ventilation air inlets for short periods during peak hours of high external pollutant concentrations and using outdoor air from a less-polluted side of the building or using fully recirculated air within the building. The atria of certain buildings may be used temporarily as a source of 'fresh' air to provide ventilation for occupants through recirculation; this is known as the `air quality reservoir effect'.

Filtration. With mechanical systems, ventilation air can be relatively easily treated using particle filters or active carbon filtration, though the performance of such plant can be variable.[5] A combination of these two methods may offer the best option for overall treatment of polluted incoming air. However, there can be significant capital and ongoing maintenance costs for such systems, which need to be carefully thought out before implementation.

Green infrastructure. Though research is still ongoing, initial guidance on the use of green walls, for example, as a barrier between local outdoor pollution sources, such as traffic, and buildings is also now an option for controlling the ingress of outdoor pollution into buildings. Guidance by Kumar *et al.* (2019), summarises best practice regarding the implementation of green infrastructure for improved urban air quality and reduced human exposure to air pollution, and may be used for this purpose.[25]

SUMMARY

It is important to reduce the ingress of outdoor pollutants into buildings to ensure good indoor air quality. However, designing buildings effectively to achieve this is challenging, since it is a complex subject area with numerous factors that need to be considered, including local outdoor pollutant sources, the nature of the surroundings, and dispersion and building ventilation processes. At present, knowledge, understanding and guidance in this area is limited. Therefore greater research and in-depth studies are required through interactive collaboration between the different disciplines to really understand outdoor–indoor interactions and ventilation, with a view to providing healthy indoor air in an integrated manner.

There is now national recognition and greater awareness of the importance of the problem of outdoor air pollution ingressing into indoor environments. Research funded by the UK Research and Innovation (UKRI) Strategic Priorities Fund (SPF) Clean Air Programme is ongoing to 'proactively tackle new and emerging air quality challenges' related to the 'importance of indoor/outdoor interface, exposure patterns and impact on vulnerable groups'.[26]

Until more formal up-to-date UK guidance is available, it is important to use existing guidance, together with any additional information that may be available through new research, to help improve air quality in indoor environments and thus the health, wellbeing, comfort and productivity of building occupants. ES

Dr Vina Kukadia is an independent consultant and Research Development Manager at the Global Centre for Clean Air Research at the University of Surrey. She has 30 years' experience in air pollution dispersion, ingress into buildings, ventilation and indoor air quality. She has produced over 250 publications, including practical guidance and confidential, technical client reports. In 1998, Vina was awarded the John Edward Worth Medal from the Royal Society for the Promotion of Health in relation to her work on indoor–outdoor air pollution.

✉ vina.kukadia@gmail.com

✉ v.kukadia@surrey.ac.uk

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OPINION

Back to the office

Carl Hawkings talks to industrial hygienist **Marcus Lurvink** about the indoor air quality considerations that enable a safer post-pandemic return to the workplace.

What were the main challenges you had in mind when thinking about people returning to their places of work?

The key elements involved redesigning workspaces, offices, control rooms and other locations for people flows and social distancing. This included non-flexible workstations (our company previously used hot-desking extensively), changes to heating, ventilation and air conditioning (HVAC) systems, and enhanced cleaning of the workplace. We developed a full return-to-office protocol covering all these matters to guide office managers on how to bring people back safely to their workplace. Social distancing rules vary across the world, e.g. 1.5 m in some European Union countries and 2 m in the UK, so this was also a consideration. The most important house rules we adopted from the World Health Organization (WHO), the Center for Disease Control (CDC) in the USA and in-country guidance was not to come into the office if experiencing any symptoms of Covid-19 and to get tested as soon as possible.

As industrial hygienists, we are used to advising on personal protective equipment (PPE), which is largely designed to protect the wearer. For managing Covid risk, we have expanded this to consider how PPE protects others, not just the wearer. Face coverings that are purely to minimise virus spread from the wearer are not technically considered to be PPE in our line of business, because they are not specifically designed to protect the wearer. Where social distancing is not possible (e.g. in certain work locations) we designed extra barriers such as face coverings, visors and screens to protect people.

In association with our company office managers we identified areas from which people should generally be excluded (e.g. areas close to HVAC extraction vents) as well as designing one-way pedestrian systems to help to keep people separate.

Throughout the pandemic, some types of work were not possible to do from home, so we developed ways to keep people safe while in the office. Also, some workers were not able to set up an adequate workstation at home, so they were supported with advice and additional equipment (e.g. external laptop screens, keyboards) and, in some cases, allowed to come into the office.

OPINION


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Could you tell us more about HVAC, air recirculation and filtration?

At the beginning of the pandemic we were very wary of airborne sources of the virus, because the most important infection route is direct contact with airborne droplets containing the virus. Company and industry guidance was not to use HVAC systems where air was recirculated. Cross-plate/heat exchangers, where there is no direct physical connection between spaces, were considered safe and left in use. Systems that allow cross-flow of air (rotary wheels/fans) can pass contaminated air between locations when not sealed properly. As new insights became available, recirculating systems were deemed lower risk than originally thought, so they have been reintroduced, especially with the warmer summer weather, which brings a risk of overheating in some of our buildings.

In some cases, upgrading of centralised HVAC filtering units was considered, in order to ensure that pollutants, particularly viruses, were effectively removed. In practice, it was not always possible to optimise this due to pressure drops caused by high-efficiency (HEPA-type) filters – the recommended filter types (F8) can reduce ventilation rates and worsen indoor air quality. So either the whole set-up of the system was modified and/or upgraded or lower filtration rates were accepted. In these situations, other options to improve indoor air quality (e.g. reducing or removing sources) or adding stand-alone filtration equipment were considered. Local stand-alone filtration units have so far not been necessary, but we have them available if needed.

We could also use lamps that generate ultraviolet C (UV-C) radiation to kill pathogens (bacteria/viruses) either as air treatment (drawing air through a beam in an HVAC system, for example) or by shining UV-C onto surfaces. I am aware of some organisations using UV-C lamps mounted on robots that move around to sterilise areas when no one is around, since UV-C is damaging to eyesight. These systems are still being investigated to ensure that they are safe and effective. It must be borne in mind that UV sterilisation has no residual effect, i.e. surfaces may quickly become recontaminated.

I have heard you use CO_2 as a surrogate for overall indoor air quality. Could you tell me more?

We use CO_2 as a marker pollutant for indoor air quality. CO_2 measurement is cost-effective and largely relates to human occupancy rates, making it a quick and easy surrogate for actually measuring ventilation rates, which is not straightforward. Outside air contains about 400 parts per million by volume (ppmv) and in an inadequately ventilated building CO_2 can easily build up to >3,000 ppmv, which is unpleasant to experience, causes drowsiness and can affect the ability to concentrate or work safely. This may be less of an issue with lower occupancy (as less CO_2 will be produced).

You mentioned that hand sanitiser was a special consideration for you. What are the issues around that and general cleaning?

Ethanol is a primary constituent of disinfectants, including most hand sanitisers, but since under Dutch law ethanol is classed as a carcinogen, alternatives are needed. One is isopropanol/2-propanol (C_3H_8O), which is not classified as a carcinogen in the Netherlands, although it is flammable. Alcohol-based products can also dry the skin and affect people with particular sensitivities, hence over-use should be avoided and hand washing with soap and water is preferable.

Our offices are now used less than before the pandemic, but cleaning is more intense. Cleaning materials are a source of indoor air pollution and many of the compounds are toxic at some levels. We are keeping them under review as new products become available, and we are looking into using lower-toxicity, low-emission products.

When building new offices or refurbishing existing offices, have you thought about choice of materials in terms of indoor air quality?

We have refurbished many of our offices over the past decade and have largely focused on trying to reduce the emissions of formaldehyde, as this is a carcinogen and can be given off from building materials such as chipboard. Many paints (especially water-based paints) do not list formaldehyde as a constituent since it is not added in the manufacturing process, but when they are applied to surfaces a reaction can take place that releases formaldehyde. Many volatile organic chemicals (VOCs) in building materials are also an issue for us.

What other topics did you discuss with the building management and security departments that helped you to design your safe back-to-work programme

Having openable windows can interfere with the HVAC system and increase the risk of dropped objects or falling incidents. Occupied rooms/offices are positively pressurised/over-pressured (i.e. at a higher-than-ambient pressure) and corridors are negatively pressurised/under-pressured (i.e. at a lower-than-ambient pressure) to ensure adequate and controlled air flow from rooms to corridors. This is disrupted by an open window. Open windows can also disturb other occupants with

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draughts and noise, and so are not usually appropriate in an open-plan office. Besides, they can allow the ingress of outdoor air pollution and, in hot countries, may lead to unacceptable temperature increases. In practice, it is important to balance these environmental and safety considerations.

We have, over recent years, removed many printers and photocopiers from occupied office spaces. This not only reduces their usage to some extent (when they are not so close to the user), but also allows us to site them more thoughtfully in relation to human exposure to emissions: in corridors, directly underneath the air extraction vents of HVAC systems. This allows the removal of the air pollutants that they generate (i.e. fine particles from toner and paper handling units, ozone from the fusers). The corridors being negatively pressurised means these pollutants do not migrate into occupied offices.

We are using technology (e.g. drones and remote cameras) to reduce human-to-human interactions in activities such as site inspections. This not only decreases the potential to spread infection, but also results in a lower safety risk as fewer people are on site.

Aside from the Covid pandemic, what other indoor air quality issues do you think about?

Having fewer people in the office was a trend even before Covid, and the pandemic simply accelerated it. We do not expect a full return to the office, and we are currently limiting occupancy to 50 per cent of pre-Covid levels. Our IT is very well set up for home working and many of our employees prefer it at the moment.

We do not yet foresee reducing office space, although there are financial pressures to do so. Instead, we are focusing our efforts on flexible use, potentially allowing other companies to occupy our vacant areas.

Thinking more about your personal life, commute to and from work etc, does your knowledge and experience as an industrial hygienist affect how you think about indoor air quality?

As an industrial hygienist I cannot help but look at my life in relation to my work – I am 'professionally deformed' as we say in the Netherlands! I am always thinking about indoor air quality on public transport, for example – before Covid I frequently travelled on public transport, and I often had colds and flu. During Covid I have not had them as often.

I foresee masks will be used more in the future in public spaces, to protect the wearer as well as others, including non-wearers. The feeling of being vulnerable in public places is encouraging people to wear masks. This has been common in certain cultures for some time, although less so currently in the Netherlands. I apply risk-based thinking and do not focus too much on the hazard alone. We have to protect ourselves from dangerous substances but on the other hand stimulate our immune systems, so we don't want to live in a completely sterile world.

Any other final thoughts on indoor air quality?

Indoor air quality is a very broad topic. Ventilation is an important way of minimising the build-up of pollutants, but there are other hazards that are less or not at all influenced by ventilation. There are risks from legionella bacteria when air is being humidified by an office HVAC, or from contaminated droplets in wash-rooms, or from exposure to asbestos when construction/demolition activities take place and asbestos fibres are present in building materials. But those are not influenced by Covid, just a reminder of risks at the office in respect of air quality. ES

Marcus Lurvink works for a large multinational company based in the Netherlands. As an industrial hygienist he specialises in human exposure to chemical, physical and biological factors. He is professionally accredited in the Netherlands by Hobéon SKO, which is recognised by the International Occupational Hygiene Association (IOHA). In his former role, Marcus worked on quality assessments of HVAC systems.

Carl Hawkings worked in the air quality and impact assessment teams at ERM for 15 years and then joined ADM Ltd, where he has worked in many sectors, including oil and gas, cement, incineration, foodstuffs, power and transport infrastructure. Most of his work in the past decade has been managing environmental impact assessments overseas, but he was acting head of the air quality team at ARUP for a while. He has been a Committee Member of IAQM for nearly 3 years and has worked on a variety of IAQM working groups and sub-committees, including the indoor air quality working group.

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Editor	Danielle Kopecky
Guest editors	Christine McHugh, Claire Holman
Subeditor	Caroline Beattie carolinebeattie.editorial@outlook.com
Designer	Kate Saker katesaker.com
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