Institute of Air Quality Management

Indoor Air Quality Guidance: Assessment, Monitoring, Modelling and Mitigation

Version 1.0

September 2021

Contents

Acknowledgements

Disclaimer: This Guidance was produced as a result of the voluntary contributions of the members of IAQM's Indoor Air Quality Sub Committee Working Group. This Guidance represents the collective view of the IAQM and not necessarily those of individual members or those of External Reviewers. All have commented in their personal capacities and not necessarily on behalf of the organisations listed below.

IAQM thanks Arup, Cundall, Hoare Lea and WSP for permission to use the case studies in Appendices E and H.

Chair of the Working Group
Dr Claire Holman (Air Pollution Services)

Co-editors
Carl Hawkings (ADM Ltd)
Dr Christine McHugh (Keane & Gray)

Members of the Working Group
Roger Barrowcliffe (Clear Air Thinking)
Ethny Childs (Secretary, IES)
Emma Gibbons (UCL)
Kieran Laxen (Air Pollution Services)
Oliver Puddle (DustScanAQ)
Chris Rush (Hoare Lea)
Peter Walsh (WSP)

External reviewers
Dr Hywel Davies (CIBSE)
Dr Sani Dimitroulopoulou (Public Health England)
Dr Vina Kukadia (University of Surrey)
Dr Gráinne McGill (University of Strathclyde)
Dzhordzhio Naldzhiev (University College London)
Dr Clive Shrubsole (University College London)
Dr Marcella Ucci (University College London)
Stuart Upton (Building Research Establishment)
Edwin Wealend (Cundall)

CIBSE
IAQM acknowledges the contributions made to this Guidance by CIBSE members. This guidance is endorsed by CIBSE as a useful contribution to improving indoor air quality.

Member consultation
The IAQM would like to extend thanks to all those who provided comments during the member consultation. These comments played a key role in the development of this document. Consultation responses can be accessed on the IAQM website.

The Institute of Air Quality Management (IAQM): IAQM aims to be the authoritative voice for air quality by maintaining, enhancing and promoting the highest standards of working practices in the field and for the professional development of those who undertake this work. Membership of IAQM is mainly drawn from practising air quality professionals working within the fields of air quality science, air quality assessment and air quality management.

Graphic Design: Danielle Kopecky

Suggested citation: IAQM (2021). *Indoor Air Quality Guidance: Assessment, Monitoring, Modelling and Mitigation (version 1.0).* Institute of Air Quality Management, London.

Contact: IAQM
c/o Institution of Environmental Sciences
6-8 Great Eastern Street, London
EC2A 3NT
T: +44 (0)20 3862 7484
E: info@iaqm.co.uk

Date: September 2021

Cover image: Clockwise from top left: © zinkevych | Adobe Stock, © Konstantin Yuganov | Adobe Stock, © Monkey Business | Adobe Stock, © Pixel-Shot | Adobe Stock

1. Introduction

1.1. Purpose of this Guidance

1.1.1. This Guidance has been produced by the Institute of Air Quality Management (IAQM) to assist its members in the assessment of indoor air quality (IAQ). It is guidance for appropriately qualified practitioners and is not intended to be a comprehensive handbook on IAQ.

1.1.2. It is applicable to proposed and existing buildings of all types including residential, commercial, retail, education, community facilities and healthcare (except specialist settings such as operating theatres). The Guidance is not designed to be applicable to other internal spaces (e.g. underground car parks, basements) but the principles may still be relevant. It is not intended to supersede any legal requirement e.g. such as related to occupational health exposure in an industrial setting. It can be used to identify IAQ issues in existing buildings, or to influence the design of proposed buildings and buildings undergoing major refurbishment or conversion.

1.1.3. For proposed buildings, it is important that IAQ is considered at an early stage in the design process, to avoid any conflicts with other design considerations, such as sufficient space for a ventilation system, airtightness requirements for energy savings, noise from mechanical ventilation and the location of the air intakes. If left late in the process, changes can be difficult to implement and can potentially be expensive to retrofit.

1.1.4. In addition to IAQM members, this Guidance will be of interest to the construction industry (architects, developers, planners, building services engineers etc.), building owners and occupiers, and regulatory authorities (environmental health, building control and planning).

1.1.5 This Guidance is intended primarily for use in the UK, where the vast majority of IAQM members work. However, it is recognised that the membership of IAQM is international and that the Guidance may be applied elsewhere. Where this occurs, if local conditions and approaches to IAQ assessment are different, careful consideration will need to be given to its applicability.

1.2. Context

1.2.1. In the UK, most people spend only a few hours per day outdoors (Diffey, 2010), yet relatively little is known of pollution concentrations inside buildings and other indoor environments. As concentrations of major outdoor air pollutants such as sulphur dioxide, nitrogen dioxide and particulate matter have reduced, the emphasis of practitioners, policy makers and others has moved indoors, with increasing understanding of the importance of a good indoor environment for people's health, well-being, and productivity.

1.2.2. IAQ is just one of a range of factors that affect the quality of an indoor environment. The indoor environment quality (IEQ) also depends on a range of factors such as noise, lighting, ventilation, airtightness, comfort (temperature and relative humidity), and décor (BSRIA, 2021). There can be trade-offs between different factors where there has not been a holistic approach to building design (Kukadia & Abela, 2015). For example, a ventilation system can improve IAQ but may lead to additional emissions from power generation, which in turn may affect outdoor air quality and increase greenhouse gas emissions. Some factors (e.g. poor IAQ) may require ventilation rates to be increased which may in turn increase noise, cost and greenhouse gas emissions. Mechanical ventilation systems may also require space that could have other uses of greater value for developers or occupants. Demand control ventilation using carbon dioxide (CO_2) as a proxy for general IAQ is a good way of managing IAQ. Overall, a balance needs to be struck between energy consumption and IAQ.

1.2.3. Indoor environments can be varied in their construction, materials, furnishings, layout, use, operation and ventilation type, so while general principles have been described in this document, there is an important role for site specific and ongoing assessment, whether by monitoring and/or modelling.

1.2.4. The assessment approaches described in this document require professional judgement from a competent and suitably experienced IAQ professional, in order to reach a conclusion on the overall significance of the impact. Full membership of the IAQM (membership was extended to include IAQ practitioners in 2019), the only professional body specifically for air quality practitioners in the UK, may be evidence of such competence and experience. Membership of some other professional bodies (e.g. those relating to occupational hygiene) having relevance to the practice of IAQ assessment may also provide reassurance of competence.

1.2.5. There are many organisations that are publishing research and tools that will help the professional gain a better understanding of IAQ (e.g. Clean Air London, CIBSE, USEPA). As experience of using this Guidance develops, and as further evidence relating to IAQ becomes available, it is anticipated that revisions of this document may become necessary. The most recent version will be available on IAQM's website.

1.3. Scope

1.3.1. This Guidance document focuses on the assessment of exposure of people in a wide range of indoor environments. The legislation to protect the public from exposure to air pollution largely relates to outdoor air. There is no legal protection for the general public in the UK regarding IAQ. However, employers have a duty of care to their employees and exposure is covered by Health and Safety at Work legislation.

1.3.2. This Guidance is explicitly not intended to override any legally defined protections of workers such as those defined in law related to the Control of Substances Hazardous to Health (COSHH) and EH40 Workplace Exposure Limits (WELs) (HSE, 2020). However, this legislation does not provide for protection of the general public inside buildings if it is not their place of work or, in some cases, if they are not an official visitor. This creates a contradiction as, if the exposure (concentration and time) is the same, the risk of health effects is the same whether the exposure occurs indoors or outdoors and regardless of the individual's status as employee, visitor or member of the public. Consideration of occupational health, in a legal sense, is therefore outside of the scope of this Guidance.

1.3.3. This Guidance aims to provide clarity regarding an appropriate approach to protecting human health from exposure to indoor air pollutants, in a range of indoor locations.

1.3.4. The scope of this Guidance is on polluting chemicals, in the gas phase in indoor environments, and particulate matter. Approaches for the assessment of mould, bacteria and viruses (e.g. SARS-CoV-2), and moisture in buildings are beyond the scope of this Guidance, but some of the principles may be applicable. Parameters such as temperature, moisture and mould are already covered in documents produced by others e.g. the Chartered Institution of Building Services Engineers (CIBSE) and the United Kingdom Centre for Moisture in Buildings (UKCMB). These are important elements that should be considered in good building design and operation and IAQ should not be considered in isolation. It is recommended that IAQ practitioners are involved at the design stages of a proposed building/refurbishment to ensure that IAQ considerations are part of the decision making process and an holistic approach is taken to building design.

1.3.5. This Guidance and method of assessment for pollutants known to be carcinogenic (e.g. benzene) is not recommended as guidelines are generally risk based, with no safe limit.

1.3.6. It is unlikely to be feasible to carry out an IAQ assessment of all potential indoor air pollutants. A suitably comprehensive approach should seek to evaluate the concentrations of key indoor air pollutants of interest/concern in specific indoor environments.

1.3.7. Odour is another consideration of IAQ. Many of the compounds discussed (e.g. Volatile Organic Compounds (VOCs)) in this Guidance have an odour that may vary from pleasant to offensive, and guidance on reducing the concentration of gaseous pollutants applies to them as much as to odourless gases. The perception of odour is mostly subjective and may require input

▲ **Image: © Carl Hawkings**

from an odour specialist. Therefore, detailed consideration of odours is outside of the scope of this Guidance.

1.3.8. The ingress of potentially toxic chemicals due to natural sources (e.g. radon (PHE, Accessed Jan 2021)) or building on land contaminated as a result of the historic uses of the site or neighbouring land, can also affect IAQ. For proposed buildings, measures should have been put in place during the planning process to ensure that the land has been fully remediated before construction is permitted.

1.4. Why IAQ is Important

1.4.1. Air pollution has a significant effect on public health (WHO, 2013). There is good evidence that long term exposure to outdoor air pollution can reduce life expectancy (COMEAP, 2009), mainly due to cardiovascular and respiratory diseases (Royal College of Physicians, 2016). Recent evidence suggests that it can also adversely affect many other aspects of human health and well-being including cognitive ability, and may cause or contribute to dementia, diabetes, obesity, and low birth weight (WHO, 2016).

1.4.2. It is apparent that exposure to indoor air pollutants could have greater significance on human health than outdoor air for several reasons:

- most of us spend more time breathing indoor air than outdoor air (WHO, 2013);
- buildings have become more airtight to reduce energy consumption which reduces uncontrolled ingress of outdoor air;
- we may be exposed to a wider range of air pollutants, particularly VOCs, inside, than outside; and
- concentrations of many pollutants are higher inside than outside (WHO, 2010).

1.4.3. There is a growing body of evidence (PHE, 2020 and USEPA, 2021b) of the adverse health effects from exposure to poor IAQ. These include irritation of the eyes and respiratory tract, allergies, asthma, central nervous system symptoms, liver and kidney damage, as well as cancer risks.

1.4.4. Pollutant concentrations indoors are a function of the source strength and how long they persist indoors. The latter depends on ventilation, how reactive they are and their deposition rate. Some pollutants, such as ozone, have a short lifetime indoors because they either deposit or react with other pollutants very quickly.

1.5. Purpose of an IAQ Assessment

1.5.1. An assessment of IAQ should ideally be undertaken as part of the scope of an overall air quality assessment required for planning, permitting or other purpose. An IAQ assessment is undertaken for a number of other reasons, including:

- establishing which pollutants are present in an indoor space and how they might affect health and well-being;
- assessing occupational exposure compliance with COSHH Regulations/EH40 (HSE, 2020) (N.B. not within the scope of this document);
- assessing post construction building air quality for compliance with building certification schemes such as BREEAM, WELL and LEED (see **Appendix A**), which may be prior to or post occupancy (post occupancy appraisal will include sources such as gas cooking);
- determination of the performance of buildings and of ventilation systems and design;
- defining ambient air quality in relation to limits and standards, where considered relevant to IAQ;
- identifying the cause of an issue reported by a building's users;
- identifying infiltration and determining the levels of ingress of external pollutants;
- assessing and demonstrating compliance with planning policy (e.g. some councils are including specific planning policy objectives in local/neighbourhood plans (KNP, 2018); and
- assessing compliance with building regulations.

2. Background

2.1. Main Pollutants and Their Health Effects

2.1.1. Outdoor air enters buildings through openings such as doors and windows, mechanical ventilation systems and by infiltration through the fabric of buildings. For old and/or poorly constructed buildings, infiltration through the fabric of the building can often be significantly higher than for a well constructed/new building. Infiltration of outdoor air may improve or worsen indoor air quality depending on the quality of the outdoor air relative to the quality of indoor air.

2.1.2. There are many additional sources of air pollutants generated indoors, some of which are briefly described below with some of their more important health effects. These internally generated pollutants can accumulate inside buildings and may also exfiltrate the building and adversely affect outdoor air quality.

2.1.3. Nitrogen dioxide (NO_2) is either emitted directly during combustion of fuels, such as gas and diesel, or is formed in the atmosphere from nitric oxide (NO), which is also emitted during combustion. Together NO_2 and NO are referred to as oxides of nitrogen (NO_x). Almost all (97% in 2019, (BEIS, Accessed May 2021)) emissions of NO_x in the UK were from the combustion of fuels (vehicles, industry, space heating boilers etc.). Gas appliances (e.g. cookers) are the main indoor sources of NO_x. Short term exposure to elevated concentrations of NO_2 can cause inflammation of the airways in the lungs (WHO, 2010). It can also increase susceptibility to respiratory infections and to allergens (COMEAP, 2016). Long term exposure to NO_2 has been associated with dementia, lung cancer, low birth weight, diabetes (PHE, 2018) and increased mortality (although there is further research recommended as opinion is divided) (COMEAP, 2018).

2.1.4. Particulate Matter (PM) is a complex mixture of solid and liquid particles suspended in the air, and its composition depends on its origin. In urban areas, the combustion of diesel, brake and tyre wear as well as construction and demolition activities can be important local sources. Any dust deposited on roads can be resuspended by moving traffic. Much of the PM, however, is formed in the atmosphere from other pollutants and is transported over long distances from the emission of its precursors. The UK also periodically experiences mineral dust pollution from the Sahara Desert. Indoor emission sources include renovation works, cooking (particularly frying), smoking, wood burning fires/stoves, burning candles. Clothing, carpets and soft furnishings also release particles/fibres into the air. In the 1990s, the emphasis of air quality management was on the particles less than 10 µm in diameter (PM_{10}), but from the late 2000s it began to move towards smaller particles that penetrate deeper into the respiratory system (e.g. $PM_{2.5}$). A range of health effects including respiratory and cardiovascular diseases, cancers and mortality, diabetes and low birthweight have been associated with exposure to PM (PHE, 2018). More recently, there is emerging evidence that it may also affect cognitive ability (Allen, *et al.*, 2017).

2.1.5. Radon is a radioactive gas and a known cause of lung cancer. It is formed by the radioactive decay of small amounts of uranium

▲ **Image: © CheapStockImage_com | Pixabay** that occur naturally in all rocks and soils and enters buildings from the ground beneath buildings or from the materials from which they are built. The air in every building contains radon, but the concentrations are typically low. PHE (now part of the National Institute for Health Protection (NIHP)) has produced a map of the risk of radon (PHE, Accessed Jan 2021) and has a Radon Action Level of 200 Bq/m^3 and a target level of 100 Bq/m^3 averaged over a year (PHE, Accessed Nov 2020). Radon Affected Areas are defined as those with 1% or more homes above the Radon Action Level. For new homes in Radon Action Areas appropriate mitigation measures are incorporated into their design and construction. There has also been a Government programme of remediating existing homes over the last 30 years (BRE, 2015). The target level is the ideal outcome for remediation works in existing buildings and protective measures in new buildings (HPA, 2010).

2.1.6. Volatile Organic Compounds (VOCs) have several definitions (e.g. BS EN16516:2017 Annex G (BSI, 2020)). VOCs are an important grouping of compounds for IAQ as they are generally gases at normal room temperatures. The definition of a VOC as a Very Volatile Organic Compound (VVOC), VOC or Semi-volatile Organic Compound (SVOC) is based on the compound's physical properties: where the compound elutes on the gas chromatograph column with respect to n-hexane and n-hexadecane.

2.1.7. VOCs are widely used in construction products, furnishings, toiletries, fragrances and cleaning products (Naldzhiev, Mumovic, & Strlic, 2020). Examples of construction products containing VOCs include surface coatings, timber preservation (Pohleven, Burnard, & Kutnar, 2019), adhesives, sealants, damp proofing and roofing materials (Weigl, *et al.*, 2014 and Woolley, 2017). There are many thousands of organic compounds that could be in the indoor environment including: aromatic hydrocarbons, saturated aliphatic hydrocarbons (n, -iso, cyclo-), terpenes, aliphatic alcohols, aromatic alcohols, glycols, glycol ethers and aldehydes.

2.1.8. Total Volatile Organic Compounds (TVOC) refers to the sum of the concentrations of the identified and unidentified VOCs, as specified in BS EN16516:2017. As compounds can vary in toxicity, use of TVOC as a measure provides limited information on the potential health effects of building occupants, and it is therefore important to consider the concentration of key compounds.

2.1.9. Aldehydes (particularly formaldehyde, acetaldehyde and acrolein) are widely used in construction and furnishing products and are slowly released into the air after construction. They come from various sources such as resins, phenol formaldehyde, and urea formaldehyde (UF) used in wood based products such as particleboard furniture, UF based lacquers and UF foam cavity wall insulation.

2.1.10. Formaldehyde (HCHO/CH_2O) is probably the VOC of greatest importance, due to its prevalence in the indoor environment and its known adverse health effects such as watery eyes, burning sensations of the eyes, nose, and throat, coughing, wheezing, nausea and skin irritation (PHE, 2019) (Salthammer, 2019). The US EPA has also classified formaldehyde as a probable carcinogen (USEPA, 2010).

2.1.11. Acrolein (C_3H_4O) causes similar health effects as formaldehyde (USEPA, 2009) and may be confounding results from studies that look at asthma and exposure to formaldehyde (Golden & Holm, 2017) (WHO, 2002). Acrolein is generated when heating various oils (e.g. in cooking) above 180°C, is formed from the breakdown of certain outdoor air pollutants and tobacco smoking (Golden & Holm, 2017). One study (WHO, 2002) found acrolein to be common in indoor environments especially where there was frying of food, tobacco smoking or proximity to vehicle emissions. A more recent review (Shrubsole, Dimitroulopoulou, Foxall, Gadeberg, & Doutsi, 2019) found acrolein to be a low priority in residential settings.

2.1.12. Terpenes (α-pinene and d-limonene) are used in cleaning products, perfumes, and deodorants (Shrubsole, Dimitroulopoulou, Foxall, Gadeberg, & Doutsi, 2019) and can be released during use. They are also important in the chemistry of other gases and the formation of secondary organic aerosols (SOAs) (see **Section 2.2**).

2.1.13. Phthalates used in e.g. PVC floorings, children's toys, are released from these products into the air. Phthalates used in some products are known carcinogens and asthmagens as well as endocrine disruptors (Woolley, 2017).

2.1.14. Other VOCs can be emitted from photocopiers (Cacho, *et al.*, 2013) and printers (Guo, Gao, & Shen, 2019) and during cooking (He, *et al.*, 2020).

2.1.15. The health effects of VOCs include irritation of the eyes and respiratory tract, allergies and asthma, effects on the central nervous system, liver, and kidney damage as well as cancer (PHE, 2019). While the health impacts of many VOCs are known, there is little evidence available on the combined effects of a range of many different VOCs, nor the combined effects with inorganic pollutants.

2.1.16. Carbon dioxide (CO_2) is the major greenhouse gas contributing to climate change but has not traditionally been thought of as a health related pollutant with local effects at source. The main source in buildings is generally people (and animals), who exhale CO_2 during respiration. CO_2 is also produced indoors from combustion of carbonaceous fuels e.g. gas cookers/heaters and from fermentation. Poorly ventilated buildings, or those with high occupancy rates, can result in high concentrations. Plants emit CO_2 when respiring (e.g. when there is insufficient light for photosynthesis) and remove CO_2 when photosynthesizing. CO_2 can also be used as a marker for ventilation rates, e.g. in the management of viral infection risk.

2.1.17. Background CO_2 concentrations are in excess of 400 parts per million by volume[1] (ppm) (or more than 0.04% by volume) and

[1] Parts per million by volume (ppm) is used here because volume per volume units are the convention for CO_2. In Europe, other pollutants are generally expressed in mass units (e.g. µg/m^3). See **Appendix B** for further explanation and conversion of units.

are increasing (Lindsey, 2020). One review of the effects of indoor exposure to CO_2 concluded that there was limited evidence of acute impacts to human health or cognition below 5,000 ppm (Fisk, Wargocki, & Zhang, 2019). Other studies show that elevated CO_2 concentrations (around 1,000 ppm and above) can impair human ability (Bierwirth, 2014 and Allen *et al.*, 2016), induce fatigue and cause physiological effects such as inflammation and bone demineralisation (Jacobson, *et al.*, 2019). Other research shows that cognition is unaffected or even enhanced (Scully, *et al.*, 2019) at some elevated concentrations. As concentrations further increase, above about 2,000 ppm, exposure over several hours may cause headaches, sweating and shortness of breath. PHE/NIHP is currently reviewing the evidence to whether CO_2 should be considered as a pollutant or as an indicator of ventilation rates (Lowther, *et al.*, In preparation). Build-up of CO_2 in enclosed/confined spaces is also a cause of serious health impacts and death.

2.1.18. Carbon monoxide (CO) is emitted during inefficient combustion processes. High concentrations indoors are typically due to the use of incorrectly installed, poorly maintained or poorly ventilated gas heaters and cookers. Mean concentrations in homes without gas stoves are often in the range 0.5-5 ppm (0.6-6 mg/m^3) (USEPA, 2021a). Near properly adjusted gas stoves, concentrations are often in the range 5-15 ppm (6-18 mg/m^3) and near poorly adjusted stoves concentrations may be 30 ppm (37 mg/m^3) or higher (USEPA, 2021a). CO preferentially binds to haemoglobin reducing its capacity to transport oxygen around the body. Exposure (to higher concentrations for a short time or lower concentrations over a longer period) can cause unconsciousness and death. There can be serious damage to the central nervous system even without unconsciousness (WHO, 2000). Exposure to low CO concentrations has been associated with a wide range of health effects including reduction of the duration of active exercise in young adults, and impairment of brain function. Long term exposure to low concentrations of CO exposure can cause cognitive memory deficits, emotional psychiatric changes, cardiac events, and low birth weight.

2.1.19. Ozone (O_3) is produced indoors by some electronic equipment such as printers, photocopiers (Cacho, et al., 2013) and some air cleaning appliances (Salonen, Salthammer, & Morawska, 2018). It is also produced outdoors from interactions between NO_x and VOCs, with high concentrations of O_3 occurring during periods of hot, sunny weather. Exposure to ozone can cause asthma, irritation and damage to eyes, nose and the airways, increase hospital admissions and increase mortality (COMEAP, 2015). Prolonged exposure to high concentrations can result in damage to the lungs and airway linings (WHO, 2000).

2.2. Indoor Chemistry

2.2.1. The concentration of an indoor air pollutant is a function of numerous processes including indoor emissions, exchange with outdoor air, deposition to indoor surfaces, removal by filtration, and indoor chemistry (Weschler & Carslaw, 2018). Indoor chemistry includes the chemical and physical transformations that occur indoors and is very different to that which occurs outdoors. This is

▲ **Image: © A Stockphoto | Adobe Stock** due in part to the much larger surface to volume ratios and the higher concentrations of VOCs indoors, but also due to the lower light levels, reduced temperature fluctuations and lack of precipitation.

2.2.2. For reactions between gas phase pollutants to be important in the indoor environment, the timescale of the reaction must be competitive with the rate of air exchange, otherwise the reactants will be removed before significant reaction can take place. In buildings with lower ventilation rates there is more time for gas phase chemistry to occur. In general, the reaction with surfaces, with the exception of reaction with the surface of airborne particles, is faster than the air exchange rate, and therefore ventilation rates are not a constraint. New surfaces soil fairly quickly, and under typical conditions five layers of SVOCs accumulate on impermeable surfaces in one to three months. After this period, the reactivity of many indoor surfaces changes little, with ongoing formation of reactive compounds from the deposition of skin oil, skin flakes, particles and other indoor pollutants (Weschler & Carslaw, 2018).

2.2.3. Much indoor air chemistry research has focused on the reaction between oxidants (O_3 and hydroxyl (OH) radicals) and VOCs. These reactions generate a complex range of secondary pollutants, some of which also have human health effects. The main route of formation of OH indoors is through reaction of O_3 with alkenes and monoterpenes. Once formed, OH can react with other terpenes and organic compounds, to form, amongst other compounds, aldehydes such as formaldehyde. The rate of reaction of O_3 with some VOCs is enhanced on surfaces compared to the gas phase; e.g. the gas phase reaction of benzo(a)pyrene (BaP) with ozone is negligible but when BaP is absorbed onto glass it produces a range of epoxides (Weschler & Carslaw, 2018).

2.2.4. Photolysis (decomposition/separation by the action of light) occurs indoors but more slowly than outdoors. Reactions requiring higher energy light such as O_3 photolysis are attenuated more indoors relative to outdoors than those reactions requiring less energy such as the photolysis of formaldehyde (Weschler & Carslaw, 2018).

2.2.5. Secondary organic aerosols (SOAs), that are particles, can be formed indoors from the reaction of O_3 with terpenes and terpene alcohols. The concentrations of these terpenoid compounds tend to be much higher indoors than outdoors. The less volatile reaction products condense onto existing particles or nucleate, producing SOA that can grow to 0.7 μm in diameter (Rohr, Weschler, Koutrakis, & Spengler, 2003). The production of SOA can be episodic, such as during the use of scented cleaning products or relatively continuous, as occurs with the use of plug in air fresheners. Other gas phase reactions and surface chemistry can also be important indoor sources of SOAs (Weschler & Carslaw, 2018).

2.2.6. Some commercially available indoor air cleaning devices and surface cleaning products have been shown to increase the concentration of both hydroxyl (HO) and hydroperoxy (HO_2) radicals by several orders of magnitude (Carslaw, Fletcher, Heard, Ingham, & Walker, 2017). A typical indoor concentration of SOAs in suburban UK is around 1 μg/m^3. During cleaning, SOAs may reach concentrations of 20 μg/m^3 (Carslaw, Mota, Jenkin, Barley, & McFiggans, 2012).

2.3. Exposure

2.3.1. The effect of a pollutant on an individual depends on a number of factors (see **Box 2.1**) all of which need to be considered when undertaking an assessment of IAQ.

Box 2.1: Factors Relating to the Effect of a Pollutant on an Individual

- The concentration of the pollutant in the various areas a person may be exposed.
- Whether the pollutant is present continuously or intermittently at each location.
- The period/duration and variability of exposure (exposure to high concentrations over a short period can result in the same effect as exposure to low concentrations for a longer period but this is not always the case).
- Whether the body accumulates, destroys or excretes the pollutant.
- The susceptibility of the individual (e.g. those with pre-existing diseases such as asthma, Chronic Obstructive Pulmonary Disease (COPD), cystic fibrosis will be much higher, those who are pregnant, older people).
- Whether there is a threshold concentration below which there is no known adverse effect.
- Exposure to several pollutants may produce effects that are greater than the sum of the effect of each, but these potential combined effects are outside the scope of this guidance and are not always fully understood.

2.3.2. IAQM recommends that an IAQ Assessment is based on the most sensitive type of person likely to be present at the location or locations being assessed (this may not be the same type of person in all locations being assessed) unless measures have already been taken to minimise exposure of some people (e.g. by limiting access to part of a building).

2.3.3. Better and more comprehensive data on air quality and exposure (i.e. time activity profiles e.g. (Dimitroulopoulou, Ashmore, & Terry, 2017)) to a range of pollutants in different types of indoor environments are needed to fully understand the impacts of indoor air pollution on human health. What we do know is that the indoor environment is complex with many different chemicals present. These chemicals are likely to change in the future as product formulations change. It is important that IAQ practitioners keep up to date with these changes.

2.4. Other Indoor Environmental Conditions

2.4.1. Healthy indoor environments can enhance the lives and health of the occupants (BESA, 2021), making people more productive and reducing sick days. There is growing interest in improving the health and well-being of employees by investing in measures that improve the working environment in terms of air quality and other factors. However, there may be conflicts between IAQ and other environmental considerations such as noise generation and energy efficiency (Kim & Choi, 2019) (e.g. see this guide to energy efficiency and ventilation systems (Liddament, 1996)). Ventilation rates may be reduced at certain times (e.g. night-time weekends) which will facilitate deposition of airborne particles, that may get resuspended when air flow is increased (by increased ventilation or human activity).

2.4.2. According to The World Green Building Council (World Green Building Council, 2016) employees can account for up to 90% of operating costs. Developers and landlords also recognise that healthy buildings can improve sales, command higher rental incomes, and attract and retain tenants in longer term leases (Kukadia & Upton, 2019).

2.4.3. Passive control of IAQ (and comfort) is preferable to active/mechanical measures. Where appropriate (taking into account issues such as security, outdoor air quality, heat loading), natural ventilation/opening windows is preferred to mechanical ventilation. Mechanical ventilation requires energy (and therefore may increase emissions) and produces noise. Mechanical ventilation and heat recovery systems require good design and maintenance to ensure filtration delivers the required performance and they do not contribute to poor IAQ. Passive ventilation may not achieve the required ventilation rates as it often relies on local action/inaction by the occupants (e.g. opening/closing windows) and so mechanical ventilation may be the only option in some cases. Where mechanical ventilation is required, heat recovery should be considered. The choice of construction/insulation materials and shading can also reduce the need for heating/cooling of a building which again may impact air quality inside and out.

2.4.4. The sealing of building façades, and the use of mechanical ventilation has been used to improve energy efficiency and reduce the ingress of noise and air pollution in urban areas (see Guidance (CIBSE, 2017b) (ANC & IOC, 2020)). It is important that the position of the intake to the mechanical ventilation system is located away from local pollutant sources (Kukadia & Hall, 2011) (Cheng, Kukadia, & Hall, 2014). The sealing of building façades can lead to unacceptably high temperatures inside buildings (known as overheating), particularly in the summer and if the building has not adequately taken this account in the design stage.

2.4.5. To reduce energy consumption, mechanical ventilation systems may extract the heat from the exhaust air, and recirculate the air, which can exacerbate the overheating problem. Mechanical ventilation systems can be designed to avoid overheating and whilst taking up space and additional capital and operational costs, some modern systems do not incur substantial extra cost or require much if any additional space. The avoidance of overheating should be an important consideration in the design of proposed buildings. Free standing air conditioning systems (and some integrated systems) recirculate air which can lead to pollutants building up over time.

2.4.6. To a lesser extent, cold temperatures in the working environment can also reduce productivity although in most indoor environments it is easier to improve the situation (by local heating, extra clothing etc.) than is the case for elevated temperatures.

2.4.7. Building designers and managers need to balance the production of good indoor environments, where people feel comfortable and perform well, with energy efficiency and use. The best way to prevent high indoor pollutant concentrations is to eliminate or control them at source. If this is not possible, the next approach is good ventilation and filtration may be appropriate; this can be e.g. filtering outdoor air prior to introduction to the indoor space or recirculating filters (e.g. cooker extraction hoods) (Kukadia & Upton, 2019).

2.4.8. In some cases, especially in tall buildings, the flow of air caused by temperature or pressure differences between the top and bottom of the building may transport polluted air from street level through the building (e.g. up the lift shafts) (known as the "*stack effect*"). Ventilation (natural or mechanical) may not be the primary solution to improve IAQ in these cases.

3. Assessment Criteria

3.1. Introduction

3.1.1. Assessment criteria for outdoor air quality are well established and often have legal/statutory status (e.g. (UK Government, 2010)) and provide clarity regarding the applicable time period and location of exposure. By contrast, there are no consistent formal IAQ assessment criteria for covering the different indoor environments and people with different sensitivities to air pollution (e.g. children, elderly, the sick). There is no primary legislation in the UK that requires IAQ standards, applicable to all indoor environments, to be achieved although indoor air quality criteria are available e.g. (PHE, 2019) (WHO, 2010)). The situation in other countries e.g. The Netherlands is different, where indoor air quality is part of public health legislation and applies equally to both indoor and outdoor environments (RIVM, Accessed May 2021).

3.1.2. Health and Safety at Work legislation does not apply to people in their home (occupied dwellings), or users of a facility run by volunteers which is not, therefore, a workplace. This leads to gaps and contradictions between exposure of different people in the same location and between indoor and outdoor criteria. **Appendix C** gives further information on organisations that have set assessment criteria and their averaging times. Some air quality criteria are shown in **Table 3.1** and **Figure 3.1** (taken with permission from (CIBSE, 2020a)).

3.1.3. The WHO have recently published revised AQ guidelines and interim targets (WHO, 2021). These are applicable to both indoor and outdoor air quality and are included in **Table 3.1**; some WHO guidelines previously published are still valid and have not been updated. Interim targets are to guide the improvement of air quality towards the ultimate and timely achievement of the AQ guidelines for those countries that exceeded the AQ guidelines. This Guidance has been written with previous WHO guidelines (WHO, 2005, WHO, 2010) in mind and the methodology and all further statements about WHO guidelines relate to these and not the new guidelines and interim targets. Professional judgement should be used to ensure that IAQ assessments take into account the potential health effects if IAQ is likely to exceed these new and tougher guidelines.

3.1.4. The UK Health and Safety Executive (HSE) requires (HSE, 2021) that an employer "...should carry out a suitable and sufficient assessment of the risk to the health of your employees and any other person who may be affected by your work, if they are exposed to substances hazardous to health." This clearly applies to a visitor to industrial premises or a member of the public passing roadworks. However, it is not clear whether non employees (e.g. residents and patients in a care home) are covered by the same legislation as employees, even though they may be exposed to the same IAQ. Residents may, indeed, be exposed for longer periods than workers at a care home.

3.1.5. Occupational health is normally assessed in relation to exposure over averaging periods of minutes to a few hours (usually up to 8 hours). Health based air quality guidelines for the general population (non-occupational exposure) are intended to protect the most sensitive individuals and relate to averaging periods ranging from less than one hour to a year. This leads to big differences in the numerical values for the various standards/guidelines e.g. the occupational exposure 8 hour limit for NO_2 of 960 μg/m^3 is over 20 times higher than the long term UK Air Quality Objective (AQO) (applicable outdoors) (DEFRA, Accessed May 2021) and the WHO guideline (WHO, 2000) which are both 40 μg/m^3 averaged over one year (used to assess outdoor exposure but this value is also applicable to indoor exposure (MHCLG, 2021b)).

3.1.6. In schools, employees in certain circumstances (e.g. laboratories) are covered by the COSHH workplace legislation whereas the pupils, and other staff in situations (e.g. where they are not working with chemicals or other hazardous substances) are covered by Government Guidance (Education and Skills Funding Agency, 2018).

3.1.7. COSHH workplace exposure limits (WELs) given in EH40 (HSE, 2020) apply to healthy adults in occupational settings, working at normal rates for normal shift periods (Channing, 2013). They are not aimed at exposure of more vulnerable individuals, or people who occupy buildings on a more permanent basis (e.g. office workers and building occupants). Some workplaces include people with underlying health conditions that makes them more susceptible to the effects of polluted air.

3.1.8. Where legislative and regulatory criteria have the same averaging time as an outdoor AQO, the regulatory value is often higher than the AQO, providing less protection to an employee at work than to a member of the public outdoors e.g.:

- the 8 hour WEL for carbon monoxide is 35 mg/m^3 compared to the 8 hour UK AQO of 10 mg/m^3; and
- Approved Document F1 (MHCLG, 2010a) gives two values for 8 hour carbon monoxide concentrations in a non-dwelling: 10 mg/m^3 (implied that this value applies in offices) and 35 mg/m^3 for "occupational exposure" (implied that this value applies in industrial settings).

3.1.9. WHO IAQ guidelines (WHO, 2010) apply to all indoor environments. However, they do not include assessment criteria for all substances that can be found in indoor environments e.g. terpenes, perfluoroalkyl substances and phthalates. The PHE guidelines (PHE, 2019) are an initial assessment of the most health relevant and frequently occurring VOCs in homes and offices and, similarly, do not cover all the substances found in indoor environments, in the current version.

Table 3.1: IAQ Pollutants and their Assessment Criteria

Pollutant	Averaging time	Guideline concentration (µg/m³)[(a)(b)(d)]
NO_2	1-hour mean	200 (WHO, 2010) (WHO, 2005)
	24-hour mean[(f)]	25 (WHO, 2021)
	Annual	40 (WHO, 2010), 10 (WHO, 2021)
PM_{10}	24-hour mean[(f)]	50 (WHO, 2005), 45 (WHO, 2021)
	Annual	20 (WHO, 2005), 15 (WHO, 2021)
$PM_{2.5}$	24-hour mean[(f)]	25 (WHO, 2005), 15 (WHO, 2021)
	Annual	10 (WHO, 2005), 5 (WHO, 2021)
CO_2	'Occupied period'	1,000 ppm (BB101 and CIBSE)
CO	15-minute mean	100,000 (WHO, 2010)
	1-hour mean	35,000 (WHO, 2010)
	8-hour mean	10,000 (WHO, 2010)
	24-hour mean[(f)]	4,000 (WHO, 2021)
O_3	8-hour mean[(f)]	100 (WHO, 2005), 100 (WHO, 2021)
	Peak season[(g)]	60 (WHO, 2021)
TVOC[(c)]	8-hour mean	300 (ADF, (MHCLG, 2010a)
Acrolein[(d)]	N/A[(d)]	0.1-0.5 (WHO, 2002)[(d)]
Formaldehyde	30-minute mean	100 (WHO, 2010)
	Annual	10 (PHE, 2019)
Benzene	Not applicable	Carcinogen; no safe level. Excess lifetime risk of leukaemia at 1 µg/m³ is $6x10^{-6}$ (WHO, 2010)
Acetaldehyde	1-hour mean	1,420 (PHE, 2019)
α-pinene	30-minute mean	45,000 (PHE, 2019)
d-limonene	30-minute mean	90,000 (PHE, 2019)
Radon (Rn)	Annual	200 Bq/m³ (PHE, Accessed Nov 2020)[(e)]

(a) See **Appendix B** for conversion of units.

(b) Ensure reference conditions (temperature, pressure etc.) are considered.

(c) Monitoring TVOC will provide no information regarding the nature of the individual compounds present, their concentrations or possible toxicity.

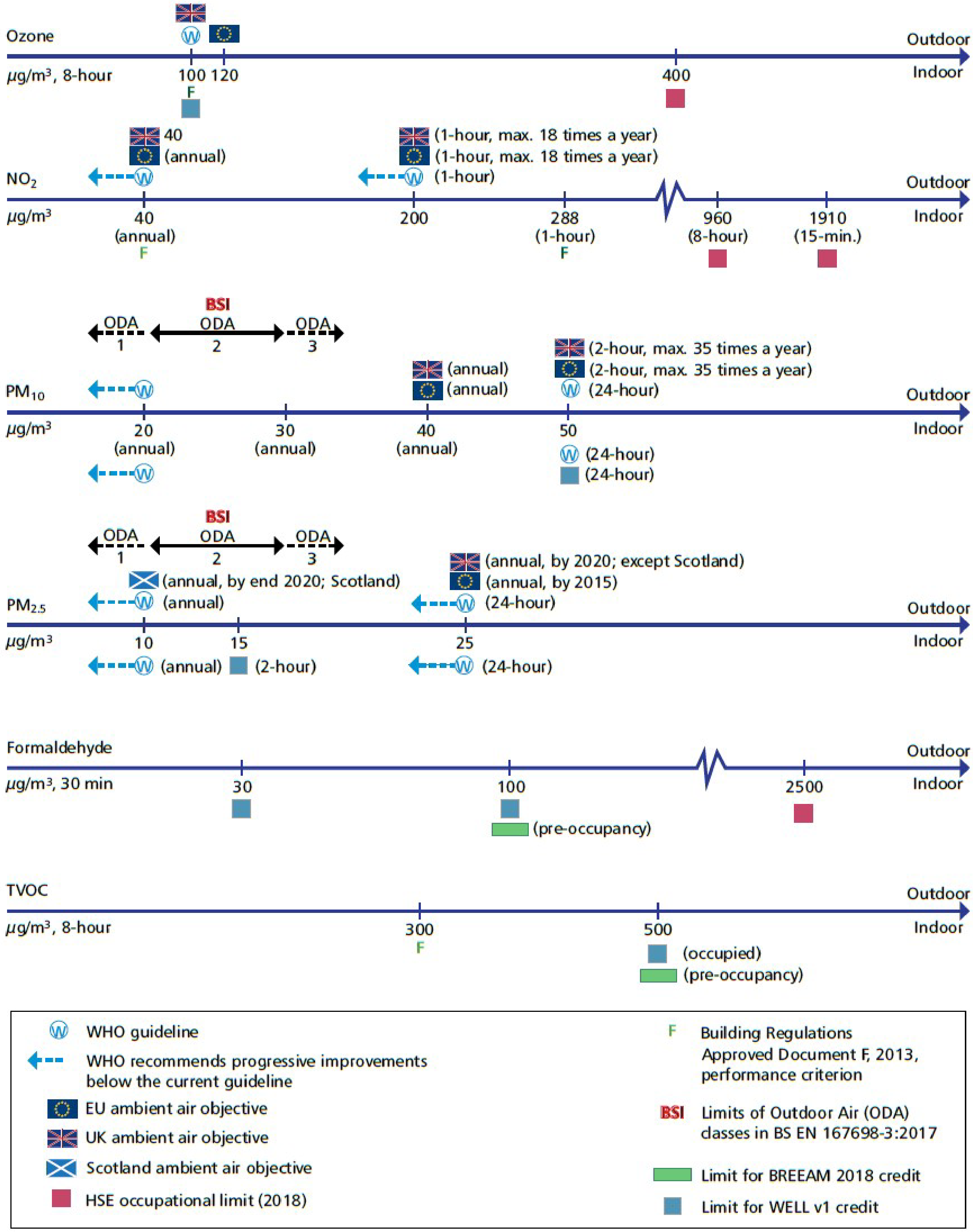
(d) Acrolein is a WHO tolerable concentration (TC) not a guideline, based on the inhalation route, lowest observable adverse effects level (LOAEL) divided by a safety factor. The LOAEL is based on long term exposure but an averaging period is not specified. Any monitoring should be representative of long term (annual or greater) exposure.

(e) This is not a health based threshold criterion but rather a trigger level for action/indicator for IAQ.

(f) 99th percentile (i.e. 3–4 exceedance days per year).

(g) Average of daily maximum 8-hour mean O_3 concentration in the six consecutive months with the highest six-month running-average O_3 concentration.

Figure 3.1: Summary of Selected Air Quality Criteria



3.2. Derived Assessment Criteria

3.2.1. Assessment criteria are sometimes derived by reducing WELs by a factor. One approach often used in the industry and suggested in D1 (HMIP, 1993) for outdoor air is to take an 8-hour WEL (HSE, 2020) and divide it by a factor of 4 (to account for continuous exposure (168 hours a week) compared to 40 hours for a normal working week) and then to divide this value by 10 to account for the most sensitive individuals in the general population. This results in an assessment criterion 1/40th (2.5%) of the 8-hour WEL.

3.2.2. For some pollutants (e.g. those with higher toxicity, or carcinogenicity) a sensitivity factor of 25 has been used, giving an overall factor of 1/100th (1% of the 8-hour WEL). Another approach defined in EH75/2 (HSE, 2000) suggests that continuous exposure of individuals at work (i.e. 24 hours per day/7 days a week e.g. as in a military submarine) could be assessed against the relevant WEL divided by 5. However, these approaches lead to criteria that are not directly based on toxicological or epidemiological data and may not be appropriate for non-industrial indoor settings and/or the general population.

3.2.3. IAQM recommends that in the absence of a suitable published criterion for a substance of interest, the assessor should refrain from assessing indoor exposure against any criterion, or if one is needed (e.g. in order to finalise design or interpret monitoring data) steps are taken to obtain guidance from the relevant public health organisation, for non-industrial indoor settings. Whichever approach is selected, a full justification should be provided in the IAQ Assessment Report.

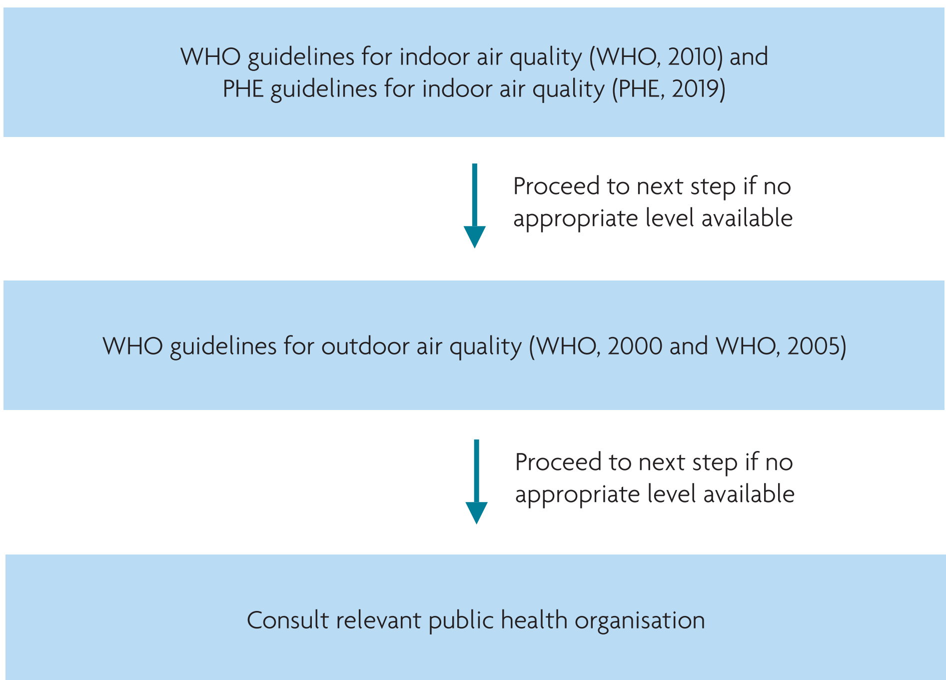
3.2.4. If guidance from public health organisations is not forthcoming in the required timescale for the IAQ Assessment, criteria derived from occupational health limits may be used. They may be applied as specified or with factors applied to derive values more appropriate to the exposure duration or the sensitivity of the receptors, as described in **Section 3.2.1.** The IAQ Assessment Report must justify any derived criteria and document discussions with any public health organisation.

3.3. Hierarchy of Assessment Criteria

3.3.1. For settings where applicable legislation or Government guidance relating to IAQ exists, this should be used for the assessment of IAQ. For those settings and user groups not covered by legislation or Government guidance IAQ should be assessed using the hierarchy of assessment criteria in **Figure 3.2**. The hierarchy is that WHO (WHO, 2010) and PHE (PHE, 2019) guidelines for IAQ take priority followed by WHO guidelines for outdoor air. If these sources do not include a relevant criterion the assessor should make contact with the relevant public health organisation (e.g. PHE, PHW, PHS, PHA) for advice on an appropriate assessment criterion, for non-industrial indoor settings (e.g. homes, schools, offices) and the general population. The WELs should generally not be applied directly as they are for healthy workers exposed to chemicals for normal shift periods.

3.3.2. In all cases, if there is a range of applicable values the most stringent assessment value should be used unless justification can be provided.

Figure 3.2: Hierarchy of Assessment Criteria



4. Assessment Approach

4.1. Introduction

4.1.1. This Chapter sets out the general approach for carrying out IAQ assessments. Most assessments will be for a proposed building/major refurbishment, referred to as 'proposed build' from here onwards, although IAQ assessments are also made for existing buildings to review the results of monitoring for IAQ, improve well being and occupant health or to resolve a problem such as complaints from occupants.

4.1.2. For many new build projects in the UK, the overall project programme can be linked to the Royal Institute of British Architects (RIBA) plan of work which is a recognised structure for building development in the UK and divides projects into seven stages. The RIBA project stages are set out in **Appendix D** and provide an illustration of the stages during design, construction and fit out, at which consideration of IAQ may be required. It is typically easier and cheaper to resolve any potential IAQ issues early in the design stage than to identify and implement them after completion of the building. Not all projects will strictly follow the RIBA plan, in which case, the stage at which an IAQ consultant's work interacts with the plan of works is not always clear. For some projects, an issue will be identified at the handover or, more likely, at the post occupancy stage (RIBA Stage 7).

4.1.3. An ambient (outdoor) air quality assessment (e.g. of a new development) often includes receptors such as schools, hospitals, and homes and assesses outdoor air quality only, equating outdoor air quality to potential indoor exposure of the occupants. This does not allow for any attenuation of the building which can vary considerably. Some studies have shown that buildings can reduce indoor concentrations by up to 73% of outdoor concentrations (Walsh, 2020). A study of London schools showed that the buildings attenuated outdoor concentrations by 20-40% (see **Appendix E**).

4.1.4. A subject often neglected is the selection of building materials and their effect on IAQ. Woolley, 2017 is a provocative and thought-provoking contribution to this debate. Ideally, an appropriately qualified consultant (which may require the combined expertise of air quality, materials and/or building specialists) should be engaged by the developer to provide advice, including on the specifications for construction and fit out materials.

4.1.5. It is important to think about IAQ when considering the fitting out and operation of a building (see e.g. (ASPB, 2021) for details of the IAQ impact of certain products and materials). An IAQ Plan for the operation of a building is often developed during the design stage and as part of the BREEAM application process (BRE, 2014).

4.1.6. An IAQ assessment needs to consider a range of issues and the methodology will depend on the specific reason(s) for the assessment e.g. there are complaints about IAQ from occupants or a developer wants to achieve a BREEAM 'excellent' rating.

4.1.7. For pollution to cause an effect there must be a source, a pathway and a receptor. There may be a single source, or multiple sources emitting a single pollutant or, more likely, a mixture of many pollutants. The pathway is the route by which the pollution can move from the source to a receptor and includes any transformation that may take place such as the formation of secondary pollutants through chemical reactions, dilution through dispersion/ventilation and loss of pollutant due to deposition onto surfaces. The receptor is, in the context of IAQ, generally a human occupant of the building exposed to the air pollutant.

4.1.8. There may be circumstances where the receptor is an inanimate object (e.g. a computer/server in a data centre, food preparation areas, other industrial activities such as paint finishing or microelectronics where clean rooms are required). There may be special requirements for monitoring in these locations (e.g. electronic equipment may be sensitive to some techniques which may generate a corrosive atmosphere or produce electrical interference) and there may be specific guidance related to the circumstances (Data Centers, Accessed May 2021).

4.1.9. The Source Pathway Receptor Model is shown in **Figure 4.1**.

4.1.10. If any part of the Source Pathway Receptor Model is missing or broken (no receptor, no pathway and/or no source) there is unlikely to be a need for an IAQ Assessment. **Figure 4.2** provides a flow chart illustrating considerations used to determine the need for an IAQ Assessment; the order in which the source, pathway and/or receptor is considered is flexible.

4.1.11. If an IAQ Assessment is required, the staged process shown below and in **Figure 4.3** should be used to determine the appropriate level of detail required. Not all stages may be required and professional judgement should be applied. These stages are described in more detail in **Sections 4.2 and 4.3**, and may vary in application depending on whether the assessment is of an existing or proposed building.

- Stage 1: Scoping Study (to define level of assessment required)
- Stage 2: Assessment
    - Simple assessment: Source Pathway Receptor
    - Detailed assessment: monitoring &/or modelling
- Stage 3: Mitigation/improvement opportunities
- Stage 4: Reporting

4.1.12. Transparency and clarity in reporting is essential. **Section 4.5.1** provides guidelines for reporting on the assessment and decision making.

Figure 4.1: Schematic of IAQ Sources, Pathways and Receptors

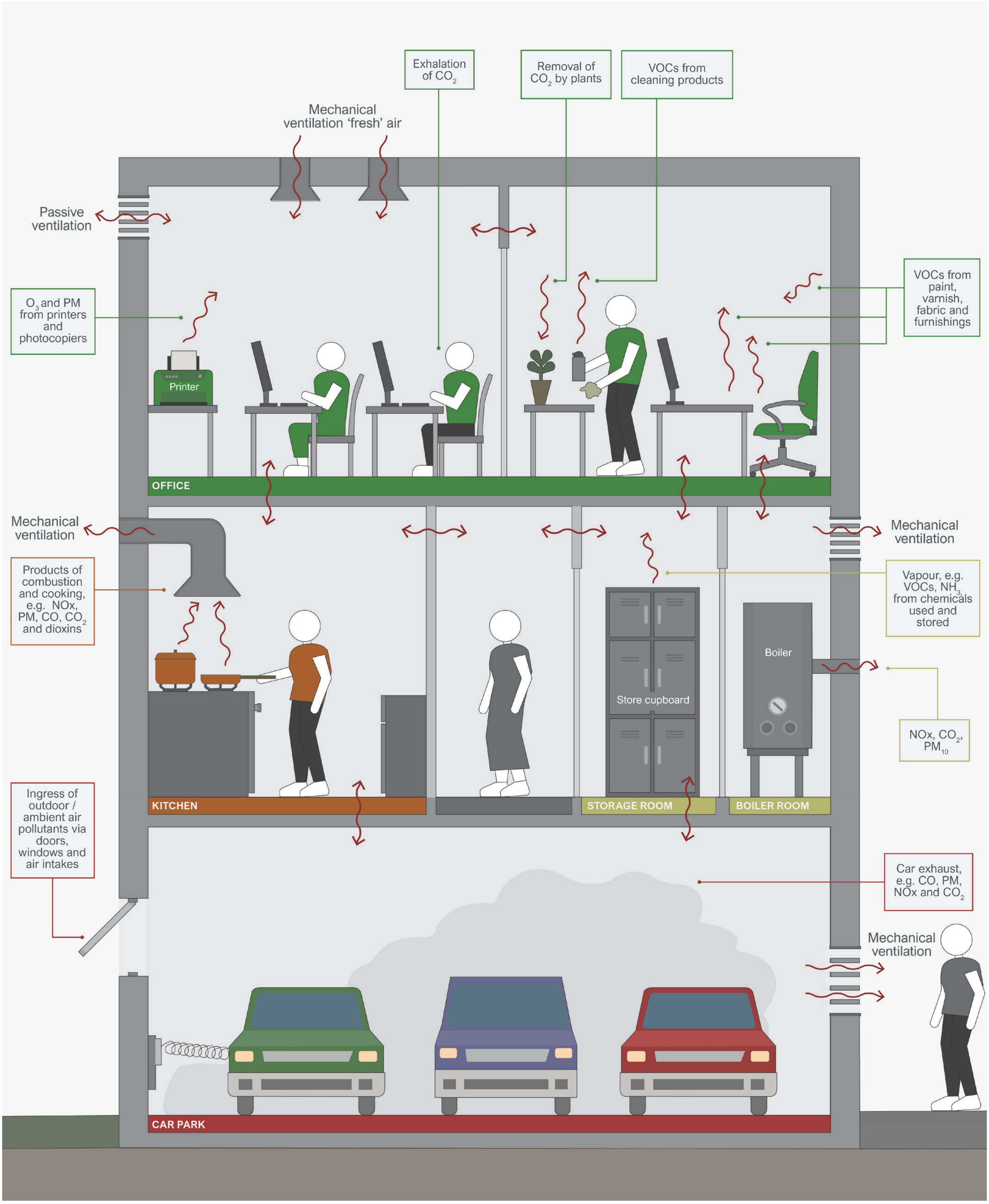
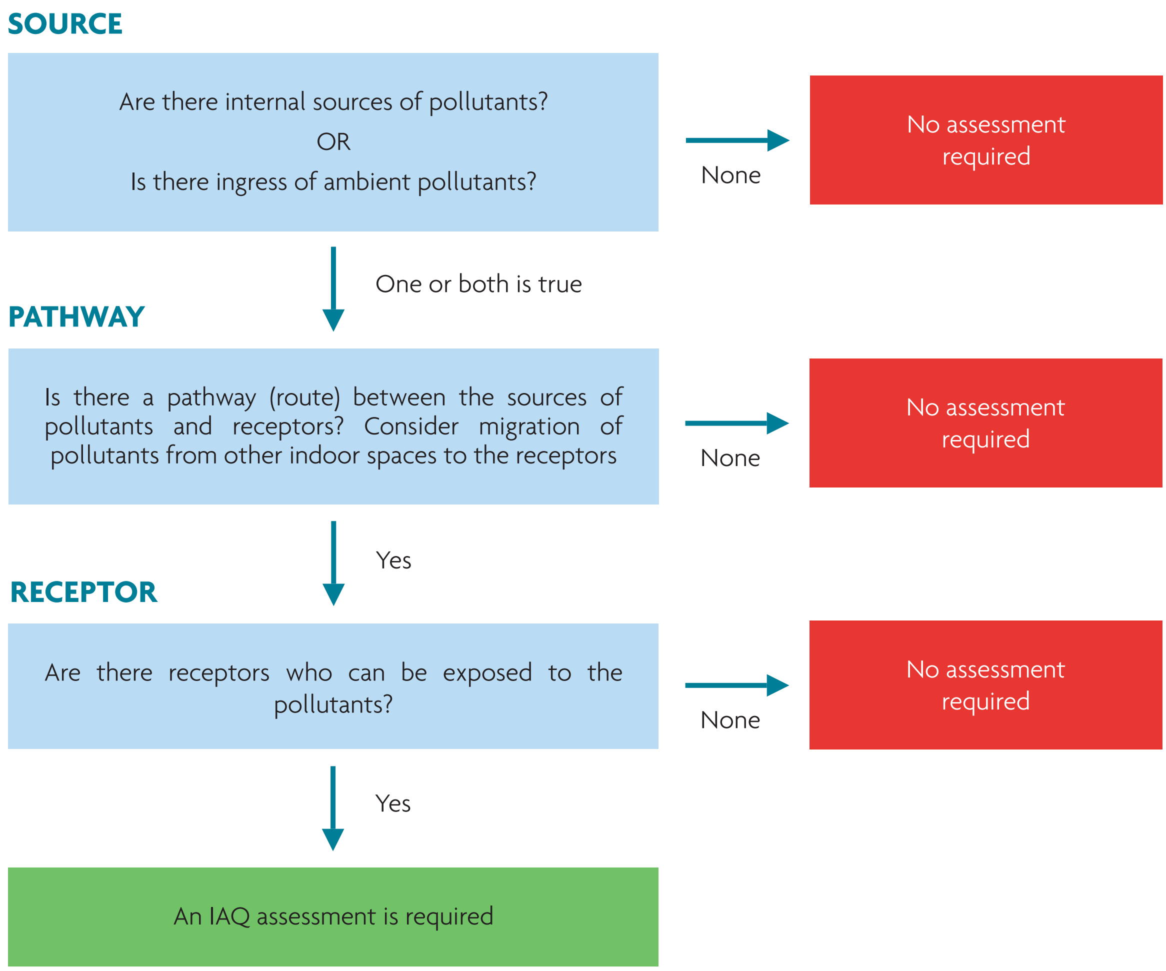


Figure 4.2: Determination of the Need for an IAQ Assessment



4.1.13. It is vital that there is good communication between the IAQ consultant and the wider team: architect, building services engineer and decision maker for product selection, to ensure that the best approach for IAQ is adopted. The way a building is actually used may differ from that planned at the design stage: occupancy rates/locations may change, and ventilation systems as designed may not fit the layout in operation. Air circulation may be affected by actual conditions and the ventilation system may fail to accommodate these changes.

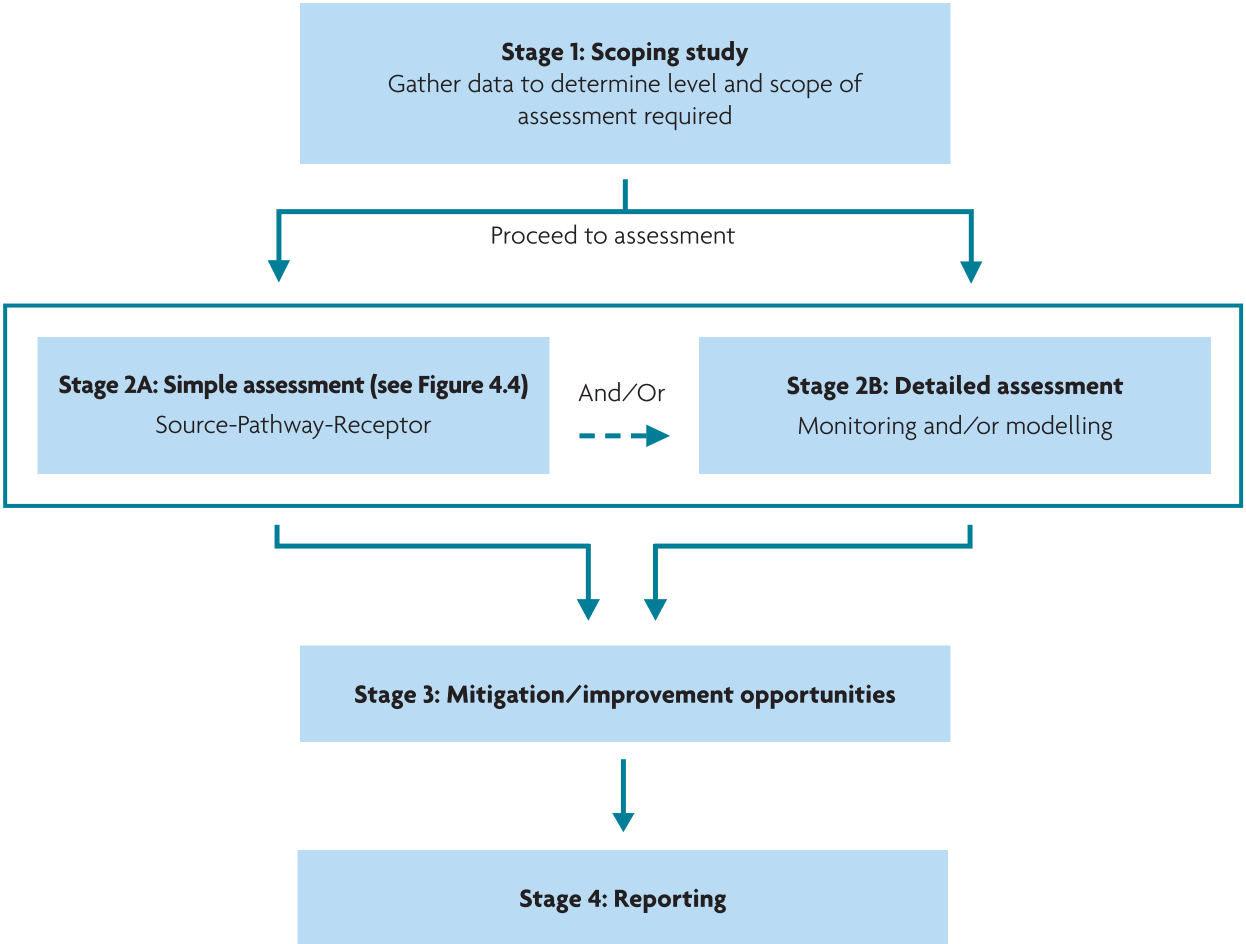
4.2. IAQ Assessment Stage 1: Scoping Study – Collation of Relevant Information

4.2.1. Stage 1 of the assessment is a **Scoping Study**, comprising the collation and review all the available information, and may include a walkthrough of the building. Where a building is already built (including a new build where IAQ has not been considered) monitoring may be appropriate in order to understand the baseline. The aim is to identify the issues, that is, the pollutants of concern in the specific context of the building under assessment, and the level of assessment required. The assessment itself is undertaken in Stage 2.

4.2.2. Factors listed in **Box 2.1** and **Box 4.1** should be taken into account in the assessment of IAQ. **Table 3.1** provides a list of some of the most important pollutants found indoors. The list of pollutants is not exclusive and there may be other pollutants that exist and need to be included in the assessment.

4.2.3. Where the IAQ Assessment relates to an existing building, and the assessment is being undertaken in response to complaints or a building user survey, the cause of the issue may not be immediately obvious. A site survey of an existing building may be appropriate to identify any problem areas and any potential solutions. Guidance exists (CIBSE, 2017a), as well as other publications on survey technique (Bunn, 2018) and checklists (Bunn & Marjanovic-Halburd, 2017). A useful flowchart on how to investigate and diagnose IAQ problems is contained in Section 6 of the USEPA's Building Air Quality Guide (USEPA, 2014). Complaints are often vague such as users reporting the building feels 'stuffy', or it is 'difficult to concentrate'. Other factors such as relative humidity

Figure 4.3: Stages of an IAQ Assessment



or temperature may be the source of the complaint or contribute to it in association with air pollution. This also needs to be taken into consideration and may need to be included in any monitoring.

4.2.4. For new build, at the design stage (i.e. RIBA Stages 2 and 3) all potential sources of pollutants that will affect the indoor environment of a building right through its life need to be considered, as far as is possible given the particular project.

4.2.5. The most commonly considered pollutants that enter a building from outside sources are NO_2 and PM. Local outdoor pollutant sources, their type, likely magnitude and distance from the proposed building should all be considered at the design stage and mitigated if required through the good design of the ventilation system, including suitable filtration (designed to remove the pollutant(s) of concern), location of the air inlets etc. (Kukadia & Hall, 2011).

4.2.6. There will always be ingress of pollutants into a building through the building fabric. If the building is poorly constructed and/or old, this route can be an order of magnitude greater than for a well constructed building, WSP found intrusion rates were almost 100% in older buildings (i.e. negligible attenuation of outdoor air pollution) and as low as 27% (i.e. 73% attenuation of outdoor pollution) for air tight buildings (Walsh, 2020). The Chartered Institute of Building (CIOB) has identified that poor construction quality is an issue throughout the construction industry due to the need for better trained staff, clearer codes and standards for quality, and a culture change where quality management is treated in the same way as health and safety (CIOB, 2018).

4.2.7. Indoor pollutant sources to consider in new builds after occupation include off gassing from the buildings' construction and fit out materials which may continue in some cases for months, or even years, after completion. Post occupation activities are also important and indoor pollutant sources in operation may include cleaning fluids, aerosol sprays, cooking etc. depending on the building's purpose for which it has been built.

4.2.8. Consideration should be given to the impact of the building on the local environment e.g. NO_x emissions from gas boilers, from other combustion plant and from vehicle emissions associated with

Box 4.1: Factors to Consider During Assessment

Pollutant sources

- Local outdoor pollutant sources (e.g. traffic, neighbouring buildings, industry)
- Indoor sources (e.g. building works, gas cookers, maintenance, decoration, cleaning, use of toiletries, candles)
- Temporal variation of pollutant sources (seasonal, weekly, daily, hourly) including the decay of pollutants present at fit out

Building design

- Ventilation strategy (hours of operation, recirculating, air changes)
- Air flow including the presence of 'dead zones'/ effectiveness of air distribution
- Number of people room is designed to accommodate
- "Stack effect"
- Heating/cooling strategy
- Pollutant filtration (e.g. poorly sealed building)
- Room volume

Building activities

- Electronic equipment
- People movement from one space to another
- Smoking/vaping
- Cleaning
- Time spent in different locations

Indoor environment

- Temperature
- Relative humidity
- CO_2 concentrations

the building. Any airborne polluting emissions (e.g. cooking emissions, fume cupboard discharges, energy generation, log burning stoves) from the building should be properly discharged, so that they disperse adequately to minimise their effect on the local environment and also avoid ingress back into the same building or into surrounding buildings.

4.2.9. When a building is operational, a wide range of sources of air pollutants will need to be considered in addition to those for new build, such as cleaning materials, use of toiletry products, and cooking emissions. The pollutant(s) of concern may be secondary pollutants formed in the indoor air due to the presence of another pollutant (such as ozone). In these circumstances, it is likely that monitoring will be required to identify the likely pollutant(s) and their sources (see **Chapter 5**). At the scoping stage of the assessment professional judgement should be used to identify the most likely pollutants that may be present and their sources for assessment in Stage 2.

4.2.10. Air can move from one part of a building to another (migration) and the potential for this needs to be considered. There can be a pressure differences due to height under very hot or very cold conditions which will result in internal air flows. This is true even for a single storey building. However, for tall buildings, the effect is more significant and, for instance, air flows up or down a lift shaft can transport polluted air. Some areas may be under positive or negative pressure (intentionally or not) and this will move air around the building, possibly worsening IAQ (e.g. if kitchens or toilets are not negatively pressurised outflow of polluted air to may result in greater exposure of occupants).

4.2.11. The IAQ professional should advise on the avoidance of products with unacceptably high emissions of chemicals and should take into account the availability of e.g. low emitting products that are commercially available. It is important to ensure that one toxic component has not been replaced by another. A good understanding of building and fit out materials is required as the content of building products is rarely labelled. As product innovations continue, it is important for the IAQ assessors to keep up to date and question what materials are made from and where emissions, particularly of VOCs, have been measured.

4.2.12. Where possible, the criteria for use in the IAQ assessment should be confirmed in the Stage 1 Scoping Study (see **Table 3.1** for some criteria) so that it is clear in what range any monitoring technique is required to perform.

4.2.13. The conclusion of the scoping study is whether to proceed to further assessment. If there is a need to further assess IAQ then generally a Simple Assessment will be the next step; it may be possible to conclude at the end of Scoping that a Detailed Assessment is required. It may not be possible given the level of design or detail available to proceed to a Detailed Assessment but if one is likely to be needed this can be a recommendation. Scoping reports at the design stage should include recommendations for design-related preventative measures. The reasons for reaching the conclusion of the scoping study should be clearly set out in a formal report to the client.

4.3. IAQ Assessment Stage 2: Assessment

4.3.1. The type of projects that require an IAQ Assessment vary, and it is not possible to be prescriptive on the assessment methodology. The aim of this section is to provide a general approach for the assessment. It should be noted that for some projects a Stage 2A Simple Assessment may be sufficient, particularly for new build, where voluntary accreditation is not being sought. Where voluntary accreditation is being sought the first step will be a Stage 2A Simple Assessment followed, post completion of the building (new or refurbishment/retrofit), with a Stage 2B Detailed Assessment. For an existing/completed new building or when investigating complaints from occupants it may be appropriate to omit Stage 2A and focus on identifying the source(s) of the issue and possible actions to resolve the issue.

4.3.2. Other projects, such as those dealing with occupant complaints, may only require a Stage 2B Detailed Assessment to understand the causes and solutions required, with no Stage 2A Simple Assessment required.

Stage 2A: Simple Assessment

4.3.3. It may be possible to determine the likely effects using a simple risk based approach. The risk being assessed in this Stage 2A Simple Assessment relates to the probability that someone/something will be harmed due to exposure to an air pollutant.

4.3.4. This approach considers the probability that a pollutant is likely to be present in a building where people spend time and the risk of that pollutant causing harm. It does not include modelling or measurement of pollutant concentrations. It simply assesses whether there could be an IAQ issue based on the information gathered in Stage 1 Scoping. This approach is intended to be conservative, i.e. is likely to over estimate the risk of unacceptable harm, and is used to identify the need for improvement in the IAQ in the assessed building. It should not be used to consider the risk from carcinogens such as benzene because there is no threshold below which there is no health effect. **Figure 4.4** shows the four steps in the Stage 2A Simple Assessment.

4.3.5. There may be synergistic effects of mixtures of pollutants but there are, in general, no health guidelines for mixtures (except the carcinogenic effects of diesel exhaust). Therefore, each pollutant for which there is a relevant health guideline should be treated individually. The highest scoring pollutant should be used to determine the outcome of the **Stage 2A Simple Assessment.**

4.3.6. In a Stage 2A Simple Assessment the issues in **Box 4.1**. need to be considered together with any atypical uses of the building being assessed.

4.3.7. This approach has been tested using information from IAQ monitoring studies for different types of buildings and the outcome has agreed well with the more detailed studies, providing some confidence in our recommended approach.

4.3.8. Other assessment methods may be appropriate and professional judgement should be used to consider whether the outcome is appropriate.

Figure 4.4: Schematic of the Stage 2A Simple Assessment

Step 1
Identify magnitude of hazard from ingress of outdoor air (see **Box 4.1**)

↓

Step 2
Identify magnitude of hazard from indoor sources of emissions (see **Box 4.1**)

↓

Step 3
Consider exposure

↓

Step 4
Risk assessment

STEP 1: Ingress of Ambient (Outdoor) Air Pollution

4.3.9. STEP 1 uses **Table 4.1** to identify the magnitude, on a scale of 0 (no ingress) to 5 (high ingress of polluted air), of the potential harm that the ingress of ambient air into the building could cause if someone is exposed in the indoor environment being assessed. The WHO AQGs mentioned in **Table 4.1** and subsequent sections of this methodology refer only to those published prior to 2021 as the full implications of the new AQGs and interim targets (WHO, 2021) has not yet been taken into account. The location of the air intakes, windows, external doors, seals etc. can make a considerable difference to the amount of ambient pollution entering a building and should be considered when determining the score from **Table 4.1** that is taken forward in the assessment. Both outdoor air quality and the pathway into the building need to be considered. In many urban areas the outdoor air quality is likely to mean that all buildings under assessment will be scored 4 or 5. Professional judgement should be used to determine appropriate ambient (outdoor) air quality concentrations which will include consideration of the output from modelling studies, monitoring data and/or online background maps.

4.3.10. **Table 4.1** also includes tobacco smoke as it may pass into a building from an outdoor smoking area. Professional judgement, taking into account the magnitude and proximity of the source, is needed but a smoking area more than approximately 10-20 metres from an inlet (vent/window etc) is unlikely to be relevant. This distance should NOT be used as a screening distance.

STEP 2: Internal Sources

4.3.11. STEP 2 identifies the internal sources of air pollutants and whether there are effective pathways to users of the building. Where the types of materials used, or to be used, is known useful information may be available. These may be obtained from life cycle inventories (LCIs) (e.g. the LCI Group) used to develop life cycle analyses (LCAs) or certification of construction and fit-out materials. Many publications (e.g. Woolley, 2017; USEPA, 2021b) give examples of products and likely emissions of concern for IAQ.

4.3.12. It may be useful to divide a building into areas where there are different sources and receptors.

4.3.13. STEP 2 uses **Table 4.2** to identify the magnitude on a scale of 0 (no emissions and/or no pathway) to 5 (very high emissions/effective pathway) of the potential harm that may be caused by emissions from internal sources (either direct or indirect). "PM" in **Table 4.2** will be the relevant size fraction(s) of the particulate matter; it may include all particle sizes potentially affecting health (PM_{10}, $PM_{2.5}$, $PM_{1.0}$ etc.) or one fraction (e.g. <$PM_{1.0}$ for tobacco smoke). Each specific VOC should be identified by a competent person (the assessor or their advisors).

Table 4.1: Magnitude of Potential Harm Caused by Ingress of Ambient (Outdoor) Pollution

Ambient Air Quality/very local source	Pathway			Key pollutants
	Openable windows/openings (including doorways) on roadside	Mechanical ventilation where inlet air is from unknown location	Openable windows/openings not near external sources of pollutant emissions or mechanical ventilation from known location	
Ambient concentration <50% of WHO AQG[(a)]	2	2	1	NO_x (NO_2), PM
Ambient concentration <75% of WHO AQG [(a)]	3	3	2	NO_x (NO_2), PM
Ambient concentration <90% of WHO AQG [(a)]	4	4	4	NO_x (NO_2), PM
Ambient concentration >90% of WHO AQG [(a)]	5	5	4	NO_x (NO_2), PM
Tobacco smoke	4	2	0	PM

(a) The AQGs in this table refer to previously published WHO AQGs guidelines (WHO, 2005 and WHO, 2010) and not those recently published (WHO, 2021). See **Section 3.1.3** and **4.3.9** for explanatory notes.

Table 4.2: Magnitude of Potential Harm Caused by Emissions from Internal Sources

Emission source	Pathway[a]			Key pollutants
	In same enclosed area as receptor	In the same or connected building as a receptor but not the same enclosed area		
		Managed ventilation/ identified S-R pathway (e.g. ventilation/open doors)	No managed ventilation/no S-R pathway	
Cleaning activity	3	2	1	Specific VOCs, PM
Storage of cleaning products	5	2	1	Specific VOCs
Open combustion source e.g. open fireplace, gas cooker	5	3	1	NO_x (NO_2), CO, PM, CO_2
Sealed combustion source e.g. wood burning stove	4	2	1	NO_x (NO_2), CO, PM, CO_2
Application/storage of new building materials	5	5	2	Specific VOCs
Newly painted/ varnished etc.	5	5	2	Specific VOCs
New furniture/ fixtures/fittings	4	4	2	Specific VOCs
Manufacturing – abrasive activities	5	5	2	PM
Manufacturing – activities involving chemicals/solvents etc.	5	5	2	PM, CO_2
Tobacco smoke	5	5	3	PM[b]
Air fresheners/scented products	5	3	1	Specific VOCs, PM
Electronic equipment e.g. photocopier, printer	3	2	1	O_3, PM

(a) Professional judgement can be used to revise these scores or add new emission sources; thorough justification should be provided in the IAQ Assessment Report.
(b) Method is not appropriate for the assessment of carcinogens from tobacco smoking.

4.3.14. Scores in **Table 4.2** may be revised and new emission sources added (e.g. personal care, dry cleaned clothes, hobby supplies, human borne dust, plants/soil) if circumstances dictate. Professional judgement should be used to take into account the magnitude/number of sources, types of pollutants, duration of exposure (which might be considerably less than occupancy time if the source is intermittent) and the effectiveness of the pathway. For example, a photocopier that is used for 30 minutes each working day would not necessarily score the same as one in constant use. All assumptions and decisions should be documented in the IAQ Assessment Report.

4.3.15. Table 4.2 should be used to score **each** activity/pollutant combination (e.g. cleaning, painting) that is within the scope of the assessment; the maximum score is then taken forward to **Table 4.4**. Depending on the outcome of the assessment in **Table 4.4** the appropriate action for each activity should then be taken as in **Box 4.2**. Each specific VOC should be scored using **Table 4.2** and the maximum score is taken forward to the next stage. It may be appropriate to undertake separate assessments for each activity and/or pollutant rather than relying on the maximum score overall.

4.3.16. As an example, in a small office environment, cleaning may result in **Negligible Risk** (from **Box 4.2**) and a gas boiler may result in **High Risk** (from **Box 4.2**); it would be the gas boiler that would be taken forward to **Stage 2B** and the assessment of cleaning would be complete.

4.3.17. Whilst smoking is prohibited in most indoor locations, it does occur, and therefore it has been included.

STEP 3: Exposure

4.3.18. STEP 3 considers the potential duration and frequency of exposure of people using the building for each pollutant. It is important that the maximum duration and frequency of exposure is considered. It may be necessary to divide a building into zones where different people (occupations) spend time and/or the exposure may be different (e.g. a receptionist may spend all their time next to an open street door whereas other occupants may only pass through this area).

4.3.19. The duration and/or frequency that individuals are present in a location are indicators of the exposure dose they may receive (the other important parameter is the concentration; which is unknown in the Stage 2A Simple Assessment). There are typically temporal variations in concentrations in indoor environments and increasing the frequency of exposure increases the probability of an individual being exposed to higher short term concentrations which may led to an acute health effect. The higher the frequency of potential exposure to air pollution is also an indicator of the potential long term exposure which may result in a chronic health effect.

4.3.20. In most non-industrial indoor environments away from busy roads, the greatest risk is likely to be due to exposure to specific VOCs.

4.3.21. Table 4.3 provides an indicator of the duration and frequency of exposure in the Stage 2A Simple Assessment. The two columns reflect whether the assessment criterion (see **Chapter 3**) is for a short duration or long duration reflecting whether there is evidence of an acute or chronic effect. For example, the PHE guidelines (PHE, 2019)

▲ **Image: © PhotoMIX | Pexels**

has two "limit values" for formaldehyde based on exposure over 30 minutes and one year. This pollutant would be assessed using the 'Acute or Acute and Chronic Response' column. Xylene mixtures should be assessed using the 'Chronic Response' column, as PHE only provide a guideline applicable to exposure over one year. Professional judgement is required to ensure that potential exposure to pollutant concentrations is correctly represented and not just a function of the time a receptor is present or the duration over which a source is emitting. Pollution may be present after an emission stops (e.g. an unextracted gas hob) or concentrations may reduce by extraction or absorption.

STEP 4: Risk Assessment

4.3.22. STEP 4 is the risk assessment. It combines the magnitude of the potential for harm from the ingress of ambient air (**Table 4.1**) and indoor sources of pollution (**Table 4.2**) with the potential exposure (**Table 4.3**), as shown in **Table 4.4**.

4.3.23. The highest value for each pollutant from either **Table 4.1** or **Table 4.2** should be used as the magnitude of potential harm; if the scores have been modified after using professional judgement and the maximum value from **Tables 4.1** and **4.2** is zero (0) then this aspect is effectively screened out. The resultant risk categorisation from **Table 4.4** should be taken forward as specified in **Box 4.2**. The tables may be used multiple times in an assessment with each set addressing e.g. a specific location or pollutant. Some versions of **Table 4.4** may include zero (0) as the overall score and the risk is therefore zero.

4.3.24. The results should be summarised in a table (as illustrated in the case studies in **Appendix E**).

Stage 2B Detailed Assessment

4.3.25. The detailed assessment may follow on from a simple assessment or may follow directly from the Stage 1 Scoping Study, missing the Stage 2A Simple Assessment stage.

4.3.26. The Stage 2B Detailed Assessment will generally include computer modelling and/or measurement, e.g. pollutant concentrations, temperature, relative humidity and airflow (N.B. ventilation rates can be determined by measuring CO_2 concentrations

Table 4.3: Potential Duration/Frequency of Exposure of the Most Sensitive Groups of Individuals

Potential duration and frequency of exposure	Pollutant class	
	Acute or Acute and chronic response	Chronic response
Intermittent & infrequent E.g. up to 8 hours/week	Medium	Low
Continuous during typical working day E.g. up to 40 hours/week	High	Medium
Continuous throughout day E.g. up to 80 hours/week	High	High
Continuous More than 80 hours/week	Very high	Very high

in new or existing buildings). Modelling is the only option for a proposed building but the cost and time involved may not be warranted. Professional judgement will need to be used to determine the approach taken and the level of detail possible and relevant.

4.3.27. The monitoring of IAQ is covered in detail in **Chapter 5**, and computer modelling is described briefly in **Chapter 6**. The choice of assessment technique will depend on the project. Both techniques have advantages and limitations. Professional judgement is needed to determine if either or both are relevant and possible, taking into account e.g. accessibility, timeframe and/or budget.

4.3.28. Measuring IAQ is not simple, as IAQ is not homogeneous spatially or temporally. For example, opening a window may or may not improve IAQ, depending on whether the pollution source is inside or outside the building. It will also affect the airflow and could bring air pollution from outside further into the building, depending on the time of day. There may be other

Table 4.4: IAQ Risk

Magnitude of Potential Harm (i.e. Max. value from Table 4.1 or Table 4.2)	Potential Exposure (from Table 4.3)			
	Very high	High	Medium	Low
5	High risk	High risk	High risk	Medium risk
4	High risk	High risk	Medium risk	Medium risk
3	High risk	Medium risk	Medium risk	Low risk
2	Medium risk	Medium risk	Low risk	Negligible risk
1	Medium risk	Low risk	Low risk	Negligible risk

Box 4.2: Stage 2A Recommended Further Actions

High Risk: For an existing or newly completed building consider whether monitoring IAQ is necessary (concentrations may be much lower indoors than outside). Consider taking immediate action(s) to reduce harm/exposure. For a proposed building consider whether the design should include mitigation (such as filtration). Use professional judgement to determine if a **Stage 2B Assessment** is appropriate.

Medium Risk: Undertake a **Stage 2B Detailed Assessment**.

Low Risk: Stage 2B Detailed Assessment not required. Go to **Stage 3 Mitigation/improvement opportunities**.

Negligible Risk: Stage 2B Detailed Assessment not required. No further assessment required.

reasons to open a window (e.g. to reduce CO_2, pathogens) which outweigh the potential negative effect it might have on IAQ.

4.3.29. **Chapter 5** describes instruments for measuring IAQ. They need space, may require power and a data connection (wired/WiFi/Cellular). For an occupied building, equipment may need to be quiet and unintrusive, so that their presence does not affect normal activity within the measurement area. Some measurement equipment may be affected by the building users themselves if positioned too close. Therefore, the choice of measurement location, given these constraints and the heterogeneous nature of IAQ, may not always be ideal. These constraints may also lead to compromises regarding the measurement equipment such that methods with lower detection limits, poor temporal resolution or lower accuracy. Similarly, the temporal variability in IAQ means that it is important that measurements are undertaken when and where there is likely to be exposure.

4.3.30. It is important to consider the conditions prevailing before and during measurements, including:

- what time has elapsed since construction or refurbishment was completed;
- whether cleaning or decorating has taken place and were potential emissions included in the IAQ assessment;
- ventilation and other heating/cooling activities; and
- whether cooking or other occupant activities might affect the measurements.

4.3.31. Temporal variations in indoor sources of air pollutants such as cleaning, cooking and outdoor sources such as traffic, and seasonal variations that affect ambient temperature and background pollutant concentrations should also be considered when planning a monitoring campaign.

4.3.32. Models can quantify the interaction between the indoor and outdoor environments and the chemistry that occurs within buildings.

4.3.33. **Chapter 6** includes a brief review of the types of models used. They are particularly useful in assessing buildings at the design stage when monitoring is not possible and in assessing multiple options for measures to find an optimal solution. It is desirable to use monitoring data to verify model results but, as in the case of buildings at the design stage, this may not be possible and typical data from similar environments/situations may be applicable.

4.4. Stage 3: Mitigation/Improvement Opportunities

4.4.1. The final stage of the IAQ Assessment (unless there is negligible risk of harm) is to identify appropriate and effective mitigation (reduction) and improvement measures. Further details can be found in **Chapter 7**.

4.4.2. Mitigation measures should consider the sources, pollutants and receptors identified. Several measures may be required that have an effect on different parts of the Source Pathway Receptor model, and therefore an integrated approach taking all of them into account may be required.

4.5. Stage 4: Reporting

4.5.1. The IAQ assessment report should consider the inclusions of the following and may include other items (e.g. appendices) as the author considers appropriate:

- outcome of the Stage 1 Scoping Study, including IAQ issues identified;
- building description: e.g. type, floor plans, sensor location, locality, ventilation system, zones, uses;
- climate data/wind direction/speed etc.;
- sources of emissions (indoor and outdoor (if relevant)) and pollutants emitted;
- pathways;
- sensitive receptors identified;
- assessment criteria;
- assessment methodology;
- assessment results and interpretation;
- mitigation, improvement and preventative (particularly for design-stage scoping reports) measures; and
- description of any ongoing monitoring (including the make, model, accuracy, resolution, sampling frequency etc. of monitoring equipment).

4.5.2. The assessment methodology section should justify the choice of assessment method made, any tools used and outline any assumptions or limitations.

5. Monitoring Indoor Air Quality and Personal Exposure

5.1. Reasons to Sample

5.1.1. Monitoring indoor air pollutants is generally preferable to modelling them if one wants to understand their impact on users of an existing building. Modelling (see **Chapter 7**) may provide additional useful information e.g. on spatial variation within a building. This Chapter explains the many factors that affect how accurate and representative the monitoring is and some of the choices to be made when designing a monitoring program. Consideration should be given as to where and how monitoring data should be archived. It could be required years later to prove/disprove subsequent claims e.g. about possible health effects arising from occupants that worked in certain buildings/areas.

5.2. What to Sample

5.2.1. The main pollutants that may affect IAQ are shown in **Chapter 3 (Table 3.1)**, along with relevant guideline concentrations. Other guidelines may be relevant, depending on the specific circumstances. Professional judgement is required to select the most suitable pollutants in Stage 1 of the IAQ Assessment. Examples of guidance and pollutants covered are also given in **Appendix C**.

5.3. Sampling Duration

5.3.1. Sampling duration is dependent on many factors, including:

- the purpose of the survey;
- the pollutant(s);
- building use and accessibility;
- assessment criteria, (averaging period/s and statistical parameters); and
- variability of the concentrations over time.

5.3.2. The IAQ sampling duration should be sufficiently long to be representative, be comparable to the appropriate assessment criteria, as well as to capture both the peaks and troughs in the variability of the pollutant concentrations.

5.3.3. Continuous monitoring devices (such as electrochemical sensors which generally record pollutant concentrations at a high temporal resolution over shorter averaging periods) will capture any variation in pollutant concentrations. Passive devices (e.g. diffusion tubes) monitoring are useful to generate longer term means and because they are low cost can be used at multiple locations to gain understanding of spatial variations. However, they may miss important variations in pollutant concentrations.

5.3.4. Collection of short term measurements (e.g. 15 minutes) may be more appropriate in more sensitive indoor environments, thereby reducing the presence of an air quality professional and/or potentially noisy monitoring equipment which may be disruptive. Also, where a sample location could be prone to tampering, short-term measurements, attended by the operator, are preferred.

5.3.5. The timing of when a measurement is taken is also a key consideration. Short term activities such as cleaning could represent an acute pollution emission 'event' and a single, short term IAQ measurement taken during such an event would not be representative or the likely exposure of occupants. Short term measurements can be repeated so that statistical analysis (e.g. coefficient of variation) is possible. Timing of repeat measurements should be spread over a period designed to be representative and capture variability.

5.4. How to Sample

5.4.1. In the UK there is no specific IAQ equivalent to the Environment Agency's Monitoring Certification Scheme (MCERTS). MCERTS deals with the performance testing and accreditation of ambient air quality monitoring equipment, data loggers and software and may apply to some techniques used to measure IAQ (e.g. Tenax tubes for BTEX). However, there is an International Standards Organisation (ISO) technical committee/working group that address various aspects of IAQ including monitoring and testing methods (ISO/TC 146). WHO (see **Appendix C**) also includes testing methods for air quality guidelines. The selection of suitable IAQ monitoring methods and equipment is often left to professional judgement of competent and suitably qualified air quality professionals.

5.4.2. IAQ monitoring can be carried out using ambient air quality monitoring equipment for some pollutants. Ambient air quality monitors can often detect concentrations well below those required to assess occupational exposure and so may be better suited to IAQ assessment than equipment designed for assessing occupational exposure in industrial workplaces. Workplace exposure tends to be measured in milligrams per cubic metre (mg/m^3) or in parts per million (ppm) whereas outdoor (ambient) air quality standards are typically in micrograms per cubic metre ($\mu g/m^3$) or parts per billion (ppb) i.e. workplace exposure is expected to be several orders of magnitude greater than outdoor air concentrations.

5.4.3. Monitoring equipment selection is largely dependent on the pollutants of interest, the assessment criteria (and related detection limits) and the available timescale for undertaking the monitoring. However, as noted above there are some ISO methods that apply, primarily for VOCs and these are sometimes pre requisites for certain assessments e.g. (BRE, 2014), (US Green Building Council, 2020) and (International WELL Building Institute, 2020). Suitable monitoring methods can either be passive/diffusive or active (powered) – see **Appendix G** for details of these types of technique.

5.4.4. To assist in the interpretation of the data it is important to collect information relating to factors that may affect the results of sampling (e.g. building occupancy, activities being undertaken prior to and during sampling, ventilation rates, weather conditions, outdoor air quality).

5.4.5. Some buildings may have more than one location from which outdoor air is drawn e.g. more than one air handling unit (mechanical ventilation system) located at different locations around/on the building. In these cases, sampling needs to be undertaken at sufficient locations within the building to ensure that any such variability is taken into account.

5.4.6. **Figure 5.1** shows an example of the effect of averaging period/sampling period on concentration data values for NO_2. The sampling took place over two full 24-hour periods and 5-minute means were recorded. The range of 5-minute mean values was 4.3-30.5 µg/m^3. The data have then been averaged over 1, 8 and 24 hours (running averages) and from the table at the top of the figure it can be seen that the range of values becomes increasingly narrowed as the averaging period lengthens until at 24 hours the range is 8.3-13.3 µg/m^3; the maximum 24-hour value represents only 44% of the maximum 5-minute mean. Examination of the data shows how concentrations can vary throughout the day and day to day (e.g. concentrations at noon are quite different on the each of the two days). These data were taken from a site with no obvious local source of NO_2 and so may not represent the magnitude of variation that might exist in other circumstances.

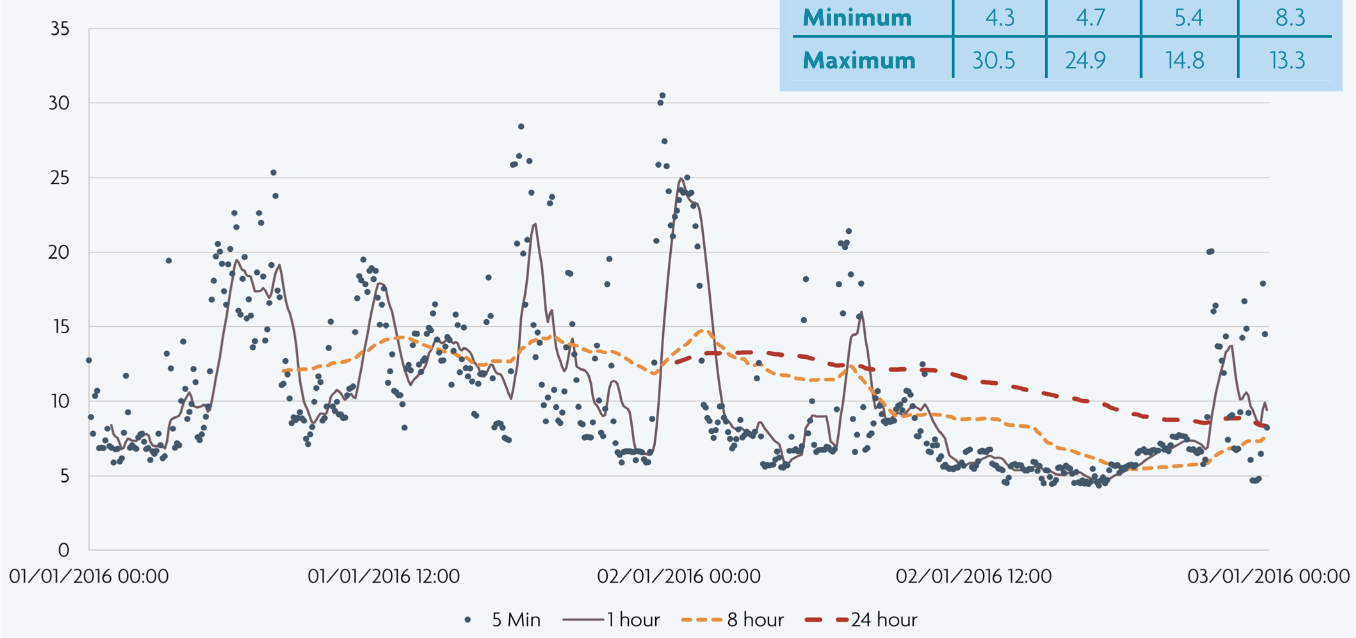
5.4.7. Methods for sampling indoor air largely follow methods already used in occupational exposure monitoring, building performance and ambient air quality monitoring and are summarised in **Table 5.1** with further information given in **Appendix G**.

5.5. Where to Sample

5.5.1. The IAQ assessor should review the existing IAQ assessment guidance (see **Appendix C**) and then adopt a 'hybrid' BREEAM/WELL approach in selecting the number and location of sampling points. In some cases it may be appropriate to consider personal sampling equipment that accompanies them throughout their occupancy of a building under assessment. It is likely to be necessary to remove/deactivate the sampler when the person exits the building and a questionnaire may be appropriate to determine how well the sampling period represents their normal use of the building. However, where an IAQ Assessment is required following a complaint or an identified issue, the monitoring should focus on area(s) of concern within the building rather than aiming to be representative of the whole building or each type of room.

Figure 5.1: Effect of Averaging Period on Reported Concentration (µg/m^3)

	5 min	1 hour	8 hour	24 hour
Minimum	4.3	4.7	5.4	8.3
Maximum	30.5	24.9	14.8	13.3



5.5.2. IAQ monitoring should be undertaken in representative regularly occupied or attended spaces. Samples should be collected from each different type of room and each space which has a different function. It is not necessary to sample in every room in a building; a single sample of air from a room may be considered to be representative of similar rooms in the same building. Examples of spaces with different uses are listed below:

- offices;
- meeting rooms;
- reception areas;
- post rooms;
- workshops;
- classrooms;
- hospitality/kitchens;
- living areas; and
- bedrooms.

5.5.3. However, in some cases there are different ventilation regimes, proximities to the outside and other factors that may need to be considered in determining the number of samples required in order to be representative. Potential effects of furnishing, room size, persons present, activities within the building, orientation of the building/vents/windows need consideration in designing the survey. Wind speed and direction may also be important factors in relation to the ingress of outdoor pollution to indoor spaces. Duplicate/replicate measurements should be taken to investigate the homogeneity of the indoor atmosphere; especially in large rooms/open plan offices. Sampling in response to a complaint or issue may include measurements within and outside the area(s) from which the issue arose or even outside the building itself.

5.5.4. For multi storey buildings, measurements should be distributed over different floors and should always be carried out on at least the lowest and highest regularly occupied floors; additional floors may also need to be included. One study (Stamp, *et al.*, 2020) showed for example, that indoor NO_2 concentrations were higher on the 4th floor compared to measurements taken on the 3rd and 7th floors. **Table 5.2** can be used as a guide to select the number of sampling locations,

Table 5.1: Range of Sampling Methods Available for IAQ Monitoring

Method	Pollutants	Typical Sampling Duration	Uncertainty$^{(a)}$ (%)
Diffusion tubes	NO_2, SO_2, NH_3, O_3, VOCs	1 to 4 weeks	±25
Exposure badges	VOCs, Formaldehyde, Ethylene Oxide, NH_3, O_3, HCN, Hg	1 to 8 hours	±100
Pumped indicator tubes	NO_2, SO_2, NH_3, O_3, VOCs, Formaldehyde, Ethylene Oxide, HCN	2 to 10 minutes	±100
Pumped sorption tubes	VOCs, Formaldehyde, Hg	15 minutes to 8 hours	±25
Personal particle monitors	PM_1, $PM_{2.5}$, PM_4, PM_{10}, TSP	5 minutes to 8 hours	±25
Filter particle samplers	PM_1, $PM_{2.5}$, PM_4, PM_{10}, TSP	1 hour to 28 days	±25%
Indicative gas monitors	NO_2, SO_2, NH_3, O_3, VOCs	1 minute to 1 hour	±100%
Indicative particle monitors	PM_1, $PM_{2.5}$, PM_4, PM_{10}, TSP$^{(b)}$	1 minute to 1 hour	±100%
Reference/equivalence continuous air quality monitoring	NO_2, SO_2, NH_3, O_3, VOCs, PM_1, $PM_{2.5}$, PM_4, PM_{10}, TSP	5 minutes to 1 hour	±15%

(a) Uncertainty is just given as an indication and are likely to represent and upper bound of the likely uncertainty range.
(b) It may not be possible to measure TSP (total suspended particles) as most samplers measure PM smaller than 20 µm (PM_{20}).

Table 5.2: Number of Sampling Points Required Based on Project Area and Number of Floors

Floors based on International WELL BI (2020)	Total Project Area[a]	
	<50,000ft²	≥50,000ft²
	<4,600m²	≥4,600m²
1	2	3
2	2	4
3-4	3	5
5-7	3	6
8-10	4	7
11-15	5	8
16-20	6	9
>20	7	10

(a) See the full reference (International WELL Building Institute, 2020) to determine how these floor areas should be applied to leased and non-leased areas.

depending on building floor area and height. However, in large, open plan offices for example, additional sampling locations may need to be added in order to obtain representative samples. In some cases, it may be appropriate to increase the monitoring to around one sensor per 250 m² (Wealend, 2021). Professional judgement should be used to determine an appropriate number of sample locations and in some cases fewer than suggested in **Table 5.2** may be required.

5.5.5. In line with the latest CIBSE Guidance (CIBSE, 2020b), IAQ measurements should take into consideration the main building users breathing zone: e.g. at seated (or standing) height for office workers, to best represent their specific exposure conditions, which typically would be away from air supply grilles and away from any identified indoor sources of pollution.

5.5.6. In line with the most relevant statutory guidance, radon measurements are only recommended if the building being assessed is located in a Radon Affected Area.

5.5.7. If any additional COSHH EH40 (HSE, 2020) substances require assessment to address exposure concerns from specific activities, measurements should be taken to best represent the exposure scenario conditions of the individual(s) potentially affected.

5.6. Suitability of the Monitoring Method

5.6.1. Specific monitoring methods and performance criteria are set out in the guidance and voluntary building assessment/certification schemes and are summarised in **Table 5.1**, **Appendix G** and for example (Kukadia & Upton, 2019).

5.6.2. When selecting a monitoring method, the proposed methodology should be critiqued as to whether it is able to meet the requirements of the indoor environment of interest, giving consideration to the following points.

- Size of the instrument: will the instrument, unobtrusively, be able to be installed within the area to be sampled?
- Requirements of the instrument operation: does the instrument require a specific power supply, data connection (wired/WiFi/cellular) particular position within an indoor space, or is it particularly sensitive to interference?
- Noise and vibration: will the instrument generate noise and vibration which could potentially disturb room occupants or affect the normal use of the room?
- Spatial variation of concentrations: what is the prevailing movement of air in a room (heating sources and ventilation channels may unduly affect pollutant concentrations by dilution or mixing which may not be representative of the rest of the room).
- Type of instrument and site access (access for servicing, filter replacement, tube changes etc.)
- Reliability and accuracy (especially if low cost monitoring equipment, how data compares to reference instruments).
- Legal or other requirements for e.g. calibration, duration, reference monitoring methods.
- Calibration and long term performance (some types of long term monitoring sensors have auto calibration for some pollutants, others require to be sent back to supplier for re calibrating. Re calibration is good practice for the overall performance of most sensors as they will drift over time).
- User interaction and potential impact on measurements (particularly in schools: example of children breathing on top of monitor and spraying deodorants near it causing different spikes; or if using passive tubes, school children may move them as well if not fixed or smartly hidden so that they are not tampered with).
- Accompanying chemicals, gases, emissions or exhausts: could there be a potential risk to health from the presence of harmful chemicals, gases or other indirect effects of its operation, e.g. does it require storage of gas calibration cylinders, will it emit chemical by products?

5.6.3. Equipment commonly used to assess pollutant concentration against EH40 WELs may not be sensitive enough to for assessment against WHO or PHE guidelines. It is important therefore to know the expected pollutant concentrations and the limitations of the monitoring techniques proposed. Some techniques may also provide the necessary sensitivity but may be too complex or expensive to be of use.

5.6.4. Scoping and review of existing or newly acquired data should inform the selection of which pollutants to measure, e.g. if the indoor environment in question is located in a Radon Affected Area radon levels should be assessed. TVOCs may be monitored and if found to be present in high concentrations then targeted monitoring for specific VOCs (taking into account potential sources) can be undertaken.

5.6.5. In some circumstances, where no IAQ guidelines exist for a specific pollutant, it may be necessary to derive a suitable monitoring method and assessment criterion (see **Section 3.2** for guidance).

6. Modelling Indoor Air Quality

6.1.1. This Chapter gives an introduction to the large and well developed subject of modelling IAQ; it gives an overview of the concepts, advantages and drawbacks of modelling.

6.1.2. Modelling is one means of assessing the concentrations of one or more pollutants within, and in/out of a building. This is an approach that is different from monitoring in several important ways, although it can be a complementary activity. While monitoring pollutant concentrations provides insight into IAQ in an existing building, it cannot do the same for a building yet to be constructed. Modelling IAQ has an advantage over monitoring in that it can be undertaken for hypothetical situations and so can play a useful role in the design process for proposed buildings. It can also assess temporal and spatial variation in concentrations that monitoring cannot easily do.

6.1.3. Modelling can be used to find solutions and explore the effectiveness of various mitigation options in the design phase as well as for existing buildings.

6.1.4. Model evolution and development is rapid, driven by the increased interest in the subject and increased availability of computing power. The IAQ assessor should consult current peer reviewed references if greater detail is required than is presented in this Chapter.

6.1.5. Pollutant concentrations in a building depend to a large extent on the way air moves around the building, which is mostly dictated by ventilation. Simulating the airflows and the pollutant concentrations within a building presents a different set of complexities from modelling outdoor airflows. Weather is largely unimportant in modelling IAQ. Turbulence caused by, for example, people movements, ventilation systems and hot objects can be important factors when modelling IAQ. Obstructions (walls, doors, desks, cupboards etc.) are also factors which influence IAQ.

6.1.6. Indoor air pollutant concentrations are also affected by multiple, often rapid, chemical reactions, deposition and resuspension.

6.1.7. The most basic approach to modelling concentrations within a single room is to assume that it can be represented as a box (see **Box 6.1**).

6.1.8. This type of model is referred to as a *"mass balance"* model. Proprietary software for this type of model, on a free and commercial basis is available. In practice, chemical mass balance models are most often constructed and used in research applications, rather than IAQ assessments.

Box 6.1: Main Features of Box Models

- Assumes an homogenous well mixed atmosphere.
- Pollutant released from a source at a known and constant rate.
- Removal of pollutant using a modelling term to represent ventilation.
- Quick and easy to program and run.

Refinements and sophistications can include:

- deposition processes;
- ingress of external pollution;
- adjacent rooms (into and from which pollutant exchange takes place); and
- complex chemical processes and transformations.

6.1.9. Open source models are available e.g. CONTAM, a multizone IAQ and ventilation model designed to determine e.g. airflow, infiltration, exfiltration, room to room airflow rates and pressure differences in building systems, dispersal of airborne contaminants transported by these airflow rates, chemical and radio chemical transformation, leading to the prediction of exposure of building occupants to airborne contaminants (NIST, 2021).

6.1.10. Mass balance models have the virtue of simplicity and are easy to understand and use. In situations where the overall time averaged concentration within a defined space is required, they can provide a result that is fit for purpose. In many cases, however, the assumption of a well mixed and steady state atmosphere within a building will be far from the reality. Airflows caused by mechanical or natural ventilation will give rise to non-uniform temporal and spatial pollutant concentrations and many pollution sources are transient or intermittent. To simulate these complex airflows requires the use of a Computational Fluid Dynamics (CFD) model. Such models are now more accessible than was previously the case and the ever increasing computational power of desktop computers makes their use practical for many applications. Importantly, they are also used routinely by building and ventilation engineers, although for different purposes (see **Box 6.2**).

6.1.11. The relative sophistication of CFD models, allied to their ability to produce colourful images of concentration and flow fields, sometimes as video, can lead to a false confidence in the accuracy of results. In practice, there are many pitfalls to trap the unwary user. In addition to the inherent limitations of the models themselves, the model results depend on a series of assumptions and simplifications made in the model set up which will add to the overall uncertainty of the results.

Box 6.2: Main Features of CFD Models

- Powerful modelling tool.
- Can simulate thermal and pressure gradients and turbulent flow in indoor environments.
- Divide a domain into thousands or millions of elements.
- Solve the mass, momentum, and energy conservation equations.
- High level of discretisation (division of geometry into smaller cells), CFD results are significantly more detailed than those of multi zone mass balance / box models.
- Can model multi zone areas, including smaller areas of uncomfortable temperature or of stagnant flow in a room.

6.1.12. In the absence of measurements, the accuracy of the model output is inherently unknown for a particular application. For the modelling of outdoor pollution, well known models are validated independently, and their performance is understood. For a CFD model used in any indoor setting, each situation is unique, and the model could produce a wide range of answers, depending on its set up and the skill of the user.

6.1.13. Properly setting up and running a CFD simulation requires a relatively high level of technical expertise to ensure that the correct boundary conditions, mesh size, and turbulence and radiation models have been used. The user of a CFD model needs to generate high quality meshes and should perform grid sensitivity studies. Great care should be taken when meshing the region near solid surfaces such as walls, occupants and furniture, where viscous effects are important. Ideally, radiative heat transfer should be modelled in all indoor CFD simulations. Failing to account for radiation in CFD will result in temperature profiles, air flow patterns and velocities that are unrealistic.

6.1.14. A further important point is that CFD models are primarily a means of simulating the airflows within a building, which enables the user to simulate dispersion at the same time. A CFD model may not allow for removal processes through deposition and chemical transformation.

6.1.15. CFD simulations can be computationally intensive, so it is not feasible at present to use them to model hourly variations throughout the year and quantify the annual performance of a building. Instead, simulations are typically run for a particular point in time that is relevant to the design.

6.1.16. Selecting the most appropriate turbulence model for the CFD simulation is also critical to obtaining accurate results. Solving the equations governing turbulent flow requires some approximations to be made and models adopt one of several techniques, each of which has implications for the computational effort required. There is a trade-off to be made between this computational time required and the accuracy of the result.

6.1.17. Despite these limitations and sources of uncertainty, CFD models can be used very successfully in IAQ applications. They are especially useful in cases where the optimisation of a pollutant concentration in one part of a room or building is critical. For example, the position of inlet and extract ducts could be important in determining the exposure of an occupant at a certain location. Sometimes, this has implications for safety, where exposure to a toxic substance or pathogen could have serious consequences, even for short periods (e.g. an operating theatre or chemical laboratory). In these circumstances, a CFD model can explore the consequences of various ventilation designs and ensure that the optimum configuration is selected. In safety critical applications CFD model results should be validated by monitoring.

6.1.18. In summary, modelling can provide an assessor with a useful tool both for identifying problems with IAQ and as a means of identifying solutions. Modelling should be undertaken in situations where the application of a particular model is valid and by users who are trained in and understand the limitations of the model being used.

7. Mitigation/Improvement Opportunities

7.1. Hierarchy of Measures

7.1.1. This Chapter sets out the governing principles for defining measures to improve IAQ. Many of the measures are more easily achieved by good design and material selection, which are best defined at the design stage, but there are also opportunities during the building operation.

7.1.2. The hierarchy of measures is based on: Removing sources, Reducing source emissions, Disrupting pathways, Protecting receptors and Removing receptors as shown in **Figure 7.1**.

7.1.3. APCC (a partnership between the Royal College of Physicians, Royal College of Paediatrics and Child Health & the Building Research Establishment (BRE)) have discussed many approaches to improving IAQ (ARCC (Ed. Turner, BD), 2017). The Home Quality Mark - One UK (BRE, 2018) is a technical manual to assess homes for many aspects of home design including IAQ and recommendations for testing materials used in construction and criteria to minimise emissions from building materials (especially VOCs and formaldehyde).

7.1.4. These are some strategies that may be used:

- **Sources**: measures should be taken first of all to remove or reduce emissions (Kukadia & Upton, 2019), remembering that sources impacting the IAQ can be inside the building e.g. furniture / paints and external to it e.g. boiler flues.
    - Removal of emission sources e.g. provision of appliances with cleaner technologies.
    - Reducing source emissions e.g. selection of low VOC emitting materials.
- **Pathways**: if source emissions cannot be eliminated or sufficiently reduced, consideration should be given to influencing the pathway between the source and receptor.
    - Undertake a site context analysis at design stage, e.g. location of air inlets in relation to sources of pollution / location of air extraction / opportunities for effective natural ventilation (wind direction/speed). In some cases it may only be possible to increase mechanical air extraction to the outside throughout the whole building or a whole floor, rather than specific areas where it might be needed. This may unduly increase energy use.
    - Mechanical ventilation can be used to move air around the building (internally, without extraction to the outside) to achieve dilution within the building (unless the building was found to be under ventilated).
    - Increased ventilation, e.g. open windows (if there are no security issues), use the building management system to provide increased ventilation to flush out (e.g. over night purging) or dilute the pollutant concentrations; use extractor fans in the kitchen and bathroom when activities take place there.
    - Removal of pollutants from air, e.g. extract at source and exhaust to outside or introduce filtration at or near a source (e.g. in a kitchen) or at the main air intakes for a building if the main source is outside (the latter is best done in the design stage).
    - Removal of pollutants from indoor air using absorbent materials included in the design of the building or retrofitted have proved successful; indoor plants and/or their growing medium may also remove some pollutants although evidence is lacking and inconclusive (Woolley, 2017).
    - Distancing of receptors, e.g. layout and occupancy considerations, such as increasing the distance between the receptor and contaminated air or moving receptors to areas of highest ventilation/dilution. The complex nature of airflows indoors may make it less effective as a strategy than when it is used outdoors.
- **Receptors**: measures to reduce the exposure of the receptor.
    - Ensure cleaning takes place when the building is not occupied by users.
    - Provide cleaning staff with a suitable, appropriately fitted face mask.
    - Add barriers between the source and receptor, e.g. placing a Perspex screen between customers and employees.
    - In industrial spaces more severe measures may be used, such as provision of PPE, use of a personal alarm to indicate when a space should be vacated, limiting exposure time, restricting access to specific areas or limiting access by vulnerable groups.

7.2. Implementation of Measures

7.2.1. In order to document and summarise the outcome of the IAQ Assessment, it is recommended that an IAQ Plan is drawn up with actions, time plan, details, responsible parties etc.

7.2.2. Where there are many sources of the same pollutant, consideration should be given to the combined risk. In isolation, an individual source may have only a small impact on IAQ. However, combined with many other sources, it may result in a significant impact on IAQ.

7.2.3. A mechanical ventilation system may be a requirement of the circumstances, e.g.:

- high demand for air at a certain temperature/humidity;
- demand for very clean air (e.g. hospitals, clean rooms, laboratories);
- buildings close to outdoor sources of pollution; or
- requirements to pressurise a room.

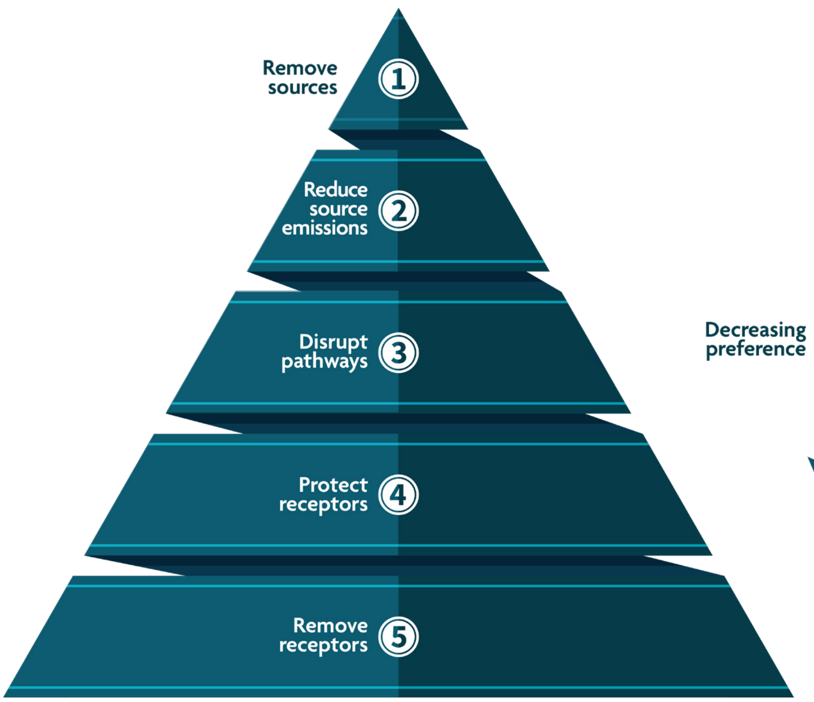
7.2.4. Mechanical ventilation may introduce contaminated air from an area where there are limited or no human receptors (e.g. air intake(s) too close to a road or extract vents/exhaust stacks on roof tops) to an area where there are receptors (e.g. inside an office) which in turn will lead to greater health impacts. This can be avoided if consideration is given at design stage to the appropriate placement of air intakes and opening windows, in relation to outdoor sources. If unavoidable in a constrained space in a polluted setting, filters may be used to clean the intake air (although this can increase energy use and noise generation from the ventilation and filtration units). A well designed mechanical ventilation and heat recovery (MVHR) unit implemented correctly will reduce the overall energy use of a building; useful links on testing and design are available from e.g. the filter group at FETA (FETA, no date).

7.2.5. Where multiple measures are available, the co-benefits of measures should be considered, for instance reducing carbon emissions as well as improving IAQ by use of energy saving measures (e.g. good practice would be to have MVHR in colder months and natural ventilation (opening windows) in the warmer months). Conversely, it is important to be alert to secondary effects and unintended consequences, e.g. increased use of mechanical ventilation increases energy use and noise, and takes up additional space.

7.2.6. As part of the assessment of effectiveness of any mitigation and to identify further works required, a level of compliance monitoring should be undertaken once a building is operational. Ongoing performance monitoring throughout the life of the building with a focus on readily accessible data to the building users and operators is key to informing optimum building operations. Input from the IAQ consultant to the Intelligent Buildings Engineer (IBG) during the design stage and Building Management Systems (BMS) operator during the operation of the building should be explored in order to ensure optimum IAQ. Specialist guidance exists to assist in this process e.g. on the design and testing of ventilation systems in healthcare (NHS England, 2021), air filtration design (FETA, no date).

7.2.7. **Appendix J** includes one approach provided to IAQM by Dr Austin Cogan and includes a series of measures for various phases of a development and how to use them in drafting an IAQ Plan. A series of examples/case studies have been produced with CIBSE. These can be found in **Appendix E** and **Appendix H**.

Figure 7.1: Hierarchy of Improvement Measures



8. Bibliography

Allen, J., Klocke, C., Morris-Schaffer, K., Conrad, K., Sobolewski, M., & Cory-Slechta, D. (2017). Cognitive Effects of Air Pollution Exposure and Potential Mechanistic Underpinnings. *4 (pp180-191)*.

Allen, J.G., MacNaughton, P., Satish, U., Santanam, S., Vallarino, J. and Spengler, J.D. (2016). Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments. *Environmental Science Perspectives, 126(4)*.

ANC & IOC. (2020). *Acoustics Ventilation and Overheating*. Association of Noise Consultants & Institute of Acoustics.

ARCC (Ed. Turner, BD). (2017). *Better Homes, Better Air, Better Health: Event Report UKCIP, University of Oxford*. Adaptation and Resilience in the Context of Change Network.

ASPB. (2021). *Featured Products*. (The Alliance for Sustainable Building Products) Retrieved May 2021, from https://asbp.org.uk

BEIS. (Accessed May 2021). *About Nitrogen Oxides.* (Department for Business, Energy & Industrial Strategy) Retrieved from National Atmospheric Emissions Inventory: https://naei.beis.gov.uk/overview/pollutants?pollutant_id=6

BESA. (2021). *A beginner's guide to indoor air quality.* Retrieved from: https://www.thebesa.com/media/1409355/indoor_air_quality_guide.pdf

Bierwirth, P. N. (2014). Carbon Dioxide Toxicity and Climate Change: A Major Unapprehended Risk for Human Health.

BRE. (2014). *Health and Wellbeing (BREEAM UK)*. (Building Research Establishment) Retrieved from Hea 02 Indoor Air Quality: www.breeam.com/BREEAMUK2014SchemeDocument/content/05_health/hea02.htm

BRE. (2015). *Radon: Protective Measures for New Buildings, Report BR211*. Building Research Establishment.

BRE. (2018). *Home Quality Mark One (delivered by BRE) (SD239)*. Buildings Research Establishment.

BSRIA. (2021). *Indoor Air Quality (TG12 2021)*. Building Services Research & Information Association (BSRIA).

BSI. (2017). *Construction Products: Assessment of Release of Dangerous Substances. Determination of Emission into Indoor Air*. British Standards Institution (BSI Group).

BSI. (2020). *BS EN 16516:2017+A1:2020, Construction Products: Assessment of Release of Dangerous Substances. Determination of Emissions into Indoor Air.* British Standards Institution (BSI Group).

Bunn, R. (2018). Towards a Theory of Carrying Capacity: Evidence from Long-term Longitudinal Case Studies of Occupant Satisfaction in Non-Domestic Buildings. *PhD Thesis*. Bartlett School of Environment Energy & Resources (UCL).

Bunn, R., & Marjanovic-Halburd, L. (2017). Comfort Signatures: How Long-term Studies of Occupant Satisfaction in Office Buildings Reveal On-going Performance. *Building Services Engineering Research and Technology*.

Cacho, C., Ventura Silva, G., Martins, A., Fernandes, E., Saraga, D., Dimitroulopoulou, C., Bartzis, JG., Rembges, D., Barrero-Moreno, J., & Kotzias, D. (2013). Air Pollutants in Office Environments and Emissions from Electronic Equipment: A Review. Fresenius *Environmental Bulletin, 22*(9), 2488-2497.

Carslaw, N., Fletcher, L., Heard, D., Ingham, T., & Walker, H. (2017). Significant OH Production Under Surface Cleaning and Air Cleaning Conditions: Impact on Indoor Air Quality. *International Journal of Indoor Environment and Health*, *27*, 1091-1100.

Carslaw, N., Mota, T., Jenkin, M., Barley, M., & McFiggans, G. (2012). A Significant Role for Nitrate and Peroxide Groups in Indoor Secondary Organic Aerosol. *Environmental Science & Technology, 46*, 9290-9298.

Cheng, H., Kukadia, V., & Hall, D. (2014). Locating Ventilation Inlets to Reduce Ingress of External Pollutants into Buildings: A New Methodology.

Channing, J. (2013). *Safety and Work (8th Edn)*.

CIBSE. (2017a). *CIBSE Journal*. (Chartered Institution of Building Services Engineers) Retrieved from Air of Authority: CIBSE's Guidance on Indoor Air Quality: https://www.cibsejournal.com/opinion/air-of-authority-cibses-guidance-on-iaq

CIBSE. (2017b). *TM59 Design Methodology for the Assessment of Overheating Risk in Homes.* Chartered Institution of Building Services Engineers.

CIBSE. (2020a). *TM40 Health and Wellbeing in Building Services*. Chartered Institution of Building Services Engineers.

CIBSE. (2020b). *TM61 Operational Performance of Buildings.* Chartered Institution of Building Services Engineers.

CIOB. (2018). *Improving Quality in Construction.* (Chartered Institute of Building) Retrieved May 1, 2021, from www.ciob.org/index.php/industry/politics-government/campaigns/construction-quality-commission

Clean Air London (CAL). (No date). *Indoor Air*. https://cleanair.london/indoor-air

Cogan, A. (2021). Personal communication.

COMEAP. (2009). *Long-Term Exposure to Air Pollution: Effect on Mortality.* Produced by the Health Protection Agency for the Committee on the Medical Effects of Air Pollution.

COMEAP. (2015). *Quantification of Mortality and Hospital Admissions Associated with Ground-Level Ozone.* Produced by Public Health England for the Committee on the Medical Effects of Air Pollution.

COMEAP. (2016). *Long-Term Exposure to Air Pollutants and Chronic Bronchitis.* Produced by Public Health England (PHE) for the Committee on the Medical Effects of Air Pollution.

COMEAP. (2018). A*ssociations of Long-Term Average Concentrations of Nitrogen Dioxide with Mortality.* Produced by Public Health England (PHE) for the Committee on the Medical Effects of Air Pollutants.

Data Centers. (Accessed May 2021). (Uptime Institute) Retrieved from Solving Air Contaminant Problems in Data Centers: https://journal.uptimeinstitute.com/solving-air-contaminant-problems-data-centers/

DEFRA. (Accessed May 2021). *UK and EU Air Quality Limits*. (Department for Environment, Food & Rural Affairs) Retrieved from UK Air: https://uk-air.defra.gov.uk/air-pollution/uk-eu-limits

Diffey, B. (2010). An Overview Analysis of the Time People Spend Outdoors. *British Journal of Dermatology, 164*, 848-854.

Dimitroulopoulou, C., Ashmore, M., & Terry, A. (2017). Use of Population Exposure Frequency Distributions to Simulate Effects on Policy Interventions on Nitrogen Dioxide Exposure. *Atmospheric Environment, 150*, 1-14.

Education and Skills Funding Agency. (2018). *Guidelines on Ventilation, Thermal Comfort and Indoor Air Quality in Schools (Version 1)*. Building Bulletin (BB) 101.

European Commission. (1998). *European Agency for Safety and Health at Work*. Retrieved from Risks Related to Chemical Agents at Work: https://osha.europa.eu/en/legislation/directives/75

FETA. (No date). *Filter Group*. Retrieved from: https://www.feta.co.uk/associations/hevac/specialist-groups/filter-group

Fisk, W., Wargocki, P., & Zhang, X. (2019). Do Indoor Carbon Dioxide Levels Directly Affect Perceived Air Quality, Health, or Work Performance? *ASHRAE*, 70-77.

Golden, R., & Holm, S. (2017). Indoor Air Quality and Asthma: Has Unrecognized Exposure to Acrolein Confounded Results of Previous Studies? *Dose-Response*.

Guo, C., Gao, Z., & Shen, J. (2019). Emission Rates of Indoor Ozone Emission Devices: A Literature Review. Building and Environment, 158.

He, W., Shi, A., Shao, X., Nei, L., Wang, T., & Li, G. (2020). Insights into the Comprehensive Characteristics of Volatile Organic Compounds from Multiple Cooking Emissions and Aftertreatment Control Technologies Application. *Atmospheric Environment, 240*.

HMIP. (1993). *Guidelines on Discharge Stack Heights for Polluting Emissions. HMIP Technical Guidance Note D1 (Dispersion).* HMSO (HMIP, Her Majesty's Inspectorate of Pollution).

HPA. (2010). *Limitation of Human Exposure to Radon RCE15*. Health Protection Agency.

HSE. (2000). *EH75/2 Occupational Exposure Limits for Hyperbaric Conditions: Hazard Assessment Document.* Health and Safety Executive.

HSE. (2002). *Control of Asbestos Regulations*. UK Health and Safety Executive.

HSE. (2020). *EH40/2005 Workplace Exposure Limits (Fourth Edition).* UK Health and Safety Executive.

HSE. (2021). Controlling the Risks. UK Health and Safety Executive. Retrieved May 1, 2021, from https://www.hse.gov.uk/toolbox/managing/managingtherisks.htm

International WELL Building Institute. (2020). *Air Quality Standards.*

International WELL Building Institute. (2020, Q1). *WELL Performance Verification Guidebook.* Retrieved from https://a.storyblok.com/f/52232/x/3be8781be5/well-community-standard-performance-verification-guidebook_q1-2020-present.pdf

ISO. (1993). *ISO/IEC Guide 98:1993 Guide to the Expression of Uncertainty in Measurement (GUM) (Withdrawn).* International Standards Organisation.

ISO/TC 146. (ongoing). Technical Committee: Indoor Air. International Standards Organisation.

Jacobson, T. A., Kler, J. S., Hernke, M. T., Braun, R. K., Mayer, K. C., & Funk, W. E. (2019). Direct Human Health Risks of Increased Atmospheric Carbon Dioxide. *Nature Sustainability, 2,* 691-701.

Kim, M., & Choi, J. (2019). Can Increased Outdoor Carbon Dioxide Concentrations Impact on the Ventilation and Energy in Buildings? A Case Study in Shanghai, China. *Atmospheric Environment, 210*, 220-230.

KNP. (2018). *Knightsbridge Neighbourhood Plan 2018-2037.* Knightsbridge Neighbourhood Forum Limited.

Retrieved from https://www.knightsbridgeforum.org/media//documents/knp_made_version_december_2018_131218_website.pdf

Kukadia, V., & Abela, A. (2015). *Designing to Reduce the Chemical, Biological and Radiological Vulnerability of New Buildings*. Building Research Establishment (BRE).

Kukadia, V., & Hall, D. (2011). *Ventilation for Healthy Buildings: Reducing the Impact of Urban Air Pollution.* Building Research Establishment (BRE).

Kukadia, V., & Upton, S. L. (2019). *Ensuring Good Indoor Air Quality in Buildings.* Building Research Establishment (BRE).

Liddament, M. W. (1996). *A Guide to Energy Efficient Ventilation.* International Energy Agency, Air Infiltration and Ventilation Centre.

Lindsey, R. (2020). C*limate Change: Atmospheric Carbon Dioxide.* Retrieved from NOAA: www.climate.gov

Lowther, S., Foxall, K., Shrubsole, C., Cheek, E., B, G., Sepaj, O., & Dimitroulopoulou, S. (In preparation). *Carbon Dioxide Indoors: A Pollution Indicator or a Pollutant. A Health-Based Perspective.*

MHCLG. (2010a). *Approved Document F (F1 Means of Ventilation).* Ministry of Housing, Communities and Local Government.

MHCLG. (2010b). *Toxic Substances: Approved Document D, Statutory Guidance.* Ministry of Housing, Communities and Local Government.

MHCLG. (2013). *Site Preparation and Resistance to Contaminates and Moisture: Approved Document C, Statutory Guidance.* Ministry of Housing, Communities and Local Government.

MHCLG. (2021a). *Building Regulations: Approved Documents L and F (Consultation Version).* Ministry of Housing, Communities and Local Government.

MHCLG. (2021b). *The Future Homes Standard: Changes to Part L and Part F of the Building Regulations for New Dwellings.* Ministry of Housing, Communities and Local Government.

Naldzhiev, D., Mumovic, D., & Strlic, M. (2020). Polyurethane Insulation and Household Products – A Systematic Review of Their Impact on Indoor Environmental Quality. *Building and Environment, 169.*

NHS England. (2021). *(HTM 03-01) Specialised ventilation for healthcare buildings.* Retrieved from: https://www.england.nhs.uk/publication/specialised-ventilation-for-healthcare-buildings

NIST. (2021). *National Institute of Standards and Technology (US Dept. of Commerce).* Retrieved from CONTAM: https://www.nist.gov/services-resources/software/contam

PHE. (2018). *How Air Pollution Harms Health.* Public Health England. Retrieved May 2021

PHE. (2019). *Indoor Air Quality Guidance for Selected Volatile Organic Compounds (VOCs) in the UK*. Public Health England.

PHE. (2020). *Air Pollution: Applying All Our Health*. (Public Health England) Retrieved May 2021, from https://www.gov.uk/government/publications/air-pollution-applying-all-our-health/air-pollution-applying-all-our-health

PHE. (Accessed Jan 2021). *UK Maps of Radon*. (Public Health England) Retrieved from www.ukradon.org/information/ukmaps

PHE. (Accessed Nov 2020). *Radon Action Level and Target Level*. (Public Health England) Retrieved from www.ukradon.org/information/level

Pohleven, J., Burnard, M. D., & Kutnar, A. (2019). VOCs Emitted from Untreated and Thermally Modified Wood - A Review. *Wood and Fibre Science, 51*(3).

RESET. (2018). *RESET Air Test procedure for Accredited Monitors V2.0*. R. Retrieved from https://www.reset.build/standard/air#air_download

RIVM. (Accessed May 2021). *Exposure.* (Rijkswaterstraat Ministerie van Infrastructuur en Waterstaat (Ministry of infrastructure and Water Management)) Retrieved from Assessing Air Quality: https://www.infomil.nl/onderwerpen/lucht-water/luchtkwaliteit/regelgeving/wet-milieubeheer/beoordelen/blootstelling/blootstelling

Rohr, A., Weschler, C., Koutrakis, P., & Spengler, J. (2003). Generation and Quantification of Ultrafine Particles Through Terpene/Ozone Reaction in a Chamber Setting. *Aerosol Science and Technology, 37*, 65-78.

Royal College of Physicians. (2016). *Projects.* Retrieved from Every Breath We Take: The Lifelong Impact of Air Pollution: https://www.rcplondon.ac.uk/projects/outputs/every-breath-we-take-lifelong-impact-air-pollution

Salonen, H., Salthammer, T., & Morawska, L. (2018). Human Exposure to Ozone in School and Office Indoor Environments. *Environmental International, 119.*

Salthammer, T. (2019). Formaldehyde Sources, Formaldehyde Concentrations and Air Exchange Rates in European Housings. *Building and Environment, 150*, 219-232.

Scully, R., Basner, M., Nasrini, J., Lam, C., Hermosillo, E., Gur, R., Moore, T., Alexander, D., Satish, U., & Ryder, V. (2019). Effects of Acute Exposures to Carbon Dioxide on Decision Making and Cognition in Astronaut-like Subjects. *Microgravity, 5.*

Shrubsole, C., Dimitroulopoulou, S., Foxall, B., Gadeberg, B., & Doutsi, A. (2019). IAQ Guidelines for Selected Volatile Organic Compounds (VOCs) in the UK. *Building and the Environment, 165.*

Stamp, S., Burman, E., Shrubsole, C., Chatzidiakou, L., Mumovic, D., & Davies, M. (2020). Long-term, Continuous Air Quality Monitoring in a Cross-sectional Study of Three UK Non-domestic Buildings. *Building and Environment, 180.*

UK Government. (2010, March 25). The Air Quality Standards Regulations 2010. UK: Statutory Instrument.

US Green Building Council. (2020). *Leadership in Energy and Environmental Design (LEED)*. Retrieved from https://www.usgbc.org/leed

USEPA. (2009). *Acrolein (107-02-8)*. US Environmental Protection Agency.

USEPA. (2010). F*ormaldehyde - Inhalation Assessment (CAS No. 50-00-0) In Support of Summary Information on the Integrated Risk Information System (IRIS)*. US Environmental Protection Agency.

USEPA. (2014). *Section 6 of the Building Air Quality Guide: Diagnosing IAQ Problems.* Retrieved from https://www.epa.gov/indoor-air-quality-iaq/section-6-building-air-quality-guide-diagnosing-indoor-air-quality-problems. US Environmental Protection Agency.

USEPA. (2021a). *CO's Impact on Indoor Air Quality (IAQ).* US Environmental Protection Agency.

USEPA. (2021b). *Introduction to Indoor Air Quality (IAQ).* US Environmental Protection Agency.

Walsh, P. (2020). Case Study: Air Quality in and Around Schools and Nurseries in Central London. *Indoor Air Quality (IES) Online Conference (22 June 2020).*

Wealend, E. (2021). personal communication with IAQM IAQ Sub-Committee.

Weigl, W., Fürhapper, C., Niedermayer, S., Habla, E., Nohava, M., Nagl, S., & Polleres, S. (2014). VOC emissions from building materials: results from lab and model room trials. *International Wood Products, 5.*

Weschler, C. J., & Carslaw, N. (2018). Indoor Chemistry. *Environmental Science and Technology, 52*, 2419-2428.

WHO. (2000). *Air Quality Guidelines for Europe*, *Second Edition.* World Health Organization.

WHO. (2002). *Acrolein (Concise International Chemical Assessment Document 43).* World Health Organsization.

WHO. (2005). *Air Quality Guidelines, Global Update.* World Health Organization.

WHO. (2010). *Guidelines for Indoor Air Quality (IAQ): Selected Pollutants*. World Health Organization.

WHO. (2013). *Review of Evidence on Health Aspects of Air Pollution - REVIHAAP Project Technical Report.* World Health Organization.

WHO. (2016). *Ambient Air Pollution: A Global Assessment of Exposure and Burden of Disease.* World Health Organization.

WHO. (2020). *Methods for Sampling and Analysis of Chemical Pollutants in Indoor Air: Supplementary Publication to the Screening Tool for Assessment of Health Risks from Combined Exposure to Multiple Chemicals in Indoor Air.* World Health Organization.

WHO. (2021). *WHO Global Air Quality Guidelines. Particulate Matter (PM_{10} & $PM_{2.5}$), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide.* World Health Organization. Retrieved from https://apps.who.int/iris/handle/10665/345329

Woolley, T. (2017). *Building Materials, Health and Indoor Air Quality. No Breathing Space?* 1st Edition. Routledge.

World Green Building Council. (2016). *Building the Case: Health, Wellbeing and Productivity in Green Offices.*

Appendix A. Glossary and Abbreviations

ADF Approved Document F: Ventilation (of the UK Building Regulations, 2010). A consultation version was published in January 2021 so please check for the latest version.

AQMA Air Quality Management Area. An area identified by a Local Authority within its boundaries where the air quality objective (AQO for a specific pollutant (or pollutants) is unlikely to be achieved.

AQO(s) Air Quality Objective(s)

BaP Benzo[a]pyrene

BAT Best Available Techniques

BCO British Council for Offices

Breathing zone The space within 20-30 cm of the person's nose and mouth.

BREEAM Building Research Establishment Environmental Assessment Method. A sustainability and certification assessment method that is used to masterplan projects, infrastructure and buildings.

BTEX Benzene, toluene, ethylbenzene & xylenes

CIBSE Chartered Institution of Building Services Engineers

CO Carbon monoxide

CO_2 Carbon dioxide

Competent person An individual with a high level of skill and experience in assessing and/or advising on air quality impacts in the key area of relevance (IAQ) for the proposed development; the individual should also be at least a full Member of the Institute of Air Quality Management at the time of preparing the IAQ Assessment.

COPD Chronic Obstructive Pulmonary Disease

COSHH Control of Substances Hazardous to Health

Existing building One that is built and has been previously or is currently occupied (see New building)

Habitable room A room used for dwelling (*self-contained unit including a house or a flat designed to be used separately to accommodate a single household*) purposes but which is not solely a kitchen, utility room (*a room containing a sink or other feature of equipment that may reasonably be expected to produce significant quantities of water vapour*), bathroom (*a room containing a bath or a shower*), cellar (*part of a dwelling that is wholly or partly below ground level, and is used only for storage, heating plant or purposes other than habitation, it is not the same as a basement*) or sanitary accommodation (*a space containing a toilet or urinal*). (MHCLG, 2021b)

Hazard Something that has the potential to cause harm

HCHO Formaldehyde (also H_2CO)

HMIP Her Majesty's Inspectorate of Pollution

HSE Health and Safety Executive (UK)

IAQ Indoor Air Quality

IAQM Institute of Air Quality Management

LOAEL Lowest Observable Adverse Effects Level

LEED (US Green Building Council) Leadership in Energy and Environmental Design

l/s/p litres per second per person

l/s/m² litres per second per square metre (floor area)

MVHR Mechanical Ventilation with Heat Recovery

New building/new build A building that is completed (just built or fully renovated) but has not yet been occupied for the purpose it was intended

NH_3 Ammonia

NIHP National Institute for Health Protection

NIRS Near direct Infra-red Spectroscopy

NIST National Institute of Standards and Technology

NO Nitric oxide (also known as nitrogen monoxide)

NO_2 Nitrogen dioxide

O_3 Ozone

Occupiable room A room in a building other than a dwelling (*self-contained unit including a house or a flat designed to be used separately to accommodate a single household*) that is occupied by people, such as an office, workroom, classroom or hotel bedroom. Utility rooms (*a room containing a sink or other feature of equipment that may reasonably be expected to produce significant quantities of water vapour*), bathrooms (*a room containing a bath or a shower*) and sanitary accommodation (*a space containing a toilet or urinal*) are not **Occupiable Rooms** (MHCLG, 2021a)

Occupied period The period during which a receptor is present at a specified location

PAH(s) Polyaromatic hydrocarbon(s)

Pathway The route that pollution takes from source to receptor

PHA Public Health Agency (Northern Ireland)

PHE Public Health England (now part of the National Institute for Health Protection)

PHS Public Health Scotland

PHW Public Health Wales

PID Photo-ionisation Detector

PM_{10} Fine particulate matter (various definitions exist but generally taken to mean particles with a mean aerodynamic diameter of up to 10 μm)

$PM_{2.5}$ Very fine particulate matter (various definitions exist but generally taken to mean particles with a mean aerodynamic diameter of up to 2.5 μm)

ppb Parts per billion (1000 million) (assumed in this document to be parts by volume unless otherwise stated)

ppm Parts per million (assumed in this document to be parts by volume unless otherwise stated)

Proposed building One that is planned, or in the design stage but is not yet completed

Radon Affected Area Areas defined by Public Health England as having a higher chance of being affected by naturally occurring radon

RESET Regenerative, Ecological, Social and Economic Targets

RIBA Royal Institute of British Architects

Risk The chance or probability that a person will be harmed or experience an adverse health effect if exposed to a hazard

Rn Radon

RTM Real-Time Monitor

SOA Secondary Organic Aerosols

STEL Short-Term Exposure Limit (HSE, 2020) 15-minute mean pollutant concentration

Suitably experienced person see Competent person

SVOCs Semi-Volatile Organic Compounds*

TSP Total Suspended Particles

TVOCs Total Volatile Organic Compounds*

TWA Time Weighted Average

UF Urea Formaldehyde

UKCMB United Kingdom Centre for Moisture in Buildings

USEPA United State Environmental Protection Agency

VOCs Volatile Organic Compounds*

WEL Workplace Exposure Limit (HSE, 2020) including STELs and 8-hour time-weighted average (TWA) pollutant concentration limit value

WELL International Well Building Institute/ also a tool for advancing health and well-being in buildings

WHO World Health Organization

* Many definitions of TVOC, VVOC, VOC and SVOC exist. Boiling point can be used with VVOCs ‹50°C, VOCs (50-240°C) and SVOCs (240-400°C). Alternatively, the order which the individual organic compounds are extracted (elute) in a gas chromatograph is used to group them. Hence it is important to clarify which compounds are being discussed when the groupings are used as they are not always the same. There are harmonised definitions between UK BSI and EU in (BSI, 2017).

Appendix B. Conversion of Units

B1.1. Conversion of units from mass-based (mg/m³ or µg/m³) to volume-based (ppm or ppb) and vice versa is dependent on the molecular weight of the compound, pressure and the temperature of conversion.

$$C_m = \frac{C_v \times M_{wt}}{22.4 \times \frac{T}{273.15}} \times \frac{P_S}{P_c} \qquad C_v = \frac{C_m \times 22.4 \times \frac{T}{273.15}}{M_{wt}} \times \frac{P_c}{P_s}$$

B1.2. Where:

C_m Concentration by mass in µg/m³ (result will be in ppb) or mg/m³ (result will be in ppm)

C_v Concentration by volume in ppb (result will be in µg/m³) or ppm (result will be in mg/m³)

M_{wt} Molecular weight of compound

T Temperature of conversion in Kelvin

P_s Standard atmospheric pressure (units same as P_c and usually has the value 101.325 kPa)

P_c Pressure at which C_v is present (units same as P_s and usually has the value 101.325 kPa)

B1.3. Pressure is usually ignored in the conversion but should be included if there is a significant difference between the pressure at which the concentration is present and standard atmospheric pressure at which the molar volume (22.4 litres/mol) is expressed. Pressure correction is included in the formula, but P_s (Standard atmospheric pressure) and P_c (pressure at which C_v is present) are usually equal and so cancel out.

Table B1: Common Conversions Between Concentration Units

To convert ppb to µg/m³, or ppm to mg/m³ multiply by:		Conversion temperature K (°C)			
Pollutant	**M_{wt}**	**273.15 (0)**	**288.65 (15.5)**	**293.15 (20)**	**298.15 (25)**
Methane (CH_4)	16	0.714	0.676	0.666	0.654
Carbon monoxide (CO)	28	1.250	1.183	1.165	1.145
Hydrogen sulphide (H_2S)	34	1.518	1.436	1.414	1.391
Carbon dioxide (CO_2)	44	1.964	1.859	1.830	1.800
Nitrogen dioxide (NO_2)	46	2.054	1.943	1.913	1.881
Ozone (O_3)	48	2.143	2.028	1.997	1.963
Sulphur dioxide (SO_2)	64	2.857	2.704	2.662	2.618
Benzene (C_6H_6)	78	3.482	3.295	3.245	3.190
To convert µg/m³ to ppb, or mg/m³ to ppm multiply by:		**Conversion temperature K (°C)**			
Pollutant	**M_{wt}**	**273.15 (0)**	**288.65 (15.5)**	**293.15 (20)**	**298.15 (25)**
Methane (CH_4)	16	1.400	1.479	1.503	1.528
Carbon monoxide (CO)	28	0.800	0.845	0.859	0.873
Hydrogen sulphide (H_2S)	34	0.659	0.696	0.707	0.719
Carbon dioxide (CO_2)	44	0.509	0.538	0.546	0.556
Nitrogen dioxide (NO_2)	46	0.487	0.515	0.523	0.532
Ozone (O_3)	48	0.467	0.493	0.501	0.509
Sulphur dioxide (SO_2)	64	0.350	0.370	0.376	0.382
Benzene (C_6H_6)	78	0.287	0.303	0.308	0.313

Appendix C. Organisations that Publish IAQ Assessment Criteria and Measurement and Testing Protocols

Table C1: Organisations that Publish IAQ Assessment Criteria and Measurement and Testing Protocols

Organisation	Pollutants	Averaging times	Applicability	Comment
HSE (HSE, 2020)	426 substance WELs listed	Generally, WELs: Workplace Exposure Limits (8-hour TWA) STELs: Short-Term Exposure Limits (15-minute TWA) Exposure for other time periods, including continuous exposure, can be calculated.	To help protect the health of workers. They apply to healthy individuals in industrial settings.	Generally based on Indicative Occupational Exposure Limit Values (IOELVs), which are health-based limits set under the Chemical Agents Directive (European Commission, 1998). STELs are set to help prevent effects such as eye irritation, which may occur following exposure for a few minutes.
WHO (WHO, 2010) (WHO, 2005) (WHO, 2000)	IAQ Guidance: Nine pollutants: benzene, CO, formaldehyde, naphthalene, NO_2, PAHs (especially BaP), radon, trichloroethylene and tetrachloroethylene Ambient Air Quality Guidance: selected pollutants plus environmental tobacco smoke and man-made vitreous fibres	From 15 minutes to 1 year and concentrations associated with life-time risk of morbidity or mortality	WHO Ambient Air Quality guidance applies to both indoor and outdoor air	Pollutants selected on the basis that they were known as being hazardous to health.
PHE (PHE, 2019)	Acetaldehyde, α-pinene, benzene, d-limonene, formaldehyde, naphthalene, styrene, tetrachloroethylene, toluene, trichloroethylene and xylene (mixtures)	From 30 minutes to 1 year and concentrations associated with life-time cancer risks	All indoor spaces	
Approved Documents F1 (MHCLG, 2010a), (MHCLG, 2021a), (MHCLG, 2021b)	Nitrogen dioxide, carbon monoxide, Total Volatile Organic Compounds (TVOCs), formaldehyde	Depending on pollutant, 15 minutes, 30 minutes, 1 hour, 8 hours and 1 year	New buildings, residential and non-residential	Securing reasonable standards of health and safety for persons in or about buildings (and any others who may be affected by buildings or matters connected with buildings).

Table C1: Organisations that Publish IAQ Assessment Criteria and Measurement and Testing Protocols

Organisation	Pollutants	Averaging times	Applicability	Comment
Approved Documents C (MHCLG, 2013)	Activity level set for radon (in Bq/m^3). Methane and Volatile Organic Compounds (VOCs) considered- no concentration set.	Typically 3 months or longer	New buildings, residential and non-residential	Securing reasonable standards of health and safety for persons in or about buildings (and any others who may be affected by buildings or matters connected with buildings).
Approved Documents D (MHCLG, 2010b)	No specified concentration criteria. Sets out criteria for insulating materials and their installation to avoid exposure to excessive formaldehyde fumes.	Not applicable	New buildings, residential and non-residential	Securing reasonable standards of health and safety for persons in or about buildings (and any others who may be affected by buildings or matters connected with buildings).
Building Bulletin 101 Guidance (Education and Skills Funding Agency, 2018)	Requires compliance with HSE WELs, Approved Document F1 and CO2 concentration limits; recommends WHO guidelines as good practice[10]	From 15 minutes to 1 year	New buildings and refurbishments, workers and students	
BREEAM (BRE, 2014)	Formaldehyde and Total Volatile Organic Compounds (TVOC)	Formaldehyde: 30 minutes TVOC: 8 hours	New buildings, post completion, pre-occupancy	
LEED (US Green Building Council, 2020)	New buildings: Particles, ozone, carbon monoxide, TVOCs, formaldehyde, 35 specific VOCs Existing buildings: carbon dioxide	Minimum of 4 hours	Range of schemes for new construction and occupied buildings	IAQ assessment credit in the LEED v4 Building Design and Construction (BD+C) rating system.
WELL (International WELL Building Institute, 2020)	All spaces: formaldehyde, TVOC, carbon monoxide, $PM_{2.5}$, PM_{10}, O_3. Regularly occupied spaces: also radon. Commercial kitchen space: carbon monoxide, $PM_{2.5}$, NO_2, formaldehyde	Same as Californian, US and WHO standards referenced in the WELL requirements	Space where someone spends 1 hour continuously or 2 hours cumulatively per day	A01 feature Fundamental Air Quality A05 Enhanced Air Quality contains tighter standards for a subset of the pollutants and benzene.

Appendix D. RIBA Stages

Table D1: RIBA Plan of Work: Illustration of Air Quality Input to Design and Construction of New Buildings

RIBA Stage	Outcome at the end of stage	Core Tasks	Core Statutory Processes	Procurement Route	Information Exchange at the end of the stage
0.Strategic Definition	This is the initial client decision-making stage, and air quality input will not normally be required. For a few projects, advice on the air quality opportunities and constraints for a development site maybe requested by the client.				
1.Preparation and briefing	Project brief agreed by the client	Contribution to Client's Indoor Environmental Quality aspirations	Provide pre-application planning advice e.g. on ambient air quality	Air quality consultant may be appointed	Studies Site Information Information Requirements
2. Concept Design	Architectural concept agreed by client	Production of IAQ Strategy	Client may obtain pre-application planning advice from local authority		Stage 2 Report signed off
3. Spatial Coordination	Design information spatially coordinated	Detailed IAQ strategy with input to design, outline strategies and costings	Planning application Review design against building regulations		Stage 3 Report signed off
4. Technical Design	Design information required to manufacture and construct	Input to ventilation strategy and materials specification	Building Regulations application Discharge pre-commencement planning conditions Construction phase plan	Building design contractor may be appointed	Final specifications of low emission materials
5. Manufacturing and Construction	Air quality consultant involvement likely to be answering questions regarding the specification of material and monitoring of construction dust/PM.				
6. Handover	Building handed over Aftercare initiated	Pre-occupancy evaluation	Comply with planning conditions as required		Results of pre-occupancy evaluation
7. Use	Building used, operated and maintained efficiently	Post-occupancy evaluation	Comply with planning conditions as required		Post-occupancy evaluation

Appendix E. Simple Assessment Case Studies

E1. Case study: A Prison Wing

E1.1. This case study primarily focusses on the issue of the IAQ risks likely to occur from second-hand smoke in a prison wing when smoking by inmates was permitted through an exemption for prisoners in the 2006 Health Act. Monitoring of the IAQ confirmed the conclusions of the preliminary assessment.

E1.2. The main pollutants chosen for this Simple Assessment were second-hand smoke ($PM_{2.5}$), limonene from cleaning activities and $PM_{2.5}$ from cleaning activities. The principal receptors under investigation were prison staff, who were in and around the emission sources for up to 8-12 hours/day. Cumulative exposure of staff to other pollutants in other locations, e.g. to ambient air pollutants when escorting prisoners, during supervision of outdoor exercise or staff exposure to indoor pollutants at their place of residence, were not taken into account. The calculations were based on exposure outside individual cells, as IAQ varied hugely between cells, as did the duration staff spent within cells throughout the working day.

E1.3. Following the methodology set out in **Section 4.3**, the exposure of the Prison Officers was assessed, taking the following into account:

- emissions from cleaning activities could have been screened out at the desktop stage but were included for completeness;
- tobacco smoke includes, $PM_{2.5}$, formaldehyde, CO and 100s of VOCs including some carcinogens (which are not assessed using this method and are outside the scope of this Guidance);
- consideration of external sources of pollutants was not considered important with the exception of PM from outdoor activities around the prison site (e.g. construction); and
- $PM_{2.5}$ from cooking activities was screened out as this prison (as do most) had centralised kitchens with good levels of mechanical ventilation.

E1.4. The **Simple Assessment** results in a **MEDIUM** risk of IAQ health impacts to prison staff and the need for a **Stage 2B Detailed Assessment** is indicated. This involves monitoring. Monitoring was undertaken and confirmed that second hand smoke was the principal health risk to prison staff and a removal of the 2006 Health Act exemption leading to a cessation of tobacco smoking was recommended. There were no requirements to take action for the items identified as low risk.

Table E1: Summary of IAQ Assessment of Prison Staff Exposure in a Prison Wing

Scenario	Duration of Exposure	Pollutant(s)	Table 4.1	Table 4.2	Table 4.3	Table 4.4
			Outdoor: indoor pathway	Harm from internal sources	Duration/ Frequency	IAQ Health Risk
Office general cleaning 6-8am Mon-Fri	<8 hrs/wk	Limonene	0	3	Low	Low
Prison wing cleaning	<8 hrs/wk	PM	2	3	Low	Low
Prison wing cleaning	<8 hrs/wk	TVOCs	0	5	Low	Low
Prison wing second hand smoke	<80hrs/wk	PM/CO/ Specific VOCs[(a)] etc.	0	3	High	Medium

(a) Based on non-carcinogenic combustion products from tobacco smoking

E2. Case Study: Primary School

E2.1. This case study focussed on indoor emissions from cleaning activities and ingress of external pollutants, largely from local road traffic. Exposure was focussed on the ground floor nursery classroom with the young children as the most sensitive receptors. They spent periods both in and outside the classroom, close to nearby traffic emissions, for up to 6 hours a day. Cumulative exposure (i.e. other pollutants in other locations e.g. at home or outside exposure in the playground, travelling to and from the nursery) were not taken into account. The calculations were based on exposure within the classroom area, and not within other indoor parts of the nursery school building, as the pathways for vehicle emissions into other areas were indirect and limited.

E2.2. Following the methodology set out in **Section 4.3**, the exposure of the nursery children was assessed as follows, taking the following into account:

- emissions from cleaning activities, includes: PM_{10}, $PM_{2.5}$, and VOCs; and
- exhaust emissions, includes: PM_{10}, $PM_{2.5}$, NO_2, CO and 100s of VOCs including some carcinogens (which are not assessed using this method and are outside the scope of this Guidance).

E2.3. The **Simple Assessment** results in a **MEDIUM** risk of IAQ health impacts to nursery children and the need for a **Stage 2B Detailed Assessment** is indicated. This involves monitoring. Monitoring was undertaken and confirmed roadside NO_2 concentrations were high at the same time children were present. Indoor NO_2 concentrations were 27%-80% of the outdoor concentrations, due to attenuation by the school building. Recommendations were made including mounting screening along school railings to disrupt pollution pathways. Although not part of the assessment, low pollution routes to and from school were also suggested as some local roads were found to have high concentration of NO_2. No IAQ recommendations were necessary.

Table E2: Summary of IAQ Assessment of Nursery School Children in a Ground Floor Classroom

Scenario	Duration of Exposure	Pollutant(s)	Table 4.1 Outdoor: indoor pathway	Table 4.2 Harm from internal sources	Table 4.3 Duration/ Frequency	Table 4.4 IAQ Health Risk
Office general cleaning 6-8am Mon-Fri	<8 hrs/wk	Specific VOCs[(a)], PM	N/A	2	Low	Negligible
Nursery School Classroom	<40 hrs/wk	PM	3	2	Medium	Medium
Nursery School Classroom	<40 hrs/wk	Specific VOCs[(a)]	2	2	Medium	Medium
Nursery School Classroom	<40hrs/wk	NO_2	4	N/A	Medium	Medium

(a) Based on typical VOCs found in commercial cleaning products such as limonene

E3. Case Study: Office Reception Area

E3.1. This case study focussed on the ingress of external pollutants into a ground floor office reception area (largely from queuing taxis located 1 metre from the reception entrance) and general cleaning activities.

E3.2. This Simple Assessment considered exposure of reception staff (up to 8 hours/day) to vehicle exhaust and cleaning activity emissions. Cumulative exposure (i.e. other pollutants in other locations e.g. at home) were not taken into account. The calculations were based on exposure within the reception area, and not within other parts of the office building, as the pathways for vehicle emissions into other areas were severely limited.

E3.3. Following the methodology set out in **Section 4.3**, the exposure of the reception staff was assessed taking the following into account:

- emissions from cleaning activities could have been screened out at **Stage 1 Scoping Study** but were included for completeness; and
- exhaust emissions includes, PM_{10}, $PM_{2.5}$, NO_2, CO and 100s of VOCs including benzene, including some carcinogens (which are not assessed using this method and are outside the scope of this Guidance).

E3.4. The **Simple Assessment** results in a **HIGH** risk of IAQ health impacts to office reception staff and the need for a **Stage 2B Detailed Assessment** is indicated with consideration of immediate measures that may reduce exposure of the receptions staff. Consideration was given to ensuring that the doors were not left open unnecessarily and taxis were encouraged to minimise idling engines. This next stage involved monitoring. Monitoring was undertaken and confirmed that NO_2 concentrations were elevated at certain midweek periods, particularly morning and late afternoon, consistent with office staff entering and leaving the building, promoting ingress of ambient pollution when office doors opened and closed. Introduction of a lobby door system was recommended to disrupt the pollutant pathway. A relocation of the office avoided the requirement for this last costly recommendation.

Table E3: Summary of IAQ Assessment of Reception Staff Exposure at a Ground Floor Reception Desk

Scenario	Duration of Exposure	Pollutant(s)	Table 4.1	Table 4.2	Table 4.3	Table 4.4
			Outdoor: indoor pathway	Harm from internal sources	Duration/ Frequency	IAQ Health Risk
Office general cleaning 6-8am Mon-Fri	‹8 hrs/wk	Specific non-toxic VOCs(a)	2	2	Low	Negligible
Office Reception Area	‹40 hrs/wk	PM	4	2	High	High
Office Reception Area	‹40 hrs/wk	Specific VOCs(a)	3	1	High	Medium
Office Reception Area	‹40hrs/wk	NO_2	5	0	High	High

(a) Based on typical VOCs found in commercial cleaning products such as limonene

Appendix F. IAQ Measurement and Testing Protocols

Table F1: Current Indoor Air Quality Guidance

Guidance	Pollutants Included	Further Guidance
Building Bulletin 10 (Education and Skills Funding Agency, 2018)	CO_2 + ADF pollutants (+ asbestos (HSE, 2002) and EH40 (HSE, 2020) substances where appropriate)	Recommends WHO (WHO, 2020) (WHO, 2010) as good practice.
Chartered Institution of Building Service Engineers (CIBSE, 2020b)	WHO and PHE guidance pollutants	CO_2 used as a proxy indicator of ventilation / bio effluent pollution during human activity. Care needed when interpreting TVOC results. National PHE guidelines for individual VOCs should be used as they are based on medical evidence of health effects. WHO IAQ guidelines to be applied in combination with the PHE values to form a more comprehensive list of target indoor pollutants. TVOC instruments are limited in their range and differentiation of VOCs detected in real time. Low measured concentrations of TVOCs are not always representative of good IAQ and should be supplemented with active (specific) VOC sorption tube monitoring. Co-located measurement of CO_2, TVOC, formaldehyde, $PM_{2.5}$ and NO_2 could be used as a more holistic way to control ventilation strategies for optimised IAQ. It is important to place sensors at a specific (**breathing zone**) height depending on the use of the building.
Building Research Establishment Environmental Assessment Method (BREEAM) Hea02 (BRE, 2014)	Formaldehyde and TVOC	Requires an IAQ Plan and measurement of IAQ in accordance with relevant British Standards (both post construction and pre occupation). Measurements must be reported using the BREEAM Assessment Scoring and Reporting Tool. Sample measurements should normally be taken in representative **habitable or occupiable rooms**. In larger rooms such as open plan offices further sampling locations should be used to understand the homogeneity of the atmosphere. Depending on the performance/repeatability of the measurement method, replicate samples may be taken. Prior to measurements being undertaken the building should have reached equilibrium in terms of its environmental conditions.
US Green Building Council Leadership in Energy Efficiency and Design (LEED) (US Green Building Council, 2020)	$PM_{2.5}$, O_3, CO, TVOC, formaldehyde & 11 other VOC (+ CO_2 for existing buildings)	LEED v4.1 Interior Design and Construction Guide (2020) sets out IAQ assessment requirements. Testing is required post construction and pre occupancy, but under ventilation conditions typical for occupancy. Baseline IAQ testing required in occupiable spaces. For retail projects testing may be conducted within 14 days of occupancy. Table 1 of the LEED Guide (US Green Building Council, 2020) sets out the allowed test methods. ISO 4224 or equivalent for CO or a direct calibrated electrochemical sensor with <50 ppm minimum accuracy. PM monitoring device requires accuracy >5 μg/m³. O_3 monitoring device requires accuracy >5 ppb, ISO 13964 or equivalent. TVOC method ISO 160006 or equivalent. Testing laboratories must be ISO/IEC 17025 accredited. ISO 160006 also applicable to other VOCs and ISO 160171.

Table F1: Current Indoor Air Quality Guidance

Guidance	Pollutants Included	Further Guidance
WELL Building Institute	Formaldehyde, TVOC, CO, $PM_{2.5}$, PM_{10}, O_3 and Radon (+ NO_2 for commercial kitchens)	WELL Performance Verification Guidebook (Q3 2020) sets out assessment requirements. **Table 2** of this Appendix provides the number of sampling points required based on project area and number of floors, the minimum measurement duration for each pollutant and the measurement device requirements. For PM real time monitor light scattering devices are required with a range of 0-11,000 $\mu g/m^3$. For formaldehyde ISO 160003 or equivalent methods should be used and a minimum of 1 field blank required per day of sampling. For TVOC ISO 160006 or equivalent methods should be used and a minimum of 1 field blank is required. For CO direct reading RTM devices are required with a range of 0-125 ppm. For O_3 direct reading RTM devices are required with a range of 0-500 ppb (and a resolution of 1 ppb). For NO_2 the method measurement range should be 0-500 ppb with a lower detectable limit of 5 ppb. Radon measurements are only required on the lowest occupied ground level of the project site and should be 0.91 m from windows and exterior doors, 20.3 cm from exterior walls and 50.8 cm above finished floors. Active or passive sampling methods are permitted, one sampler is required in each 2300 m^2 of the lowest occupied ground level.

Table F2: Typical Individual Sampling Durations for Indoor Air Pollutants

Purpose of Survey/Guidance	Pollutants Monitored	Required Sampling Duration
Personal Exposure, COSHH	A wide range of pollutants with STELs and WELs	15 minutes or 8 hours (includes concept of time weighted averages)
Building Performance, BREEAM/ LEED	Formaldehyde	30 minutes
	TVOC	8 hours
Building Performance, WELL	Formaldehyde	Up to 8 hours
	TVOCs	
	CO	
	$PM_{2.5}/PM_{10}$	
	O_3	
	Radon	3 months
Building Material Emissions & Ventilation, e.g. Building Regulations	CO and NO_2	1 hour
	CO, NO_2 and O_3	1 year
	Radon	3 months (2-7 days for screening)
Risks to Health, e.g. WHO	Various	15 minutes to 1 year
Intrusion of polluted external air	O_3 and SO_2	15 minutes
	NO_2 and SO_2	1 hour
	CO and O_3	8 hours
	SO_2 and PM_{10}	24 hours
	NO_2, PM_{10}, benzene and PAHs	1 year

Appendix G. Examples of Monitoring Equipment

G1.1. Passive samplers have a single sampling time/interval of hours to weeks. Active (pumped) devices have a single sampling time/interval of a few seconds to hours. Continuous analysers (monitors) can provide data with high temporal resolution over long periods of time.

Table G1: Examples of Monitoring Equipment

Type	Example	Description	Pollutants
Passive sampling	Badges	The sorption badge sampling device can be used for either personal or area monitoring. The badge contains adsorbent material, the type of which is dependent on the target pollutant. After sampling the badge is sealed and returned to the laboratory for desorption and chemical analysis.	VOCs, gases, Formaldehyde, Radon
Passive sampling	Diffusion tubes/ Tenax/Sorbent Tubes	The Palmes tube is a diffusion sampling device used for area monitoring. The diffusion tube cap contains a pollutant specific adsorbent material. Tubes are deployed vertically with the bottom cap removed. Air is sampled through diffusing up the length of the tube and the pollutant is adsorbed onto the cap. After sampling the bottom cap is replaced, sealed and the tubes returned to the laboratory for desorption and chemical analysis.	VOC adsorption tubes SO_2, NH_3, O_3, NO_2
Passive sampling	Activated charcoal detectors (ACDs)	ACDs are passive devices deployed for 1-7 days to measure indoor radon. The principle of detection is radon adsorption on the active sites of the activated carbon. After sampling, the detector is sealed, and the radon decay products equilibrate with the collected radon.	Radon
Pumped sampling	Filters	Small wearable sampling head which holds a 25mm filter used for the collection of inhalable dust, which is drawn onto the filter using a sampling pump. The filter is weighted before and after sampling to estimate the PM concentration. Can also be used to measure components of the PM by extraction of the PM from the filter followed by chemical analysis	Gravimetric analysis, Chemical analysis e.g. for metals, Asbestos, Bioaerosols
Pumped sampling	Tenax/Sorbent Tubes	Glass or stainless steel tube packed with a material for adsorbing gases. Sample air is drawn through the tubes at a known rate, gases and vapours are adsorbed onto sorbent material. Tubes are capped and sealed at the end of the sampling period and sent off to a laboratory for analysis.	TVOCs, specific VOCs, inorganic acids, amines
Pumped sampling	Sample Bags	Vacuum bag constructed of inert material (Tedlar) fitted with a gas valve. A small air sample is pumped into the bag, the valve is then sealed, and the sample is sent to the laboratory for analysis. Limit of detection is constrained by the analytical method and the size of air sample collected.	Organic gases, Inorganic gases
Pumped sampling	Liquid/Bubble Samplers	Impingement bubble sampler, collection of air samples into a liquid allows up to an 8-hour air quality sample. Samplers are filled with complementary liquid, such as sterile distilled water, phosphate buffered salve (PBS), physiological saline, etc.	Bioaerosols

Table G1: Examples of Monitoring Equipment

Type	Example	Description	Pollutants
Pumped sampling	Colorimetric indicator sampling	Glass tube packed with an adsorbent material with a colorimetric property responding to pollutant concentration. Sample air is drawn through the tubes at a known rate, gases and vapours are adsorbed onto sorbent material. Colour indication and scale provides an instantaneous result. Detection limit is relatively high at several parts per million.	Inorganic gases, Organic vapours
Indicative samplers	Electro-chemical detection	Electrochemical sensors provide a continuous, instantaneous response to specific airborne pollutant gases. Their signal responses are significantly influenced by both temperature and humidity, as well as cross-sensitivity to other pollutants.	Specific gases
Indicative samplers	Optical Particle Counting	Optical particle counting devices use light scattering combined with assumptions about particle density/shape etc. to provide an estimate of the airborne particle mass concentration. They are often small, light-weight battery operated devices, capable of personal monitoring, and some devices are capable of a counting a wide range of particle sizes, typically between about 0.3 μm and 10 μm.	Particulate matter
Indicative samplers	Photo-ionisation Detection	Photo ionization detectors (PIDs) are capable of continuous measurement of VOCs at low concentrations. Due to their small size PIDs can provide a compact method of detecting indoor VOCs. Most PIDs do not provide pollutant speciation, and record Total VOCs rather than individual concentrations.	VOCs, often as TVOC
Real-time reference samplers	Gas analysers	Gas analysers provide real time ambient air pollutant measurements. Reference detection methods for gaseous pollutants in ambient air are restricted to chemiluminescence (NO_x), ultra violet fluorescence (SO_2), infra-red absorption (CO) and ultraviolet analysis (O_3). These methods are capable of detection limits down to single digit ppb. Reference method gas analysers are large, usually require a mains electricity power supply and are often noisy. They are therefore not suitable for tranquil and spatially constrained indoor environments.	Inorganic gases, e.g. NO_2, SO_2, NH_3, O_3
Real-time reference samplers	Near direct Infra-red Spectroscopy (NIRS)	NIRS is able to monitor composition changes in complex samples. It is well established in the fields of medicine, agricultural and food science, and is emerging as an IAQ tool.	TVOCs, NO_x, SO_2 and Particulate Matter
Real-time reference samplers	Optical Particulate Matter Measurements	Light scattering and optical particle spectrometers are frequently used for ambient PM monitoring. Such monitors generally make assumptions about particle density/shape etc. in order to provide an estimate of the airborne particle mass concentration. A number of these systems are equivalent to the reference method for airborne particulate matter monitoring and can supply continuous near real time particulate matter concentrations.	Particulate Matter
Real-time reference samplers	Reference Method Photo Ionisation Detection	Reference method PIDs are capable of near real time ppb detection of a range of VOCs in ambient air. Detection systems can be noisy, expensive, require a significant amount of space and regular maintenance and calibration.	TVOCs

Appendix H. Case Studies: Monitoring

H1. Case Study 1: Office Headquarters IAQ Review

H1.1. The environmental quality of a second floor central London office was assessed following complaints of 'stuffiness' in both the summer and winter. The office had been occupied for several years, with the initial fitout and commissioning conducted in 2007. There was found to be a general perceived negative impact on productivity due to the environmental conditions, as well as reported negative health effects and a sense that the design of the workplace did not make the employees feel valued.

Monitoring and analysis

H1.2. Quantitative environmental monitoring of representative office areas was conducted over a one month period using space utilisation and Indoor Environmental Quality (IEQ) sensors measuring TVOCs, CO_2, temperature, humidity and $PM_{2.5}$ concentrations in ten different zones numbered 2.01 to 2.10. These data were used in conjunction with qualitative data from Building User Surveys (BUS) to understand the performance of the space. **Figure H1** shows a qualitative record of CO_2 concentrations in the ten different zones.

H1.3. Following the IEQ monitoring an initial desktop study of the existing ventilation systems indicated that based on the occupancy density, there was insufficient ventilation to meet the British Council for Offices (BCO) recommended supply rate of 12 litres per second per person (l/s/p), which affected the northern side of the office due to its higher occupancy density. Most spaces did not meet the Building Regulation minimum standard air supply rate (the higher rate of 10 l/s/p or 1 l/s/m^2 (floor area)); current good practice performance for a new modern office building would typically achieve 14-16 l/s/p. This underperformance was confirmed by both the IEQ and BUS data. The clearest indication was from the recorded concentrations of CO_2 which significantly exceeded the good practice threshold of 1,000 ppm, peaking at over 1,600 ppm.

H1.4. Another reason for the reported '*stuffiness*' of the office areas was low Relative Humidity (RH). Good practice RH is between 40% and 60% whereas the IEQ sensors measured RH below this range for 60% of the time and below 30% RH, for 25% of the time. These low RHs were unusual for the time of year and warranted further investigation. Beyond drying out the skin, eyes and nose, low humidity increases the rate of transmission of viruses such as influenza and may have a direct impact on absenteeism. Additionally, recent studies have shown that these low RHs can also affect occupant well-being and productivity.

H1.5. Total Volatile Organic Compounds (TVOC) were observed to be high in areas with high CO_2 concentrations, as shown in **Figure H2**. TVOCs are often brought into the space by users and as such are a function of occupancy and the amount of fresh air delivered to the space. Increased ventilation (or reduced occupancy) in these areas will bring concentrations down. A number of zones indicated spikes in VOCs, and a steady increase over the weekend when occupancy was significantly reduced. This was probably due to VOCs being emitted in the office from cleaning activities using high VOC products or some other internal source. Further detailed investigation was recommended to confirm the source and risk to health.

H1.6. $PM_{2.5}$ measurements were found to be very low across all sensors, with very slight increases in a couple meeting rooms. This was expected as external (ambient) concentrations were relatively low, and the bag filters installed on the ventilation system should remove most of the particulate matter from the supply air when concentrations are elevated outside. The ambient concentrations shown in **Figure H3** were taken from the nearest background monitoring station, Sir John Cass School, which displays local effects and may not be applicable to the office site.

Recommendations for improvement

H1.7. At the end of investigation, it was recommended that a detailed review of the ventilation system be commissioned to understand whether more ventilation could be supplied to the floor via the existing air handling units or how additional local ventilation units could be incorporated to supplement the existing supplies. It was also recommended that the opportunity be investigated to increase humidity by introducing humidification to the mechanical plant and/or introducing a significant number of plants (greenery) into the office space.

H2. Case Study 2: Residential Post-Construction VOC Monitoring

Campaign

H2.1. IAQ sampling and analysis was undertaken in two newly finished residential apartment blocks.

H2.2. Monitoring of formaldehyde and VOCs was undertaken, following good practice, such as the methods referred to in the Building Research Establishment Environmental Assessment Method (BREEAM) and the Home Quality Mark (HQM) (BRE, 2018).

H2.3. The results of the sampling were compared with guidelines from the WHO and (MHCLG, 2010a) (replicated in the HQM Technical Manual) as follows:

- formaldehyde: 100 μg/m^3, averaged over 30 minutes; and
- total VOC: 300 μg/m^3, averaged over 8 hours, with no individual compound exceeding 30 μg/m^3.

Figure H1: Carbon Dioxide (CO_2) Time in Range (8am-6pm, Mon-Fri)

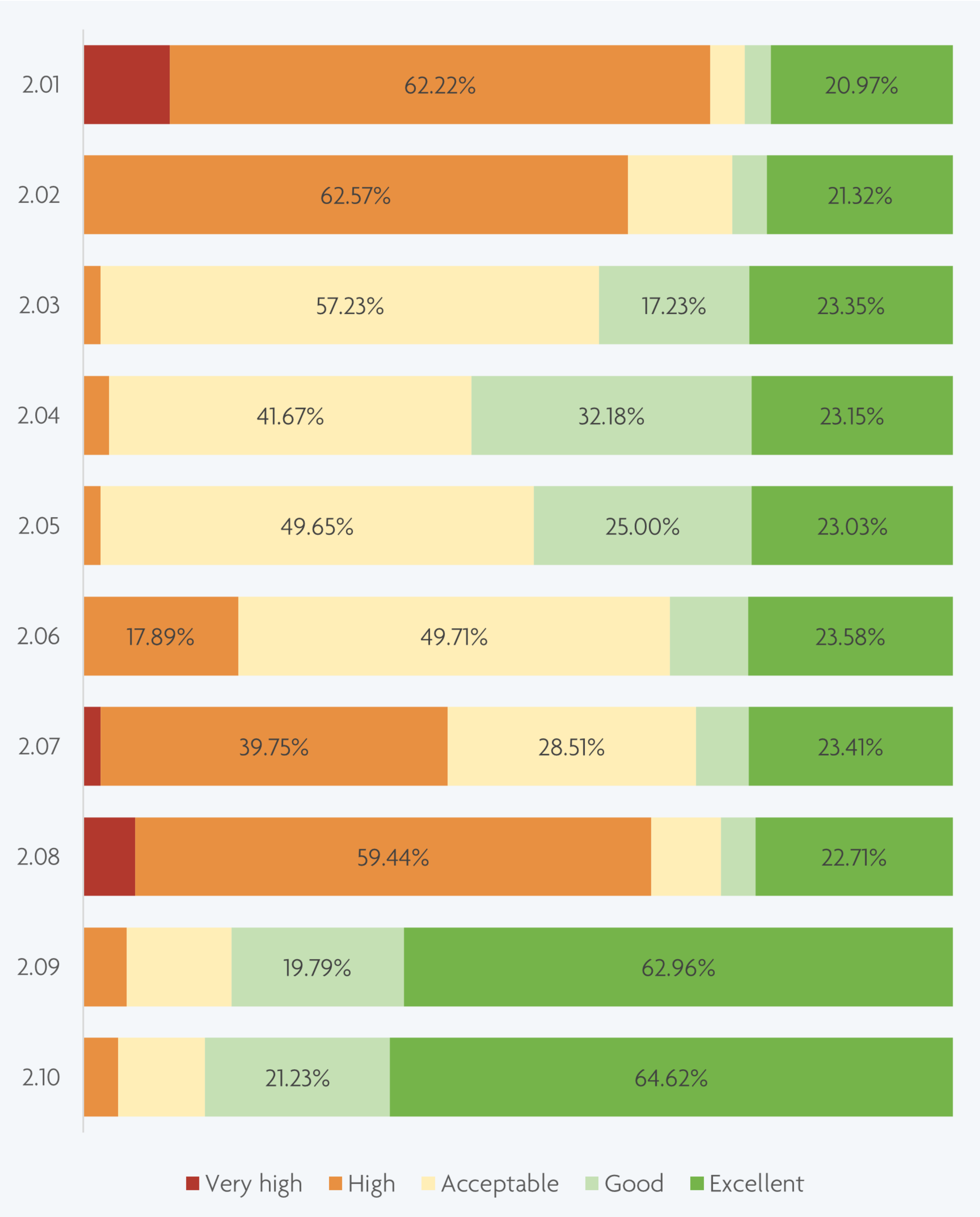


Figure H2: 15-minute Mean TVOC Concentration Over a 7-day Period

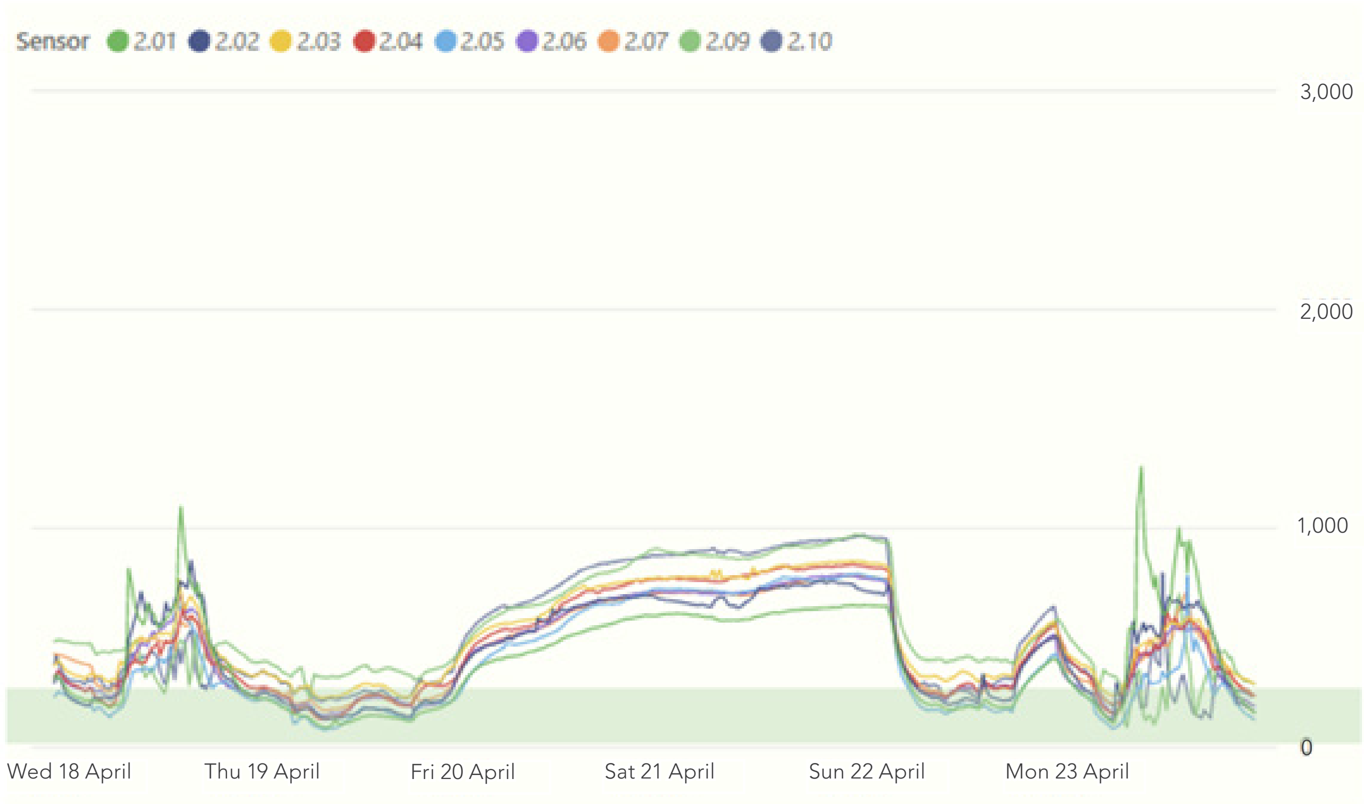
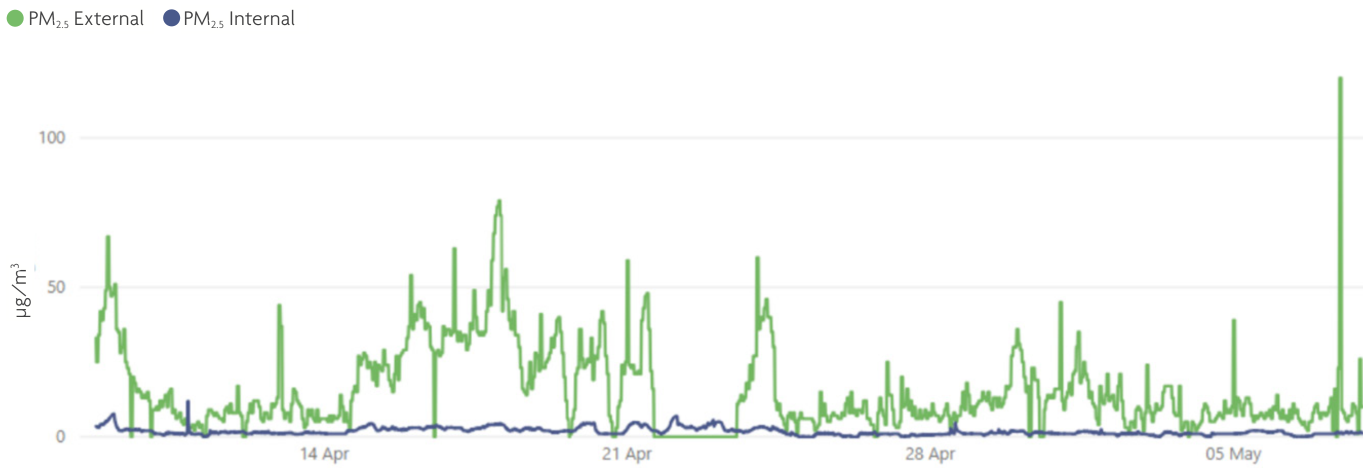


Figure H3: Comparison of Outdoor and Indoor $PM_{2.5}$ Concentrations (Sir John Cass School Urban Background)



H2.4. The following sampling locations were selected after consultation with the client to ensure that sample measurements were "taken in representative habitable or occupiable rooms" (see **Appendix A** for definitions of these terms), to enable the homogeneity of air within habitable spaces of the building as a whole to be adequately characterised.

A. Two bedroom apartment with polished concrete and carpet flooring,

B. Studio apartment with wood laminate flooring,

C. One bedroom apartment with polished concrete and carpet flooring,

D. Two bedroom apartment with wood laminate and carpet flooring,

E. Two bedroom apartment with wood laminate and carpet flooring, and

F. One bedroom apartment with wood laminate flooring.

H2.5. The sampling and analysis of the formaldehyde and VOCs in air was carried out in broad accordance with the following standards, or slight modifications of the standards as detailed in the report of the assessment and/or recommended by the laboratory.

- BS EN ISO 160005 and ISO160006 Indoor air (for formaldehyde), and
- BS EN ISO 160002 and ISO16003:2011 (for VOCs).

H2.6. Sampling was carried out over periods representative of the averaging periods of the relevant IAQ standards, by competent personnel in accordance with a documented ISO9001 accredited quality system, using instruments with calibration traceable to national standards, where appropriate. Sampling was undertaken in each of the listed rooms once they were complete, but before they were occupied.

H2.7. The pumped sampling was undertaken at approximate head height and away from walls, ceilings and floors. Formaldehyde samples were obtained at a flow rate of approximately 200ml per minute over a 60-minute period (i.e. a total of 12 litres of sampled air). A flow meter was used to calibrate the flow rate through the samples at the start of testing. The average reading (taken at the start and end of testing) was taken. Total and 'top 10' VOC samples were obtained at a flow rate of approximately 100ml per minute for 60 minutes (i.e. a total of 6 litres of sampled air).

H2.8. The VOC sampling flow rate was chosen in accordance with the laboratory recommendation, and the sampling volume was chosen to prevent benzene from reaching the estimated 'breakthrough volume' in the VOC sampling tube, or the point at which the tube would stop absorbing VOC within the sampling media.

H2.9. The formaldehyde sampling flow rate was chosen in accordance with that recommended by the laboratory, deviating from the 30-minute sampling period recommendation in ISO160002 to ensure that laboratory levels of detection were adhered to.

Table H1: Monitoring Results, Formaldehyde

Location	Mass adsorbed (blank corrected, µg)	Derived concentration (µg/m³)	Exceeds the 100 µg/m³ criterion?
D. Kitchen/ Living Space	0.85	57.2	No
D. Bedroom	0.80	53.5	No
E. Kitchen/ Living Space (test 1)	0.41	22.2	No
E. Kitchen/ Living Space (test 2)	0.42	23.3	No
E. Bedroom (test 1)	0.42	23.7	No
E. Bedroom (test 2)	0.48	28.3	No
F. Kitchen/ Living Space	0.57	36.6	No
B. Living Space	0.58	44.2	No
B. Bedroom	0.34	27.8	No
A. Living Space	0.13	10.2	No
A. Bedroom	0.15	12.5	No
C. Living Space	0.24	18.0	No

Table H2: Monitoring Results, TVOCs

Location	Mass adsorbed (blank corrected, µg)	Derived concentration (µg/m³)	Exceeds the 300 µg/m³ criterion?
D. Kitchen/ Living Space	27,285	4,458	Yes
D. Bedroom	29,604	4,837	Yes
E. Kitchen/ Living Space (test 1)	17,541	2,811	Yes
E. Kitchen/ Living Space (test 2)	16,805	2,719	Yes
E. Bedroom (test 1)	16,372	2,675	Yes
E. Bedroom (test 2)	17,532	2,783	Yes
F. Kitchen/ Living Space	32,499	5,363	Yes
F. Bedroom	33,984	5,446	Yes
B. Living Space	6,324	1,033	Yes
B. Bedroom	7,321	1,196	Yes
A. Living Space	3,573	584	Yes
A. Bed area	1,956	294	No
C. Living Space	3,346	536	Yes
C. Bedroom	3,415	587	Yes

Table H3: Monitoring Results, Top 10 VOCs

Location	Mass adsorbed (blank corrected, µg)	Derived concentration (µg/m³)	Exceeds the 100 µg/m³ criterion?
D. Kitchen/ Living Space	Alpha Pinene	503	Yes
D. Bedroom	Alpha Pinene	569	Yes
E. Kitchen/ Living Space (test 1)	Propanoic acid, 2-methyl, 3-hydroxy-2,2,4-trimethyl-pentyl ester	557	Yes
E. Kitchen/ Living Space (test 2)		535	Yes
E. Bedroom (test 1)		445	Yes
E. Bedroom (test 2)		495	Yes
F. Kitchen/ Living Space	Toluene	777	Yes
F. Bedroom		771	Yes
B. Living Space	Propanoic acid, 2-methyl, 3-hydroxy-2,2,4-trimethyl pentyl ester	177	Yes
B. Bedroom		256	Yes
A. Living Space		163	Yes
A. Bed area		89	Yes
C. Living Space		149	Yes
C. Bedroom		161	Yes

H2.10. Duplicate measurements were undertaken in Apartment E (with the duplicate testing commencing ten minutes after the first testing).

H2.11. In all testing locations, apartments were finished and fully serviced, and apartment doors remained closed during the testing period. It is understood that the client requested that work in communal areas was not undertaken between the day before and after the testing and for heating, ventilation and cooling systems to operate as defined in their testing specification prior to the monitoring team attending site.

H2.12. Sampling was undertaken in each of the listed rooms once they were complete, but before they were occupied.

Recommendations for action

H2.13. The results showed that the formaldehyde concentrations at all sampling locations complied with the 100 μg/m^3 criterion. However, the measured TVOC concentrations did not comply with the 300 μg/m^3 criterion at any of the monitoring locations (with the exception of the bedroom in flat A). Moreover, the largest substance measured as part of the 'Top 10' VOC analysis exceeded the 30 μg/m^3 criterion at each of the monitoring locations.

H2.14. It was recommended that IAQ could be improved following the implementation of mitigation. Such mitigation would comprise purging or 'flushing out' throughout all occupiable spaces of the buildings in consultation with the mechanical engineer, typically by operating the mechanical air supply and extraction system continuously (24 hours per day) with 100% outdoor air supplied (i.e. no recirculation). Normal air temperatures and humidities should be maintained in the building during flush out. In areas which are naturally ventilated spaces or where natural ventilation accompanies the mechanical system, windows and doors could be opened where appropriate and practicable. Flushing out is typically carried out for a minimum of 7 days (but may be necessary for much longer); monitoring may be required in some case to determine whether concentrations have reduced adequately.

H3. Case Study 3: Local Authority Headquarters

H3.1. The headquarters of a large local authority, located in a city centre office building, was refurbished in 2010 and designed for a maximum occupancy of 2500 staff. In 2018, concerns were raised over the IAQ of the office, originating from a complaint made by an occupant relating to 'stuffiness'. This complaint resulted in an extensive series of monitoring campaigns to ensure that both the performance of the ventilation system and the resulting indoor environment were in compliance with the relevant guidelines.

H3.2. An initial two-week monitoring study was undertaken by Environmental Building Solutions Ltd (EBS) in 2018 and, following this, Hoare Lea was appointed to conduct a three month IAQ monitoring study. Five Awair Omni air quality units were employed to monitor five core parameters: temperature, relative humidity (RH), CO_2, TVOCs and $PM_{2.5}$. The units were placed at a minimum distance from any fresh air supply points, at breathing height for occupants, and away from direct influences such as printers and sunlight. The locations on each floor were selected according to the RESET Air methodology (RESET, 2018) for monitor placement.

H3.3. RESET Air (https://www.reset.build) is a building certification system created and administered by GIGA (https://www.giga.build) which is aligned with other major health and well-being standards such as WELL and Fitwel (https://fitwel.org). This study considered both 'RESET Acceptable' and 'RESET High Performance' standards however, as RESET originated in China where air quality is significantly worse than the UK, the 'High Performance' Limits were targeted.

Monitoring Results

H3.4. The monitoring results confirmed that the office temperature was well maintained by the existing ventilation system, with the data showing little to no impact on average indoor temperatures from outdoor fluctuations. The data also indicated that RH was generally well maintained, despite it being a primary concern due to occupant complaints of dry air and the use of humidifiers. However, although an average range of 34-40% was achieved each day, there were a number of trough measurements where RH was found to be lower than the 30% threshold set by WELL.

H3.5. CO_2 measurements were found to have exceeded the 600 ppm RESET High Performance standards on 18.5% of measured instances, however, concentrations rarely (<0.1%) exceeded the 1000 ppm Acceptable Performance Limit. These results confirmed the findings of the previous EBS assessment which indicated that sufficient fresh air was provided, but that the potential existed for additional air flow to push the site towards 'High Performance'.

H3.6. Concentrations of TVOCs consistently exceeded the RESET High Performance limits of 400 μg/m^3 (133 ppb), even directly after the air flush in the early mornings (06:00-08:00) when the ventilation system is first activated. No visible cleaning spikes were present in the data, as illustrated in the daily profile in **Figure H4**, indicating that the sources of VOCs were likely to be linked to the occupants and occupant activities rather than any mechanical systems or building envelope factors.

H3.7. The monitored $PM_{2.5}$ concentrations were generally well below the 12 μg/m^3 RESET High Performance limit, indicating that the filtration system was performing well and removing the vast majority of $PM_{2.5}$. The outdoor pollution concentrations correlated strongly with rush hour, and an average $PM_{2.5}$ concentration reduction of 60% was observed between the outdoor and average indoor concentration.

Figure H4: Average Internal TVOC Profile by Day

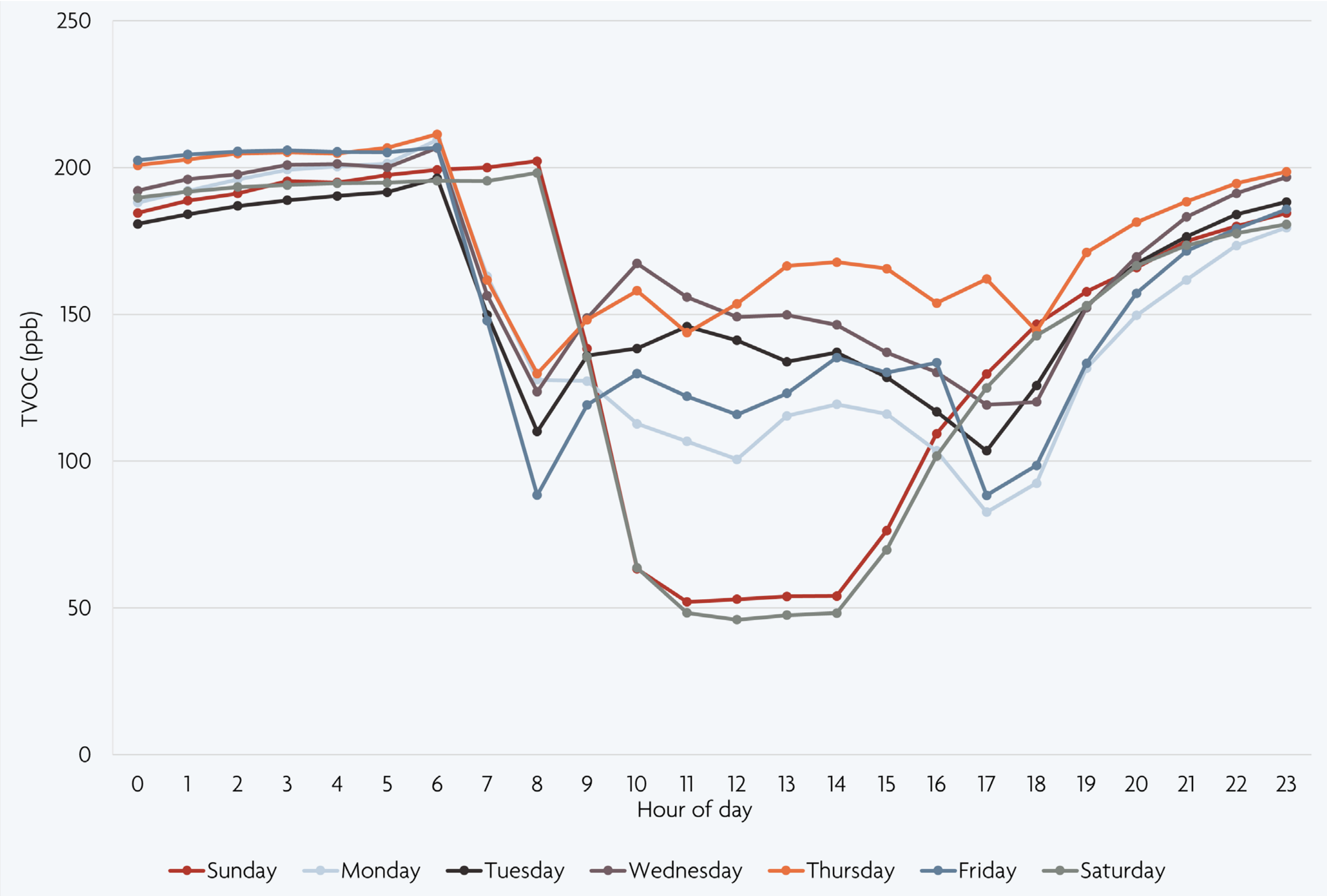


Table H4: Summary Statistics for Each Air Quality Parameter Monitored

Monitored Parameter	Percentage of Measurements Outside of Range (%)				
	Ground Floor	Floor 2	Floor 11	Floor 12	Average of Values
Temperature	0.5	0.0	1.3	0.7	0.6
Relative Humidity	0.0	0.6	1.2	1.4	0.8
Carbon Dioxide (CO_2)	15.4	28.6	15.8	14.0	18.5
Chemicals (TVOCs)	95.4	88.3	88.0	88.8	90.1
Particulate Matter ($PM_{2.5}$)	0.5	0.0	1.3	0.7	0.6

H3.8. The percentage of time (between Monday-Friday, 08:00-18:00) that the measurements were above the relevant assessment criteria is given in **Table H4**. The assessment criteria were those of BCO for temperature), WELL for relative humidity and RESET High Performance for CO_2, TVOC and $PM_{2.5}$.

H3.9. Overall, the results indicated that the environment within the office building was generally well maintained. Performance was particularly strong when considering temperature, relative humidity and particulate matter, with all three parameters meeting the RESET High Performance requirements. Although TVOC concentrations (and to a lesser extent CO_2) regularly exceeded both the RESET Acceptable and High Performance limits, this did not contradict findings in the other UK offices Hoare Lea have monitored.

Recommendations

H3.10. As TVOC concentrations regularly exceeded the RESET High Performance criteria and, as the sources of VOCs were not easily identified from the data set collected, it was recommended that samples were analysed using gas chromatography. This allows the individual VOCs present in the highest quantities to be identified, and their sources established so that appropriate mitigation measures can be determined if and where necessary. Further room for improvement was identified through increasing ventilation flow rates to mitigate peak CO_2 concentrations. In addition, as the measurement period was undertaken outside of the typically drier winter months, it was recommended that a further monitoring period be commissioned during the winter months when heating would be employed, and humidity performance may be impacted. This would give an indication of whether or not there were sufficient grounds for investment in a humidification system at the site.

Appendix I. Data Quality and Uncertainty

I1. Monitoring Data Quality

I1.1. There is no fixed data quality for IAQ monitoring; data quality is determined by the end use of the survey results. However, realistically, the expected quality of data will reflect the limitations resulting from time constraints, resource (staff and funding) limitations, selected monitoring method and its averaging period. As a basic necessity, IAQ monitoring should generate data which are representative of indoor air concentrations in the location under investigation, including accuracy and precision of data.

I1.2. ***Accuracy*** is the closeness of a measurement to the true value, or degree of agreement between observed value and reference value. ***Precision*** is the degree to which an instrument or process will repeat the same value.

I1.3. Data quality can be affected by any or all of the following factors:

- validation of method: am I measuring what I set out to measure;
- uncertainty: how well do I know the result of what I have measured;
- traceability of results: can I compare this result with other results;
- precision and accuracy: are the measurements representative of concentrations;
- reliability of sampling and detection systems;
- representative sampling location and duration;
- suitably experienced sampling personnel,
- calibration of sampling devices; and
- sufficient data capture percentage.

I1.4. As with all sampling methods, calibration of IAQ monitoring devices needs to follow manufacturers recommended methods, as well as any prescribed methodologies required by the assessment standard or methodology being applied.

I1.5. A short summary of calibration types are listed in the following table with sampling methods and conditions surrounding their application. A selection of IAQ monitoring methods is listed in **Table 5.2** (**Section 5.4**).

I1.6. The selection of an appropriate sampling method will need to consider the calibration type and its associated requirements and equipment. Constraints surrounding certain indoor settings may not permit the use of certain calibration equipment, (e.g. noisy and potentially harmful ozone generators, or calibration gas cylinders), therefore, the whole sampling process needs to be considered when choosing an indoor sampling method. Sampling methods which rely on infrequent calibration, or performance comparison, rather than periodic or routine calibration are likely to be associated with a lower sampling certainty and may be susceptible to reservations over their representativeness.

I2. Uncertainties

I2.1. The uncertainty (ISO, 1993) of a monitoring result is an aggregate of all uncertainties that contribute to the result. This is made up of the uncertainties around the performance

Table I1: Calibration Types and Corresponding Sampling Method

Calibration Type	Sampling Method
Laboratory calibration	Passive sampling, gravimetric filter sampling, filter sample collection
Factory calibration	Indicative sensors
Periodic off site calibration	Real time continuous occupational exposure monitoring
On site span checks	Indicative sensors, Continuous reference method gas monitoring method
On site periodic calibration	Continuous reference method gas monitoring method
Routine calibration e.g. flow rates	Pumped sampling filters/sorbent tubes
Proxy calibration or performance comparison with a reference method	Indicative continuous monitoring or low costs sensors

characteristics of a monitoring device (e.g. the instrument's response stability, linearity or response, interference effects e.g. from other pollutants, repeatability and reproducibility) as well as the uncertainty of the calibration standard(s).

I2.2. Each monitoring method has a range of uncertainty, and generally the magnitude of relative uncertainty (uncertainty in relation to measurement value) increases inversely to the measured concentration. As the measured concentration decreases, so the relative uncertainty increases.

I3. Traceability

I3.1. Instrument traceability, that is, how an instrument measurement can be demonstrated to be representative, is typically undertaken using a 'Transfer Standard' for the calibration, performance testing, and auditing of monitoring devices. Transfer Standards must be traceable to primary standards that are in turn derived from fundamental units of length, mass, temperature, and time.

I4. Sampling Medium and Detection Approach

I4.1. Selection of how and what to use to monitor is largely dependent on the performance standards required to be met (if, any) such as BREEAM or WELL; the probable pollutant concentrations to be encountered (i.e. are concentrations too low for passive monitoring), whether the sample will be large enough to be representative of the airspace and likely source.

Appendix J. Examples of measures to manage IAQ (design, construction, operation and monitoring)

J1. Dr Austin Cogan undertook a review of BREEAM, WELL, LEED, Building Regulations, ASHRAE, and various publicly available IAQ plans in July 2020 (Cogan, 2021) and created the contents of this appendix. They include possible measures to consider in the design (**Table J1**), construction (**Table J2**) and operation (**Table J3**) of a development. **Table J4** includes measures to consider when monitoring of IAQ is appropriate.

J1.1. These tables are applied on a risk based approach, taking into account the areas in a building and the exposure of occupants. This will involve consideration of the different areas within a development (office areas, kitchens, plant rooms, hallways/walkways, lunch rooms/canteens, toilets, stairwells, recreational areas) and possible exposure of people in the building. For example, visitors may have access to meeting rooms, reception and toilets but not the office areas. Dr Cogan's approach is to divide a development into a number of zones and determine for each measure listed an applicable recommendation (in one of four categories: required, highly recommended, desirable or not applicable).

J1.2. N.B. Some of the distances, volumes, temperatures are advisory from guidance and some are legally enforceable - in all cases the recommended measures should follow the latest building regulations.

J2. Monitoring Recommendations

J2.1. The monitoring recommendations should feed into an indoor air quality monitoring plan, which sets out the specific locations, equipment, durations, and frequency of the monitoring. Once monitoring has been carried out, the measurements should be reviewed against the relevant assessment levels, and where necessary, further mitigation measures may need to be applied. The findings of all monitoring should be clearly set out in a report.

Table J1: Design Measures

1. Fresh air should be provided into the building at sufficient air change rates to ensure moisture is minimised, no mould is visible, and bio-effluents (body odours) are minimised.
2. Ventilation pathways should be designed to minimise the ingress of outdoor air pollution and minimise the build-up of air pollution indoors, in accordance with BS EN 16798-3:2017.
3. Ventilation inlets and exhausts should be located in relation to each other and sources of outdoor pollution in accordance with PD CEN/TR 16798-4:2017, BRE FB 30, BRE IP 9/14 and CIBSE TM21. These give guidance on the optimum locations of ventilation inlets, openable windows, background ventilators and trickle vents.
4. Ventilation inlets and exhausts should be positioned at least 10 metres (or an appropriate, justified distance) apart.
5. Ventilation, kitchen, or any combustion exhausts should not be discharged into enclosed spaces, such as courtyards, where pollution will not be readily dispersed.
6. Where present, HVAC systems should incorporate suitable filtration to minimise external air pollution.
7. Areas of the building subject to large and unpredictable or variable occupancy patterns should have carbon dioxide (CO_2) or air quality sensors included.
8. Where sensors are present, these should be linked to the mechanical ventilation system, where possible, to provide demand-controlled ventilation.
9. For naturally ventilated buildings or spaces, where sensors are present, these should have the ability to alert the building owner or manager when CO_2 levels exceed recommended levels, and/or are linked to controls with the ability to adjust the quantity of fresh air, i.e., via automatic opening windows or roof vents.
10. For naturally ventilated or mixed mode buildings, the design should demonstrate that the ventilation strategy will provide cross flow of air to maintain ventilation rates in accordance with CIBSE AM10.

11. Pollutant dispersion modelling should be carried out to determine outdoor air quality and inform the locations of ventilation inlets and exhausts.
12. Where outdoor air quality exceeds standards and ventilation inlets are exposure to these levels, the ventilation system should include appropriate gas phase and/or particle filtration (such as MERV 13 or Class F7).
13. If gas phase and/or particle filtration is used, care should be taken to ensure the filter performance allows sufficient reductions in pollution.
14. Appropriately design pipework and ducting to prevent condensation forming on their surfaces.
15. Careful consideration should be given to landscaping. Plants and soil should not be located close to air intakes, as pollen, soil borne dust, VOCs, fertilizers, and pesticides can contaminate the air, and overgrown plants can block the inlets. It is important to consider the full potential after plants have matured.
16. Plan the shape and orientation of the building to allow prevailing winds to move pollution away from the building. Avoid designs that would trap pollutants in stagnant air pockets.
17. Where possible, air inlets should be located upwind of any local sources of pollution.
18. Where possible, onsite pollutant sources should be located downwind of any air inlets.
19. Develop a pressure map to help ensure that indoor air contaminants do not contaminate surrounding areas.
20. Ventilation practices that place crawlspaces, basements or underground ductwork below atmospheric pressure will tend to increase radon concentrations from the surrounding soils and should be avoided.
21. Include fine particle filtration within the ventilation system to minimise dust and pollen effects on occupants.
22. An infiltration co-efficient of less than 1 (or an appropriate, justified indicator) (the ratio of indoor pollutant measurement to outdoor pollutant measurement).
23. Forced ventilation/extraction in rooms or enclosed spaces where there are active emission sources, like for example commercial kitchens.
24. Careful use of internal plants/greenery to improve air quality.
25. Consideration of pressure differentials in tall buildings with voids from ground level to the top of the building where air movement can pull in ground level pollution and 'suck' it up to the higher levels.
26. Avoid including any fireplaces in the design.

Table J2: Construction Measures

1. Where construction materials are installed or applied in parts of the building where their emissions are likely to affect indoor air quality, materials should be low-VOC emitting.
2. If paints will be used in wet areas, these should protect against mould growth. Suitable paints are usually in accordance with EN 15457 (fungal resistance tested) or EN 15458 (algal resistance tested).
3. Care should be taken to avoid construction practices that could result in contamination of installed products, which could lead to indoor air pollution.
4. To prevent the absorption of moisture and humidity by adsorptive materials, the delivery of such materials should be sequenced appropriately so that they are not present in the building until all wet work is completed and dry, and such materials should be stored in fully sealed moisture-impermeable packaging.
5. If any adsorptive materials are exposed to moisture of humidity, then sufficient ventilation should be provided to dry the materials within a reasonable time frame.
6. Where dusty construction activities are carried out inside the building, temporary ventilation should be provided to extract dust from the building once the works are completed.

7. For mechanically ventilated buildings, operation of the permanently installed air handling equipment should be avoided during construction. Where this is not possible, all filtration media must be replaced prior to occupation.
8. All ductwork and ventilation equipment should be protected from dust during construction and, where necessary, cleaned prior to occupation.
9. When working in a portion of an occupied building, air should be prevented from moving from the construction area to the occupied area.
10. No construction or waste materials should be stored in mechanical or electrical rooms.
11. Mechanical ventilation may be used for ventilation during construction if the system intakes only outside air and operates with a minimum of 1.5 air changes per hour (or an appropriate, justified indicator), and all filters are regularly inspected and replaced when they lose efficiency, and all filters are replaced prior to occupation, and all intakes, grilles and terminal units are cleaned prior to occupation.
12. All areas within buildings are cleaned prior to occupation. Wet methods should be used to clean up residual dust, rather than dry sweeping, and areas allowed to dry prior to occupation.
13. Replace all intake filters, after cleaning is complete, prior to occupation.
14. A building flush-out should be performed before occupancy. This should not start until all construction is completed, all ventilation has been balanced for proper operation and all new filtration media have been installed. During the flush-out, all ventilation systems should operate at normal flow rates using only outdoor air until 4,500 m^3 of air per m^2 of floor area (or an appropriate justified, indicator) has been supplied. The interior temperature should be maintained at least 15°C and the interior relative humidity should be maintained below 60% - comfort factors which may have legal enforceability in the workplace.
15. The use of tobacco products, electronic smoking devices and other controlled substances should be prohibited within the building and within 7.5 metres (or an appropriate justified distance) from all outdoor air intakes, operable windows, and building entrances during construction.
16. Where appropriate, walking routes of construction workers should be controlled to avoid dust contaminating other areas.
17. Where appropriate, tack mats should be used along walking routes from dusty areas to minimise dispersion of dust.
18. Where possible, a non-occupied buffer zone should be established around dusty working areas.
19. Where highly dusty activities are carried out indoors, temporary solid screens or barriers should be erected, or the area enclosed, to avoid dust contaminating other areas.
20. No liquid fuelled generator plant should be used indoors or located near any ventilation intakes, open windows, doors, or trickle/purge vents.
21. A responsible person should be identified to ensure all contractors are trained appropriately and measures are implemented.
22. Regular inspections should be carried out to check measures are being effectively implemented, and where necessary adjust operations to prevent contamination of occupied areas.
23. If necessary, resolve any indoor air quality complaints that are received.
24. Use safety meetings, signage, and subcontractor agreements to communicate the goals of this indoor air quality strategy.
25. The site should be frequently cleaned to minimise dust re-suspension.
26. Public exposure to construction dust and odours in areas outside the building should be minimised.
27. For any retained building structures, if wet or mouldy material is identified prior to refurbishment, the material surfaces should be dried and remediated after demolition works are completed.
28. If the building includes occupied areas during the construction phase, any indoor dusty activities should be avoided during hours of occupation where possible.
29. Allow any wet-spray cellulose to dry before covering.

30. Allow for curing time and off-gassing when scheduling construction activities.
31. Install carpeting, acoustic panels and furnishings after interior finishes have been allowed time to cure and dry.
32. Ensure all construction workers are provided appropriate personal protection equipment to avoid adverse health effects from indoor air pollutants.
33. If any materials containing silica are used during construction, any sanding or cutting of the materials should be carried out using water suppression of dust.
34. If any Non-Road Mobile Machinery (NRMM) is used indoors, the exhaust fumes must be funnelled or piped to the exterior.
35. Consider monitoring dust levels during construction at a range of locations to ensure effects are minimised.

Table J3: Operational Measures

1. All filters, inlets and extracts should be properly maintained. Filters should be changed regularly according to manufacturer specifications and inlets/extracts should be checked regularly and any visible dirt should be removed.
2. The use of tobacco products, electronic smoking devices and other controlled substances should be avoided within the building and within 7.5 metres (or an appropriate justified distance) from all outdoor air intakes, operable windows, vent, and building entrances.
3. Good cleaning and dust control procedures should be adopted to help minimise indoor air quality.
4. Non-toxic, low-VOC cleaning equipment should be used.
5. During initial occupancy, extend the hours of the ventilation system operation. During the first hot weather period, increase the outdoor air fraction and continuously run the ventilation system.
6. Verify all inlets and extracts are working correctly.
7. Check all exhaust grilles and hoods are operating correctly.
8. Conduct a building walkthrough to evaluate the indoor air quality and resolve any issues identified.
9. Use of only necessary and appropriate pest control practices, and nonchemical methods where possible.
10. Maintain covered soil in all planting areas to minimise the potential for soil dust.
11. Provision of regular cleaning of all areas used by bicycles, to minimise dirt and dust.
12. Avoid the use of candles, incense, perfumes, and air fresheners.
13. Minimise use of paints, glues, and inks.

Table J4: Monitoring Recommendations

1. All monitoring of formaldehyde and other VOCs should be carried out using pumped sampling or chemical analysis, in accordance with ISO/IEC 17025.
2. Formaldehyde sampling and analysis should be performed in accordance with ISO 16000-2 and ISO 16000-3 or ASTM D5197, NIOSH 2016, EPA TO-11 or EPA-11A, or EPA Compendium Method IP-6 or IP-6A.
3. Formaldehyde sampling should include measurements of one continuous hour or the duration of sampling volume prescribed by the referenced testing methodology. One exposure field blank sample must also be prepared and analysed per day of sampling.
4. VOC sampling and analysis should be performed in accordance with ISO 16000-5 and 16000-6 or ISO 16017-1, ASTM D5197, or EPA TO-17.

5. VOC sampling should include measurements of one continuous hour or the duration of sampling volume prescribed by the referenced testing methodology. One exposure field blank sample must also be prepared and analysed per day of sampling.
6. Particulate matter sampling (including consideration of which size fraction(s), e.g. TPM, PM_{10}, $PM_{2.5}$) should be carried out using an appropriate method, with a minimum detection limit appropriate for the criterion selected.
7. Particulate matter (including consideration of which size fraction(s), e.g. TPM, PM_{10}, $PM_{2.5}$) sampling should include measurements of a suitable duration (e.g. at least 1 hour) and frequency (e.g. every 1 minute) to capture variability and appropriate for the criterion selected.
8. Carbon monoxide and ozone sampling should be carried out using an appropriate method (e.g. real-time direct reading instrument), with a minimum detection limit appropriate for the criterion selected.
9. Carbon monoxide sampling should include measurements of a suitable duration (e.g. at least 1 hour) and frequency (e.g. every 1 minute) to capture variability and be appropriate for the criterion selected.
10. Nitrogen dioxide sampling should be carried out using an appropriate method (e.g. real-time direct reading instrument), with a minimum detection limit appropriate for the criterion selected.
11. Nitrogen dioxide sampling should include measurements of a suitable duration (e.g. at least 1 hour) and frequency (e.g. every 1 minute) to capture variability and be appropriate for the criterion selected.
12. Monitoring should be conducted under typical conditions. For example, for naturally ventilated spaces, the windows should be open during testing, and for mechanically ventilated spaces, the windows should be closed and ventilation active during testing.
13. Sampling locations must be representative of typical occupied areas within the sampling zone and located where occupants would often be situated.
14. Sampling must be taken between 1.1 - 1.7 metres (or suitably justified height) above the finished floor, where occupants under consideration would typically be seated or standing (assessment of infants may require a lower height).
15. Sampling locations must represent of exposure of the population being considered which may require sampling to be e.g. at least 1 metre away from walls, doors, windows, air supply/exhaust outlets and any occupants that are present during monitoring.
16. For buildings with multiple floors, measurements must be distributed across different floors, including the lowest and highest regularly occupied floors (see **Table 5.2**).
17. Ideally, monitoring samples should be collected from the same locations on three consecutive days during normal operating hours, and the average calculated for each set of three samples.
18. If possible, samples should also be taken outside the air intakes at the same time as indoor samples are taken.
19. Where levels are identified to exceed limits or guidelines, appropriate measures should be implemented in accordance with the IAQ Plan to reduce levels to within the acceptable limits.
20. Where existing buildings are retained, monitoring of indoor air quality within these buildings should be carried out prior to construction.

IAQM
c/o Institution of Environmental Sciences
6-8 Great Eastern Street, London
EC2A 3NT

+44 (0)20 3862 7484

info@the-ies.org
www.iaqm.co.uk

IAQM