National Construction Code

Indoor air quality Verification Methods

Handbook

Australian Building Codes Board

AIRAH

The Australian Building Codes Board

The Australian Building Codes Board (ABCB) is a standards writing body responsible for the National Construction Code (NCC), WaterMark and CodeMark Certification Schemes.

The ABCB is a joint initiative of all levels of government in Australia, together with the building and plumbing industry. Its mission is to oversee issues relating to health, safety, amenity, accessibility and sustainability in building.

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Preface

This handbook is one of a series by the ABCB. Handbooks expand on areas of existing regulation or relate to topics that are not regulated by the NCC. They provide advice and guidance.

The Indoor Air Quality Verification Methods Handbook assists in understanding the indoor air quality (IAQ) Verification Methods in NCC Volumes One and Two (F6V1 and F6V2 in NCC Volume One and H4V3 of NCC Volume Two).

It addresses issues in generic terms and is not a document that sets out specific compliance advice for developing solutions to comply with the requirements in the NCC. This handbook is intended to guide readers in developing solutions relevant to specific situations in accordance with the generic principles and criteria contained herein.

Contents

Reminder

This handbook is not mandatory or regulatory in nature. Compliance with it will not necessarily discharge a user's legal obligations. The handbook should only be read and used subject to, and in conjunction with, the general disclaimer at page i.

The handbook also needs to be read in conjunction with the NCC and the relevant legislation of the appropriate state or territory. It is written in generic terms, and it is not intended that the content of the handbook counteract or conflict with the legislative requirements, any references in legal documents, any handbooks issued by the administration or any directives by the appropriate authority.

1 Background

This handbook provides guidance to practitioners seeking to understand the IAQ requirements of the NCC. It primarily provides support to understand IAQ Verification Methods F6V1 and F6V2 of NCC Volume One and H4V3 of NCC Volume Two.

These IAQ Verification Methods quantify ventilation system performance through the specification of maximum air contaminant limits (for a range of indoor air contaminants). These maximum levels must be achieved for the quality of the indoor air to meet the relevant Performance Requirements (which outline the minimum necessary standards buildings or building elements must attain).

The IAQ Verification Methods help define the point where adequate air quality is achieved, which allows the performance of a proposed ventilation building solution to be verified.

The purpose of this handbook is to:

- describe the principles behind the development of the IAQ Verification Methods
- provide examples of how they can be applied in practice
- provide information and data sources to support the use of the IAQ Verification Methods.

Due to the COVID-19 (Coronavirus disease 2019) pandemic there has been renewed interest in, and research into, ventilation and IAQ in buildings.

This handbook has been revised and updated in response to the COVID-19 pandemic to ensure it provides signposts to contemporary tools and approaches to IAQ and indoor air contaminant management.

Noting the NCC Verification Methods do not include specific criteria for biological contaminants including viruses, infectious aerosols are essentially particles, and many of the common IAQ control and mitigation strategies (dilution, directional airflow, air cleaning etc.) will still apply.

1.1 Scope

This handbook covers the following IAQ Verification Methods:

- F6V1 Verification of suitable indoor air quality
- F6V2 Verification of suitable indoor air quality for carparks, and
- H4V3 Verification of indoor air quality.

The handbook provides some background on the application of these Verification Methods within the NCC compliance framework as well as on the general principles of building ventilation, air contaminants, IAQ and a range of air contaminant controls. It provides an understanding of the ventilation Performance Requirements of the NCC and how the IAQ Verification Methods could be used to demonstrate compliance with those requirements.

The handbook also provides some broad guidance on design strategies, modelling principles, and sampling and testing protocols that could assist practitioners develop and validate Performance Solutions for maintaining adequate air quality in buildings with outdoor air ventilation.

1.2 Limitations

This handbook is intended to make users aware of provisions that may affect them, not exactly what is required by those provisions. If users determine that a provision may apply to them, the NCC should be read to determine the specifics of the provision.

This handbook does not deal with the health aspects of tobacco smoke, vaping or e-cigarette exposure. This reflects the provisions in the NCC Deemed-to-Satisfy (DTS) Provisions and Australian Standard AS 1668.2-2012 (incorporating amendments 1 and 2) which are based on the ventilation of enclosures where smoking does not occur.

Biological contaminants including house dust mites, moulds and fungi, allergens, bacterial and viral pollutants, are not covered by the IAQ Verification Methods. While biological contaminants such as moulds, fungi, and infectious aerosols are known air contaminants that can degrade IAQ, the methodology for the accurate modelling, sampling, testing and measurement of many biological species is not universally agreed. Acceptable limits for many biological contaminants have not been established and the NCC IAQ Verification Methods do not include maximum contaminant limits for biological contaminants such as airborne virus, bacteria or mould spores.

However, the inclusion of biological contaminants and the extension of the Verification Method to cover Performance Requirements F6P4(b) and H4P5(2)(b) may be considered for a future edition of the NCC as knowledge in the area increases.

For further information regarding moulds and fungi that may result because of condensation and inadequate ventilation, refer to the ABCB Condensation in buildings handbook.

1.3 Design and approval of Performance Solutions

The design and approval processes for IAQ solutions is expected to be like that adopted for demonstrating compliance of other NCC Performance Solutions. Since the design approval process for Performance Solutions varies between the responsible state and territory governments it is likely to also be the case with IAQ and requirements should be checked for the relevant jurisdiction.

Notwithstanding the quantified input and acceptance criteria, other qualitative aspects of indoor air quality, which are discussed in this handbook, require assessment and analysis throughout the design and approval process.

The advice of an appropriately qualified person should be sought to undertake this assessment and analysis where required and may be aided by the early and significant involvement from regulatory authorities, peer reviewer(s) and/or a technical panel as appropriate to the state or territory jurisdictions.

1.4 Using this document

Abbreviations and symbols used in this handbook are in Appendix A.

General information about complying with the NCC and responsibilities for building and plumbing regulation is in Appendix B.

Further reading on data sources, IAQ models and simulation software are in Appendix C and Appendix D.

Further reading and references are also in Appendix E.

Different styles are used in this document. Examples of these styles are provided below.

NCC extracts[1]

Examples

Alerts or Reminders

[1] NCC extracts italicise defined terms as per the NCC. See Schedule 1 of the NCC for further information.

2 Building ventilation

2.1 Building ventilation systems

2.1.1 Ventilation

One definition for ventilation is "the deliberate provision of a clean outdoor air supply to a building or space to meet criteria associated with the use of that space". Clean outdoor air is provided to indoor spaces for several reasons including:

- oxygen for human respiration
- dilution or removal of airborne contaminants
- for the correct operation of combustion appliances
- for thermal comfort
- for smoke control or smoke clearance.

Living people metabolise oxygen from air and this used oxygen needs to be replaced. Ventilation reduces carbon dioxide build-up caused by human respiration, and reduces the build-up of odour, bio effluent, and other air contaminants in occupied spaces. Ventilation can be used to remove contaminants at or near their source for disposal to atmosphere and can assist cooling and comfort needs.

Ventilation can be either natural, mechanical or a combination of the 2. The selection of a building's ventilation system is largely up to the designer once the requirements of building regulations have been satisfied.

2.1.2 Natural ventilation

Natural ventilation can be defined as "ventilation that depends on the naturally occurring agencies of wind and temperature difference to cause air movement between the inside and outside of a building, between enclosures within a building and within enclosures".

Ventilation air is generally delivered through openings of a particular size and distribution in the external facade of a building. Air moves in and out of these openings (windows, doors, vents and grilles) and circulates throughout the space being ventilated through naturally occurring forces (wind, thermal and stack effects). In simple systems, openable windows and doors are relied on to provide access to ventilation. In some buildings, natural ventilation systems are complex and controllable engineered systems.

The minimum requirements that need to be achieved to naturally ventilate a building are set by the NCC. Where a building or space cannot meet these minimum natural ventilation requirements then mechanical ventilation is required.

2.1.3 Mechanical ventilation

Mechanical ventilation can be defined as “ventilation that depends on fans and other air movement devices to cause air movement between the inside and outside of a building, between enclosures within a building and within enclosures”. In mechanical ventilation systems the outdoor air is essentially pumped to where it is needed using fans.

Mechanical ventilation systems are versatile and can be applied to almost any situation or condition. They provide good control over airflows and an opportunity to filter or clean outdoor and recirculating air streams. Mechanical ventilation can respond to the varying needs of occupants and varying indoor pollutant loads and provides a good opportunity to manipulate building and enclosure pressures.

2.1.4 Hybrid and mixed-mode ventilation

Mixed-mode ventilation systems use a combination of the natural and mechanical ventilation approaches but with independent operation and control between the 2 systems (i.e. 2 separate systems with control integration only).

Hybrid ventilation systems use natural and mechanical ventilation, or features of both, in an integrated system. Natural and mechanical ventilation forces can be combined or operated separately, with the operating mode varying depending on the needs of the building and occupants at any given time.

2.1.5 Ventilation system operability

Ventilation systems are generally designed for operation by an operator. All ventilation systems need to be operated as designed to achieve the intended IAQ outcomes.

For mechanical ventilation, systems need to be turned on and the quantity of outdoor air supplied needs to be consistent with the design intent. Some mechanical ventilation systems can modulate outdoor air ventilation rates.

For natural ventilation, openable openings are generally designed for operation by the occupants. Ventilation openings such as windows, doors and vents (as applicable) need to be open for ventilation air to flow as designed. The size, orientation and ‘percentage open’ of each opening combines with outdoor weather conditions to vary outdoor air ventilation rates.

2.2 Indoor air and indoor air contamination

2.2.1 Common indoor air contaminants

In the indoor environment, people are confronted by a range of contaminants from many different sources, including organic substances such as microorganisms and microbial debris, bio effluent and aerosols, pollens, danders and animal hairs, as well as inorganic contaminants such as metals, fibres, fine particles, and gases.

Table 2.1 to Table 2.6 below provide common air contaminants, their sources and potential health effects (reproduced from AIRAH[2] DA[3] 26 Indoor Air Quality). Note that not all of the following contaminants are covered by the NCC Performance Requirements or the IAQ Verification Methods.

Table 2.1 Animal products

Contaminant	Source	Health effects
Danders	Protein materials from skins of domestic animals.	Allergic responses in susceptible individuals, including asthma, hay fever, eczema and hives.
Particles from feathers, bird, bat and rodent excreta	Birds & bats roosting in buildings, rodent infestation.	Shortness of breath, hay fever, wheezing and asthma.
Scales, hairs and faecal matter from dust mites, cockroaches and other insects and arthropods	Microscopic mites (which feed on shed human and domestic animal skin scales). Other insects and arthropods.	House dust mite faecal matter and shed hairs can initiate asthmatic responses and various allergic conditions.
Bacteria such as Legionella pneumophilia	Waters and soils containing the organisms, e.g. aerosols from air-conditioning system cooling towers & shower roses, dust from potting mix & building site debris.	Potential infectious agents. Infections may range from fever & cough to severe pneumonia and death. Potential sensitising agents, particularly airborne pyrogens.
Mycobacterium tuberculosis	Infected individuals.	Tuberculosis.

[2] Australian Institute of Refrigeration, Air conditioning and Heating
[3] Design Application

Contaminant	Source	Health effects
Moulds and mould metabolites	Fungi actively growing (Mycotoxins including Trichothecenes, aflatoxins). Non-actively growing fungi (Spores, hyphae fragments, organic metabolites).	Potential infectious agents. Allergic reactions. Allergic reactions.
Viruses	Viruses in droplets from infected people can remain viable in air for at least 2 hours.	Various viral diseases, from minor to life threatening including rhinovirus (common cold) influenza, measles, severe acute respiratory syndrome (SARS), middle east respiratory syndrome (MERS), COVID-19.

Table 2.2 Microorganisms

Contaminant	Source	Health effects
Bacteria such as Legionella pneumophilia	Waters and soils containing the organisms, e.g. aerosols from air-conditioning system cooling towers & shower roses, dust from potting mix & building site debris.	Potential infectious agents. Infections may range from fever & cough to severe pneumonia and death. Potential sensitising agents, particularly airborne pyrogens.
Mycobacterium tuberculosis	Infected individuals.	Tuberculosis.
Moulds and mould metabolites	Fungi actively growing (Mycotoxins including Trichothecenes, aflatoxins). Non-actively growing fungi (Spores, hyphae fragments, organic metabolites).	Potential infectious agents. Allergic reactions. Allergic reactions.
Viruses	Viruses in droplets from infected people can remain viable in air for at least 2 hours.	Various viral diseases, from minor to life threatening including rhinovirus (common cold) influenza, measles, severe acute respiratory syndrome (SARS), middle east respiratory syndrome (MERS), COVID-19.

Table 2.3 Combustion products

Contaminant	Source	Health effects
Carbon monoxide	Incomplete combustion of carbon in fuels in gas fires and stoves, kerosene heaters, wood burning stoves and open fires, especially if with inefficient flues and poor ventilation; smoke; car exhaust in buildings, carparks and near busy roads.	Haemoglobin in the blood is converted to the more stable carboxyhaemoglobin, so that oxygen carrying capacity is reduced. This can lead to headache and nausea, dizziness, impaired vision, loss of brain function, unconsciousness and death. Particularly harmful to angina sufferers, pregnant women and their foetuses.
Carbon dioxide	Unvented heaters and stoves. People in overcrowded rooms.	Giddiness and headache. Loss of mental acuity.
Nitric oxide	Fuel burning, including unflued gas burners, smoke.	Respiratory disorders.
Nitrogen dioxide	Fuel burning especially gas and kerosene; smoke.	Respiratory disorders especially in young children and people with other respiratory illnesses, shortness of breath and wheezing. Since nitrogen dioxide is less soluble than, say, sulphur dioxide it penetrates much more deeply into the lungs, where it can cause acute lung damage. Eye irritation.
Sulphur dioxide	Wood burning fires and stoves.	Since sulphur dioxide dissolves to form sulphurous acid, it has an irritant effect on moist surfaces of the nasal passages. The adverse effects are increased with increased body activity. Sulphur dioxide deposited on mucous membranes is transported by the bloodstream and damages liver tissue. Effects are more severe in the elderly and people with respiratory disorders.

Table 2.4 Organic compounds

Contaminant	Source	Health effects
Formaldehyde (methanol)	Urea-formaldehyde insulating foam, particle board, carpet backing, permanent-press clothing, smoke.	Eye irritation, dermatitis, headaches, nausea and respiratory complaints. Carcinogenic.

Table 2.5 Insecticides

Contaminant	Source	Health effects
Organochlorides, including aldrin and dieldrin.	Soil treatment for termite control.	Highly toxic, especially to nerve and liver tissue. Carcinogenic.
Chlordane/ heptachlor	Termite, ant, cockroach and spider control.	Nausea, headaches, convulsions. Damages membranes. Suspected carcinogen.
Dichlorvos	Some pest strips and flea collars. Some surface spray insecticides.	Flu-like symptoms, breathing difficulties, asthma.
Lindane	Flea control and some head lice treatments.	Affects liver function.

Table 2.6 Others

Contaminant	Source	Health effects
Organic solvents	Adhesives, cosmetics, solvents, polyurethane insulation materials, paints, cleaning liquids, duplicating machines, various plastics, correction fluids, and smoke.	Effects vary with the solvent concerned. Many cause irritation of eyes and respiratory tract; some cause nausea; some are carcinogenic.
Ozone	Photocopiers, ultraviolet light sources, electrostatic air cleaners, car exhausts, photochemical smog.	Respiratory disorders, especially in asthmatics, the elderly and people with pre-existing respiratory diseases, eye irritation. Reduced exercise capability.
Radon and radon daughters	Radioactive decay of uranium-238 in soil, masonry, depending on the geographic region. Particularly high in granite regions.	Carcinogenic, especially with respect to lung cancer. The effect with smoke is greater than additive.

2.2.2 Effects of exposure

Exposure to indoor air contaminants can cause adverse health effects for enclosure occupants (see Table 2.1 to Table 2.6). Health effects can be acute or chronic and can differ from person to person. To limit the health risk, concentrations of individual substances in the indoor air should be controlled. This can be achieved using a variety of strategies including ventilation. Not all potentially dangerous chemicals are known, and many individual chemicals have not had safe exposure standards determined.

Exposure to air contaminants can also cause discomfort for building occupants. People vary widely in their sensitivity to air contaminants, and it is unlikely that 100% of people will be 100% satisfied with the IAQ of a space for 100% of the time.

Refer to section 3.1 of this handbook for a description of the potential adverse health effects of the air contaminants listed in the IAQ Verification Methods.

2.2.3 Quantifying indoor air contamination

In simple mathematical terms the indoor air contaminant concentration of a space can be considered in terms of the relationship:

$$\mathrm{C_i} = \mathrm{C_o} + {}^{S}/_{Q}$$

Where:

C_i is the indoor air contaminant concentration

C_o is the outdoor air contaminant concentration

S is a measure of contaminant source generation within the space

Q is the outdoor air supply rate (ventilation).

In terms of this relationship, the objective of ventilation systems for contaminant control is to maintain C_i as close as possible to C_o. This can be achieved by maximising the outdoor airflow rate Q and minimising indoor contaminant generation rate S. The relationship S/Q is therefore of paramount importance when considering the dilution performance of ventilation systems.

For correct calculation and modelling, additional terms would need to be added to this mathematical model to account for:

- infiltration and exfiltration
- settling and adsorption
- the fate of contaminants over time
- the action of air cleaning devices, and
- internal sinks removing contaminants from the air.

The concentration of pollutants in an enclosure is typically affected by the:

- generation rate of air contaminants indoors
- level of air contaminants in the regional outdoor air
- location of outdoor air intake openings relative to local outdoor pollution sources
- level of air recirculation employed in a ventilation system
- level of air cleaning employed
- level of contaminants generated within a ventilation system.

2.2.4 Generation of indoor air contaminants

Indoor air contaminants are generated by many diverse sources in buildings, including:

(1) the occupants and their activities
(2) the building itself
(3) air contaminants entering with the incoming outdoor air.

Occupant related air contaminants are generated due to human respiration, body odour, human activities, and the processes being carried out by humans in the ventilated space. Occupant related sources of indoor air contaminants include:

- bio effluent from humans (including exhaled aerosols and gases)
- body odours, skin cells, cosmetics
- equipment use, copying, printing, paper dust etc.
- unflued or natural draft gas fired appliances, such as water and space heaters
- wood burners and other combustion-based space heaters
- processes or activities specific to the building, welding, woodworking, printing etc.
- biological contaminants such as bacteria, viruses, fungi, mould, spores, mites, or pollen.

Non-occupant related sources of air contaminants include those generated by the building environment and the building materials. Furnishings and equipment may also generate air contaminants. Building related sources of indoor air contaminants include:

- the building structure and materials
- the interior furniture and furnishings
- moist or unclean components of the heating, ventilating and air-conditioning (HVAC) system
- equipment, computers, and photocopiers not in use
- cleaning materials and storage areas.

Outdoor air is a potential source or generator of indoor air contaminants. Atmospheric duct is composed of both inert particles and viable and non-viable biological particles such as fungal spores, bacteria, and pollens. Outdoor air may also contain organic gases such as carbon monoxide, carbon dioxide, radon, ozone, sulphur dioxide nitrogen dioxide and volatile organic compounds (VOCs).

2.2.5 Indoor air quality

The term “indoor air quality” (IAQ) means different things to different people. There is no single accepted definition for it. There are no specific legislated standards for IAQ in Australia, although there are exposure standards set for a range of chemicals in industrial environments.

IAQ is a measure or an analysis of the condition of air in an enclosure (a room) and it includes the physical, chemical and microbiological makeup of the air within and around buildings and structures, especially as it relates to the health and comfort of building occupants.

Adding the term “adequate” or “acceptable” to IAQ adds an additional level of complexity to the analysis, as the expected subjective response of people to the air now needs to be measured or approximated. Acceptable IAQ includes health and comfort considerations.

ISO[4] 16814 contains the following definition of Acceptable IAQ: Air in an occupied space toward which a substantial majority of occupants express no dissatisfaction and that is not likely to contain contaminants leading to exposures that pose a significant health risk (ISO 2008).

The NCC ventilation Performance Requirements call for “adequate” air quality. The minimum acceptable contaminant limits for "acceptable indoor air quality" that verify that the indoor air is of adequate quality are defined in the IAQ Verification Methods Tables F6V1 and F6V2 in Volume One and Table H4V3 in Volume Two.

2.2.6 Indoor environment quality

People may perceive problems with ventilation or IAQ as more serious when there are other factors reducing their indoor comfort such as:

- hot or cold air temperatures
- high or low air speeds
- noise or vibration
- ergonomic factors, workstation design, lack of space, poor lighting; or even
- work type or load.

4 International Standardization Organisation

Many of these issues could be considered under the heading “Indoor Environment Quality” (IEQ) of which IAQ and ventilation forms only one, albeit an important part. The ASHRAE[5] position paper on IAQ provides useful background information on the relationship between IAQ and other human comfort variables (ASHRAE 2020).

2.3 Outdoor air and outdoor air contamination

2.3.1 Background to outdoor air contamination

Outdoor air in Australia has the potential to contain a range of pollutants and air contaminants including both particulates and gases. Common organic gas air contaminants that may be in outdoor air include:

- carbon monoxide – from the combustion of fuels
- sulphur dioxide – from the combustion of sulphur containing fuels, volcanoes
- nitrogen dioxide – from the combustion of fuels in power stations and vehicles
- ozone – created in the lower atmosphere by the chemical reactions between nitrogen oxides, oxygen and VOCs in the presence of sunlight, creating a photochemical smog including ozone.

Particulate matter (PM) is also a common air contaminant in the outdoor air.

These outdoor air contaminants are all included in the National Environment Protection (Ambient Air Quality) Measure (NEPM).

2.3.2 National standards for outdoor air pollutants in Australia

Most building ventilation systems, including those assessed using the NCC IAQ Verification Methods, use outdoor air as part of the ventilation strategy. Quantitative information about local, regional and state outdoor air quality helps ventilation system designers address the impacts that outdoor air contaminants may have on indoor air quality.

The underlying assumption on which the NCC Performance Requirements are based is that the outdoor air in Australia is usually clean and suitable for building ventilation purposes.

2.3.3 Documenting Australia's air quality

Through the National Environment Protection Council (NEPC), the Australian, State and Territory Governments agreed to the NEPM for Ambient Air Quality (AAQ). The measure was developed by governments in consultation with health professionals, environmental groups and the

[5] American Society of Heating, Refrigerating and Air-conditioning Engineers

community to improve the health of Australians through improved outdoor air quality (NEPM 1998).

On 15 December 2015, the National Clean Air Agreement was established to:

- address reviewing and strengthening air quality monitoring and reporting standards
- develop targeted measures to reduce emissions from key sources of air pollution
- improve access to air quality information for communities
- foster partnerships with industry.

The National Clean Air Agreement work plans deliver a rolling program of activities to respond to air quality priorities.

2.3.4 National air quality standards

The NEPM sets air quality standards that apply throughout Australia. Jurisdictions put strategies in place to reduce or control emissions to achieve the standards. The standards relate to 6 specified outdoor air pollutants; carbon monoxide, nitrogen dioxide, ozone, sulphur dioxide, lead and particles. Four of these are air pollutants that have maximum contaminant limits specified in the NCC IAQ Verification Methods.

The National Air Quality Standards were set based on scientific studies of air quality and human health from all over the world, as well as the standards set by organisations such as the World Health Organization (WHO) (NEPC 2011). Australian conditions, e.g. climate, geography and demographics, were considered in estimating the likely exposure of Australians to these major air pollutants. Each air quality standard has 2 elements; the maximum acceptable concentration and the period over which the concentration is averaged, see Table 2.7.

Table 2.7 NEPM Ambient air quality standards (Source: NEPM 1998, amended 2021)

Air contaminant	Concentration and averaging period
Carbon monoxide	9.0 parts per million (ppm) maximum measured over an 8-hour rolling average period
Nitrogen dioxide	0.08 ppm averaged over a 1-hour period
Nitrogen dioxide	0.015 ppm averaged over a 1-year period
Ozone	0.065 ppm of ozone averaged over an 8-hour period
Sulphur dioxide	0.10 ppm averaged over a 1-hour period
Sulphur dioxide	0.02 ppm averaged over a 24-hour period
Lead	0.5 µg/m³ (micrograms per cubic metre averaged over a 1-year period)
Particles as PM_{10}	50 µg/m³ averaged over a 24-hour period

Air contaminant	Concentration and averaging period
Particles as PM_{10}	25 µg/m³ averaged over a 1-year period
Particles as $PM_{2.5}$	25 µg/m³ averaged over a 24-hour period
Particles as $PM_{2.5}$	8 µg/m³ averaged over a 1-year period

The AAQ NEPM has been amended over time to include reporting standards for $PM_{2.5}$, an 8-hour ozone standard, more stringent sulphur dioxide and nitrogen dioxide levels, and the standards are now nominated as maximum values, with no allowable exceedances.

There is an 'exceptional events rule' that applies to PM standards exceedances during fire events. The rule allows exclusion of exceedance days determined as being directly associated with an exceptional event when assessing compliance with the NEPM standards. This rule also applies to ozone exceedances, given the linkages between elevated ozone levels and fire events.

2.3.5 Monitoring and reporting

The NEPM includes requirements for individual jurisdictions to monitor and report on performance in reducing the levels of the 6 specified air contaminants. The goal is for the standards to be met in all jurisdictions with consistent reporting on levels of air pollution across Australia. Each jurisdiction monitors and publishes data on these 6 air contaminants.

Australia generally experiences good outdoor air quality, rarely exceeding NEPM standards for most contaminants. Concentrations of carbon monoxide, nitrogen dioxide, lead and sulphur dioxide generally complied with national air quality standards, but levels of particles and ozone pollution continue to be of concern.

However, local air quality can be reduced by specific events (which release pollutants for a short period) or specific industries (which affect the local area). The peak reported levels of $PM_{2.5}$ remain above the air quality NEPM standard in all capital cities and many regional areas in Australia. The air quality NEPM standards for $PM_{2.5}$ are set to decrease in 2025 (AG 2021).

Dilution of indoor air contaminants with untreated outdoor air supply is only possible where the outdoor air quality is equal to, or better than, the NEPM. Ongoing reporting shows high levels of compliance for the minimum outdoor air quality requirements at all the monitoring sites for all the listed contaminants. AAQ measurements suggest that the NEPM carbon monoxide standard is now rarely exceeded except in circumstances directly adjacent to heavy traffic roads. Particle counts are typically only exceeded during short-term pollution events such as smog, bushfires, and sand or dust storms.

Uniform minimum outdoor air conditions provide a platform to use dilution ventilation, without the need to treat outdoor air, except perhaps for particle filtration, to achieve minimum acceptable indoor air quality.

2.3.6 Sources of outdoor air contaminants

General and regional sources of outdoor air contaminants are outlined in Table 2.1 to Table 2.6. Major sources of particles include the following:

- bushfires and hazard reduction burns
- electricity generation
- mining and agriculture
- domestic wood heaters
- vehicles
- windborne dust and sea salt spray, and
- pollen and spores from grasses, plants and trees.

Many of these sources are beyond the control of building and ventilation system designers. Local air contaminant sources can be influenced by building layout and ventilation design decisions. Where the local air quality is poor, outdoor air cleaning or filtration may be required, prior to use as ventilation air.

3 NCC IAQ Verification Methods

3.1 Performance-based ventilation solutions

The NCC encourages innovation in building and construction, primarily by performance-based measures that enable performance-based building solutions to demonstrate compliance. Performance Solutions (see A2G2 of the NCC Governing Requirements) are the key to unlocking the performance-based NCC. Any means of satisfying the Performance Requirements not detailed in a DTS Solution is termed a Performance Solution.

A2G2(4) specifically identifies the documentation required where a Performance Solution is proposed as a means of meeting a Performance Requirement/s. The process demonstrates clear expectations, better information to end users and a greater auditing ability through improved record keeping and documentation.

3.2 NCC ventilation Performance Requirements

The NCC contains Performance Requirements, Verification Methods and DTS Provisions for ventilation and IAQ. The NCC Objectives and Functional Statements provide guidance on the intent of the Performance Requirements.

It is only the Performance Requirements of the NCC that are mandatory, and it is these requirements that building solutions must comply with.

Verification Methods and DTS Provisions are not mandatory but can be chosen as the compliance pathway for a specific building solution.

Refer to Appendix B for more information on complying with the NCC.

3.2.1 NCC Volume One

F6P3 in NCC Volume One requires a building's ventilation system to include the supply of outdoor air.

F6P3 Outdoor air supply

A space in a building used by occupants must be provided with means of ventilation with *outdoor air* which will maintain adequate air quality.

Where a mechanical air-handling system is installed, F6P4 of NCC Volume One requires it to achieve control of smells considered objectionable (including food, cooking and toilet odours), and the accumulation of harmful germs, harmful microorganisms, other disease-causing agents, and toxins.

F6P4 Mechanical ventilation to control odours and contaminants

A mechanical air-handling system installed in a building must control—

(a) the circulation of objectionable odours; and

(b) the accumulation of harmful contamination by micro-organisms, pathogens and toxins.

F6P5 of NCC Volume One requires any contaminated air be disposed of, so it does not cause any nuisance or hazard to occupants (of either the subject building, or another building), people on neighbouring allotments, or people on a road.

F6P5 Disposal of contaminated air

Contaminated air must be disposed of in a manner which does not unduly create a nuisance or hazard to people in the building or *other property*.

3.2.2 NCC Volume Two

H4P5(1) in NCC Volume Two requires an occupied space within a building to be provided with outdoor air ventilation which will maintain adequate air quality.

H4P5(1) Ventilation

(1) A space within a building used by occupants must be provided with means of ventilation with *outdoor air* which will maintain adequate air quality.

Where a mechanical air-handling system is installed, H4P5(2) in NCC Volume Two requires that it controls the circulation of objectionable odours and the accumulation of harmful contamination by micro-organisms, pathogens and toxins.

H4P5(2) Ventilation

(2) A mechanical air-handling system installed in a building must control—

(a) the circulation of objectionable odours; and

(b) the accumulation of harmful contamination by micro-organisms, pathogens and toxins.

H4P5(3) in NCC Volume Two requires contaminated air be disposed of in a manner which does not unduly create a nuisance or hazard to people in the building or other property.

H4P5(3) Ventilation

(3) Contaminated air must be disposed of in a manner which does not unduly create a nuisance or hazard to people in the building or *other property*.

3.3 Role of Verification Methods

In some instances, where Performance Requirements are unquantified, Verification Methods have been developed to facilitate use a performance compliance pathway.

Verification Methods are designed to facilitate determination of compliance of a building solution with the specific NCC Performance Requirements nominated in the method. Verification Methods are not mandatory, they provide a clear compliance pathway for Performance Solutions. They can significantly simplify the process, costs and complexities of demonstrating compliance.

3.4 Verifying ventilation Performance Requirements

It is the ventilation Performance Requirements of the NCC that are mandatory.

The NCC Volume One Performance Requirement F6P3 and Volume Two Performance Requirement H4P5(1) state "*a space in a building used by occupants must be provided with means of ventilation with outdoor air which will maintain adequate air quality*". In both NCC Volumes One and Two, adequate IAQ is based on the assumption that it can be provided by dilution of indoor air contaminants through the addition of outdoor air, either through mechanical or natural ventilation.

The ventilation Performance Requirements can be satisfied by a Performance Solution, a DTS Solution, or a combination of the 2.

3.4.1 Commercial buildings (excluding carparks)

Commercial buildings are Class 2 to 9 buildings. The NCC requirements for the ventilation of spaces in Class 2 to 9 buildings are set out in the Volume One Performance Requirements F6P3, F6P4 and F6P5.

The provision of adequate air quality by the ventilation system can be verified by using Verification Method F6V1 Verification of suitable indoor air quality.

For a Class 2, 3, 5, 6, 9b or 9c building or Class 4 part of a building, compliance with F6P3 and F6P4(a) is verified when it is determined that the building under typical conditions in use is provided with sufficient ventilation with outdoor air such that contaminant levels do not exceed the limits specified in Table F6V1.

F6V1 is intended to cover the general case and specifically excludes biological contaminants (Performance Requirement F6P4(b)), industrial contaminants (covered by Workplace Exposure Standards) and contaminants associated with environmental tobacco smoke (smoking is not permitted within most non-residential buildings). These exclusions are discussed further in section 3.5.4 of this handbook.

This means that building solutions using F6V1 must also demonstrate (separately) that the proposed ventilation solution controls the accumulation of harmful contamination by micro-organisms, pathogens and toxins as required by F6P4(b) in NCC Volume One. Refer to Appendix B for more information on options to demonstrate compliance with the NCC.

Similarly, F6P5, covering the disposal of contaminated air, must be met using another compliance option.

The provision of adequate air quality by the ventilation system can also be verified by using the DTS Provision in Clause F6D6. The requirements of F6P3, F6P4(a), F6P4(b), and F6P5 are all deemed to be achieved if compliance with F6D6 is achieved. This clause specifies that either natural ventilation, (the detail is shown in Clauses F6D7 and F6D8) or mechanical ventilation (that complies with AS 1668.2–2012) must be provided.

F6D7 requires natural ventilation openings of not less than 5% of the floor area of the room required to be ventilated and F6D8 provides further detail on borrowed ventilation requirements.

3.4.2 Carparks

Carparks are Class 7a buildings. The NCC requirements for the ventilation of spaces in Class 7a buildings are set out in the Volume One Performance Requirements F6P3, F6P4 and F6P5.

The provision of adequate air quality by a ventilation system can be verified by using the Verification Method F6V2 Verification of suitable indoor air quality for carparks.

For a Class 7a building, compliance with F6P3 and F6P4(a) is verified when it is determined the building is provided with sufficient ventilation with outdoor air such that carbon monoxide exposure levels do not exceed the limits specified in Table F6V2.

Compliance with requirements F6P4(b) and F6P5 must be assessed separately using this pathway.

The provision of adequate air quality by the ventilation system can also be achieved by using the DTS Provision in Clause F6D11. The Performance Requirements F6P3, F6P4(a), F6P4(b), and F6P5 are all deemed to be achieved if compliance with the DTS Provision F6D11 is achieved. This clause specifies that either mechanical ventilation that complies with AS 1668.2–2012, or natural ventilation that complies with AS 1668.4–2012, must be provided to every storey of a carpark, except an open-deck carpark.

3.4.3 Houses

The NCC Performance Requirements for the ventilation of spaces in Class 1 and 10 buildings are set out in H4P5 of Volume Two.

The provision of adequate air quality by the ventilation system can be verified by using the Verification Method H4V3 Verification of indoor air quality. For a Class 1 building, compliance with H4P5(1) and H4P5(2)(a) is verified when it is determined that the building under typical conditions in use is provided with sufficient ventilation with outdoor air such that contaminant levels do not exceed the limits specified in Table H4V3.

H4V3 is intended to cover the general case and specifically excludes biological contaminants (Performance Requirements F6P4(b)). These exclusions are discussed further in section 3.5.4 of this handbook.

This means that building solutions using H4V3 must also demonstrate (separately) that the proposed ventilation solution controls the accumulation of harmful contamination by micro-organisms, pathogens and toxins as required by H4P5(2)(b) for NCC Volume One. Refer to Appendix B for more information on options to demonstrate compliance with the NCC.

Similarly, H4P5(3) must be met using another compliance option.

The provision of adequate air quality by the ventilation system can also be achieved by using the DTS Provisions. The requirements of H4P5(1), (2) and (3) are all deemed to be achieved through compliance with the DTS Provision H4D7. This means mechanical ventilation is provided in accordance with AS 1668.2-2012, or if compliance with Part 10.6 of the ABCB Housing Provisions is met, i.e. natural ventilation openings of not less than 5% of the floor area of the room required to be ventilated are provided and further requirements on borrowed ventilation are met.

3.5 Understanding the IAQ Verification Methods

3.5.1 Overview

The IAQ Verification Methods provide a compliance pathway to demonstrate that the ventilation related Performance Requirements of the NCC have been met. They include measurable criteria that aids in judging compliance and provides clarity to designers of the required ventilation outcomes. The NCC contains 3 IAQ Verification Methods. The application of each depends on the building classification:

- F6V1 in NCC Volume One applies to Class 2, 3, 5, 6, 9b, 9c buildings or a Class 4 part of a building and can be used to demonstrate compliance with F6P3 and F6P4(a)
- F6V2 in NCC Volume One applies to Class 7a buildings and can be used to demonstrate compliance with F6P3 and F6P4(a)

- H4V3 in NCC Volume Two applies to Class 1 buildings and can be used to demonstrate compliance with H4P5(1) and H4P5(2)(a).

3.5.2 Verification Methods F6V1 and H4V3

The Verification Methods F6V1 in NCC Volume One and H4V3 in NCC Volume Two are identical in terms of the language used and the maximum contaminant limits specified for acceptable IAQ. The only differences are the building classification that they apply to and the Performance Requirements that will be met.

The Verification Methods are applicable to both mechanical and natural ventilation solutions, as well as hybrid and mixed-mode systems and any other innovative ventilation approach. It is useful to look at the specific terms used in the Verification Methods to better understand what is required by the code.

> *"… **when it is determined** that the building **under typical conditions in use** is provided with **sufficient ventilation with outdoor air** such that **contaminant levels do not exceed** the limits specified in Table…"*

Looking at specific terms from this sentence:

'When it is determined' – The NCC does not specify how it is determined that the design will meet the contaminant limits specified. Options include determining by calculation, modelling, post construction testing or some other method that the indoor air will meet the contaminant limits.

'Under typical conditions in use' – This means that the verification of indoor air contaminant levels should be carried out across the full spectrum of building occupancy, operation profiles, and internal processes and activities that will be typical of the building in operation. Schedules for building occupation and system operation need to be developed as well as schedules covering air contaminant generation profiles including from building materials, outdoor air pollutants and occupant activities.

'Sufficient ventilation with outdoor air' – This means that any building ventilation solution that is verified using this method must incorporate outdoor air intake and ventilation as part of the solution. A system that does not include the addition of outdoor air to indoor spaces cannot be verified using this method.

'Contaminant levels do not exceed' – The Verification Method ultimately depends on the result of the indoor air contaminant control processes. These must prove the indoor air contaminant concentrations will never exceed the maximum limits specified in the appropriate contaminant limits table of the method being applied.

Tables F6V1 and Table H4V3 specify the maximum air quality values and the averaging time for each of the nominated pollutants. The pollutants covered and limits specified are identical in the 2 tables.

These Verification Methods cover all buildings except Class 7a, 8, 9b and 10. Class 7a buildings are a special case covered by Verification Method F6V2 Ventilation of suitable indoor air quality for car parks.

3.5.3 Verification Method F6V2

Method F6V2 of NCC Volume One applies to Class 7a buildings, i.e. carparks. These buildings house vehicles with operating internal combustion engines. Carbon monoxide is determined as the critical air contaminant for these enclosures (Standards Australia 2012).

Accordingly, the NCC Verification Method for this building classification is based on the maximum concentration of carbon monoxide, and 4 different averaging times are specified. This reflects the fact that the health effects of carbon monoxide relate to both the concentration level and the exposure time at that level.

Again, the carpark ventilation solution can be natural or mechanical or a combination of the 2. Any carpark ventilation system that is verified using this method must incorporate outdoor air ventilation as part of the solution. If there are people working in the carpark, then government Workplace Health and Safety/Occupational Health and Safety (WHS/OH&S) regulations and the related Workplace Exposure Standards for Workers also apply (SWA 2019).

3.5.4 Exclusions

The IAQ Verification Methods in the NCC do not cover all issues, all situations or all building applications. There are several important exclusions from the methods including:

- several building classifications that are not covered
- the types of air contaminant that are not covered
- the elements of the ventilation Performance Requirements that are not covered.

3.5.4.1 Building classifications

The following building classifications[6] are excluded from the IAQ Verification Methods:

- Class 7b — for storage or display of goods or produce for sale by wholesale.
- Class 8 — a laboratory, or a building in which a handicraft or process for the production, assembling, altering, repairing, packing, finishing, or cleaning of goods or produce is carried on for trade, sale, or gain.

6 Refer to Section A of the NCC for a description of building classifications.

- Class 9a — a health-care building, including those parts of the building set aside as a laboratory.
- Class 10 — a non-habitable building or structure.

Ventilation solutions for these building types cannot be verified using the NCC Verification Methods. However, the alternative Assessment Methods; Expert Judgement, evidence of suitability, Comparison with DTS Provisions, or another non-NCC Verification Method, may be used to assess a ventilation Performance Solution for these building classifications.

3.5.4.2 Contaminants

There are many air contaminants not included as pollutants in the Verification Methods that may be encountered in the real-world indoor environment. The Verification Methods are intended to cover the general case and specifically exclude biological contaminants (Performance Requirements F6P4(b) and H4P5(2)(b)), industrial contaminants (covered by Workplace Exposure Standards) and contaminants associated with environmental tobacco smoke (smoking is not permitted within most non-residential buildings).

- **Biological contaminants** – Biological air contaminants can degrade IAQ. However, the methodology for the accurate modelling, sampling, testing and measurement of many biological species is not universally agreed. Biological contaminants including house dust mites, moulds and fungi, allergens, bacterial and viral pollutants, are all not covered by the IAQ Verification Methods.
- **Disposal of contaminated air** – contaminated air must be disposed of in a manner which does not unduly create a nuisance or hazard to people in the building or other property. This requirement cannot be met using the IAQ Verification Methods.
- **Industrial contaminants** – Industrial and commercial workplaces can be subject to specific air contaminants that are not listed pollutants in the Verification Methods. The Workplace Exposure Standards for those air contaminants that are listed in government WHS/OH&S regulations and codes would still apply to these workplaces, (SWA 2019).
- **Environmental tobacco smoke** – The maximum contaminant levels listed in the IAQ Verification Methods assume that there is no environmental tobacco smoke, vaping or e-cigarette smoke present.

As more information on air contaminants becomes known, better detection strategies are developed and more experience is gained about IAQ design, it is expected in future editions of the NCC, additional pollutants may be added to the tables, and some may be removed.

4 Indoor air contaminant control

4.1 Air contaminants to be verified

Indoor air quality guidelines in buildings are generally developed to consider the occupants that are likely to be exposed. For industrial exposures where the workforce is expected to be adult, healthy and working for 8 hours a day over 5 days a week, the exposure levels of the Safe Work Australia publication *Workplace Exposure Standards for Airborne Contaminants* are appropriate (SWA 2019).

In public places, offices and homes however, the occupant populations can be expected to include the very young, the elderly and the infirm and Workplace Exposure Standards may not be appropriate for these populations. Guidelines for indoor air quality in non-industrial environments are generally more aligned to ambient air quality standards, which are typically much more stringent than the Safe Work standards, to account for variations in the exposed population.

The IAQ Verification Methods in the NCC specify maximum exposure levels for the following air contaminants:

- carbon dioxide
- carbon monoxide
- nitrogen dioxide
- ozone
- total volatile organic compounds, TVOC
- formaldehyde, CH_2O
- particles, PM_{10} and $PM_{2.5}$.

This section of the handbook provides a description of each of the nominated indoor air contaminants, their common sources and health impacts and the background behind the level specified in the NCC IAQ Verification Methods.

Alert

In 2021 the WHO published more stringent air quality guidelines, and developed interim targets to guide the structured improvement of air quality for those countries that presently exceed the levels within those new guidelines (WHO 2021). Some previously published WHO guidelines are still valid and have not been updated. The NCC IAQ Verification Methods were developed based on the previous WHO air quality guidelines (WHO 2006, WHO 2010) and not the 2021 guidelines and interim targets.

4.1.1 Carbon dioxide

4.1.1.1 Description

Carbon dioxide (CO_2) is a colourless, odourless and natural chemical component of the atmosphere that is non-toxic in low concentrations. The global average atmospheric carbon dioxide level in 2021 was 414.72 ppm. It is unusual to reach much above 400 ppm in the ambient environment.

4.1.1.2 Health effects

At elevated levels carbon dioxide can cause headaches and may cause changes in respiratory patterns. Increasing concentrations of 5% to 10% will lead to dizziness, confusion, dyspnoea, sweating, dim vision followed by vomiting, disorientation, hypertension, and ultimately loss of consciousness.

The Worksafe Australia exposure standard for the occupational environment is 5000 ppm which is the 8-hour time weighted average limit for occupational exposures. Worksafe standards are developed for a presumed fit adult working population and are generally less stringent than ambient or IAQ standards or guidelines.

There is growing evidence that carbon dioxide levels above 1000 ppm can result in reduced levels of concentration in humans and reduced work performance and productivity levels. However, elevated carbon dioxide concentrations also indicate inadequate ventilation that tends to increase the concentrations of all contaminants with indoor sources. Research into the health and performance impacts of indoor carbon dioxide levels is ongoing (ASHRAE 2022).

4.1.1.3 Sources

Natural sources of carbon dioxide include respiration, biological life, decay processes, and volcanoes. The combustion of fossil fuels is the primary anthropogenic source of carbon dioxide in the atmosphere. Metabolic processes and combustion devices are the main sources within indoor environments.

Carbon dioxide is formed by the combustion of carbon-containing substances, and important potential indoor sources include unflued or poorly flued heaters and cooking appliances, motor vehicle exhaust in enclosed carparks or garages, and environmental tobacco smoke (note that smoking is not permitted in most non-residential buildings in Australia). In the absence of combustion devices, metabolic processes often dominate as the primary source of carbon dioxide indoors.

Indoor air carbon dioxide concentrations can be reliably used as an indicator of acceptable ventilation (and body odour dilution) only in the absence of significant indoor sources of the gas that are not related to respiration (e.g. combustion processes).

4.1.1.4 Principles behind the maximum contaminant limit specified

Although not a contaminant of health concern in most buildings, carbon dioxide levels are often monitored as an indicator of building occupancy and the associated concentration of human bio effluent. The IAQ Verification Methods specify a carbon dioxide maximum contaminant limit of:

- 850 ppm averaged over 8 hours.

Typical carbon dioxide level limits and recommendations for a range of purposes are in Table 4.1.

Table 4.1 Various carbon dioxide level limits and recommendations

Comments	Carbon dioxide concentration (ppm)
Australian occupational exposure limit (SWA 2019)	5000
ASHRAE 62.1 recommendation (as an indicator for body odour)	1000
AS 1668.2 recommendation (for carbon dioxide controlled ventilation)	800 - 600
NCC IAQ Verification Method (as an indicator for body odour)	**850**
Typical outdoor air range	400 - 300

Because carbon dioxide is used as a measure for body odour in the IAQ Verification Methods the contaminant limit is not based on the occupational exposure health limit of 5000 ppm. The maximum contaminant limit has been set at a carbon dioxide level of 850 ppm over an 8-hour period which is based on a 450 ppm rise above an assumed ambient carbon dioxide level of 400 ppm. This represents what is considered an adequately ventilated building from an occupant “odour amenity” point of view.

4.1.2 Carbon monoxide

4.1.2.1 Description

Carbon monoxide (CO) is a colourless, odourless, poisonous gas that is a by-product of incomplete combustion. The natural concentration of carbon monoxide in outdoor air is around

0.2 ppm. Larger cities have the potential to have higher levels of carbon monoxide due to emissions from vehicle traffic and industrial processes. The NEPM maximum concentration of carbon monoxide allowed in outdoor air is 9 ppm (NEPM 1998).

4.1.2.2 Health effects

Carbon monoxide adversely affects both healthy and unhealthy people. When inhaled, it readily mixes with haemoglobin in the blood, inhibiting the blood's ability to carry and exchange oxygen. Once more than 2.5% of haemoglobin is bound to carbon monoxide health effects become noticeable. High concentrations can cause headaches, fatigue, confusion, and drowsiness. Prolonged and repeated exposure can affect the heart.

At very high concentrations of carbon monoxide, up to 40% of the haemoglobin can be bound to carbon monoxide in this way. This very high concentration will almost certainly kill. People with heart problems, children and unborn babies are particularly at risk. Carbon monoxide does not readily leave the body once it enters.

Refer to AS 1668.2-2012 Appendix H for a detailed commentary on carbon monoxide exposures in occupational environments and the resulting blood carboxyhaemoglobin (COHb) levels (Standards Australia 2012a).

Given that there have been deaths in Australian buildings from exposure to carbon monoxide indoors, and the very significant number of people potentially exposed to it, carbon monoxide is considered an indoor pollutant of significant health concern.

4.1.2.3 Sources

Natural sources of carbon monoxide include volcanoes and bushfires. Anthropogenic sources include the burning of fossil fuels for power generation, motor vehicle exhaust, petrol and metal refining, other manufacturing industries and food processing.

Carbon monoxide can be generated indoors by:

- burning cigarettes and incense
- internal combustion engines
- oil or gas fired boilers
- furnaces
- stoves and water heaters
- wood heaters, and
- solid fuel stoves etc.

Improperly flued or under-ventilated combustion devices present the highest risks.

4.1.2.4 Principles behind the maximum contaminant limit specified

The maximum contaminant limits for carbon monoxide specified in the IAQ Verification Methods are:

For a Class 2, 3, Class 4 part, Class 5, 6, 9b or 9c building:

- 90 ppm averaged over 15 minutes*
- 50 ppm averaged over 30 minutes
- 25 ppm averaged over 1 hour*
- 10 ppm averaged over 8 hours*.

For a Class 7a building:

- 100 ppm never to be exceeded
- 90 ppm averaged over 15 minutes
- 60 ppm averaged over 1 hour
- 30 ppm averaged over 8 hours**.

The less stringent requirements for a Class 7a building reflects the increased carbon monoxide contaminant generation rates in these buildings, due to the unavoidable operation of internal combustion engines, and the transient nature of occupants within this class of building.

These maximum contaminant limits are generally consistent with or more stringent than the *WHO Guidelines (WHO 2010) and **Australian occupational exposure limits set by Safe Work Australia (SWA 2019).

4.1.3 Nitrogen dioxide

4.1.3.1 Description

Nitrogen dioxide (NO_2) is a foul-smelling, suffocating, brownish, oxidising gas that reacts in the air to form corrosive nitric acid, as well as toxic organic nitrates. It plays a major role in the atmospheric reactions that produce ground-level ozone and smog.

4.1.3.2 Health effects

Nitrogen dioxide can cause headaches, irritation to the eyes, nose and throat and can cause lung congestion and respiratory problems. There is evidence that it suppresses the body’s immune system. Prolonged and repeated contact can lead to low blood pressure and an increased risk of infection. People with asthma and people with heart disease are most at risk.

4.1.3.3 Sources

Nitrogen dioxide is formed naturally in the atmosphere by lightning, and some is produced by plants, soil and water. However, most nitrogen dioxide found in the outdoor air is a result of road traffic vehicle exhaust and other fossil fuel combustion processes.

The sources of nitrogen dioxide in outdoor air are much the same as for carbon monoxide. Major sources include the burning of fossil fuels for power generation, motor vehicle exhaust, petrol and metal refining, other manufacturing industries and food processing. Up to 80% of the nitrogen dioxide in cities comes from motor vehicle exhaust. In sunlight, nitric oxide rapidly changes into nitrogen dioxide.

Unflued gas heaters and cookers are the major sources of nitrogen dioxide indoors as well as potential transport of the contaminant from attached garages and carparks.

4.1.3.4 Principles behind the maximum contaminant limit specified

The maximum contaminant limits for nitrogen dioxide specified in the IAQ Verification Methods are:

- 40 µg/m³ (0.0197 ppm) averaged over 1 year; and
- 200 µg/m³ (0.0987 ppm) averaged over 1 hour.

These limits were adopted from the WHO air quality guidelines for nitrogen dioxide, set to protect the public from effects on health of nitrogen dioxide gas itself. The limit is not designed to address combustion related co-pollutants of nitrogen dioxide (WHO 2010).

4.1.4 Ozone

4.1.4.1 Description

Ozone (O_3) is a colourless gas with a distinctive “electric” smell. Ozone is present in both the stratosphere (upper atmosphere) and the troposphere (lower atmosphere).

Stratospheric ozone is not a pollutant and is called the “ozone layer” because it protects organic life on the planet by reducing the levels of damaging UV-B radiation reaching the Earth's surface. Ground level ozone on the other hand is considered an air pollutant because it is harmful to human health and the environment.

Ozone concentrations in Australia tend to be lower indoors in buildings than outdoors. This is because Australian buildings generally have limited indoor sources of ozone and the effectiveness of interior furnishings and the building fabric in removing ozone from the air.

4.1.4.2 Health effects

Ozone can irritate the eyes, nose, throat and lungs and can cause allergic reaction in sensitised individuals and exacerbation of asthma.

Exposure to elevated concentrations of ozone increases risk from respiratory irritation and changes in lung function, particularly for people that already suffer from a respiratory illness (WHO 2006).

4.1.4.3 Sources

Ground level or tropospheric ozone is formed in the lower atmosphere when ozone precursors, typically oxides of nitrogen (NO_x), carbon monoxide, and VOCs react in warm, sunny conditions. Anthropogenic sources of these ozone precursors include emissions from industrial facilities, electric power stations, motor vehicle exhausts, fumes from engines, as well as emissions from paints, aerosols and solvents.

Natural sources of ozone precursors include eucalyptus trees, (which contribute significant emissions of volatile organic compounds), bushfire and hazard reduction events, which can all have an impact on local ozone concentrations.

Indoors, ozone is generated by high voltage electrical equipment such as photocopiers, laser printers and by ozone-generating air-cleaning devices.

4.1.4.4 Principles behind the maximum contaminant limit specified

The maximum contaminant limits for ozone specified in the IAQ Verification Methods is:

- 100 µg/m³ an 8 hour daily maximum limit.

This limit was adopted from the WHO guidelines. This concentration will provide adequate protection of public health, though some health effects may occur below this level for sensitive individuals (WHO 2006).

4.1.5 Total Volatile Organic Compounds

4.1.5.1 Description

VOCs are carbon containing compounds that evaporate at room temperature. This means they have a high enough vapour pressure to vaporise from materials and surfaces into the indoor air at normal room temperatures, a process known as off-gassing.

VOCs are a diverse class of compounds that include alkanes, aromatics, aldehydes, ketones, alcohols and ethers. There can be many of these contaminants in indoor air. They are usually present as complex mixtures of many compounds at low concentrations, and there are up to several hundred different compounds that can potentially be found in low concentrations in the indoor environment. When considered as a whole and in combination they are termed “Total” VOCs or TVOC.

Semi volatile organic compounds (SVOCs) are a subgroup of VOCs that tend to have a higher molecular weight and higher boiling point temperature than other VOCs. All indoor VOCs are present partly as gaseous airborne chemicals and partly as chemicals that are adsorbed onto indoor surfaces and particles, settled or airborne. In many cases a large fraction of the SVOCs in a space are present on surfaces and settled particles and only a small fraction is present as a gas or on airborne particles. Increased ventilation may not be highly effective in reducing local concentrations of SVOCs because these higher molecular weight VOCs are present mostly on indoor surfaces and not in the air.

4.1.5.2 Health effects

In outdoor air, VOCs are a health concern because they are an integral part of the reaction system that leads to the formation of photochemical smog pollution.

In indoor air, VOCs may cause eye and upper respiratory irritation, nasal congestion, headache, and dizziness. Most individual VOCs are probably not present at a sufficient concentration indoors to cause these sensory irritation symptoms themselves. However, mixtures of multiple VOCs, that can include specific highly irritant VOCs produced by indoor chemical reactions, appear likely to be sources of irritation to occupants in buildings. VOCs can react with oxidants such as ozone and possibly nitrogen oxide and nitrogen dioxide to form reactive species and strong irritants, including various acids and aldehydes.

Several VOCs found in indoor air, have been shown to cause cancer in animals when exposed to high concentrations. A few of these VOCs, for example formaldehyde and benzene, are considered to cause cancer in humans however the magnitude of the cancer risks currently has a high level of uncertainty (IARC 2012).

The health effects depend on the specific composition of the VOCs present and the length of human exposure. Some people can become sensitised to VOCs and react to extremely low concentrations in subsequent exposures. The cumulative exposure to several compounds at low concentrations, or the synergistic effects, may also have an impact on the strength and nature of individual reactions.

4.1.5.3 Sources

VOCs are released from most materials, whether synthetic or natural. VOC emissions are released at room temperature from materials or products in the form of gases. Sources include new materials such as office furnishings, adhesives, paints, caulking, fillers, pressed wood products, floor coverings underlays and adhesives, stored supplies, printers and photocopiers, electrical equipment, cosmetics, cleaning products, and personal hygiene products.

Many VOCs come from solvents used in products for a variety of purposes including as solvents in chemical strippers, clothing and furniture cleaners and as carriers for polishes, paints, and varnishes. Wet applied products such as adhesives, paints, fillers and sealants commonly contain volatile organic solvents that are released during and immediately after application while the product dries and cures. Solvents are also inherent in many personal grooming products, including cleaners, disinfectants, deodorizers, and perfumes.

There is also potential for a long-term slow release of VOCs from residual solvents as well as the gradual production of new air contaminants due to species degradation. The highest VOC emissions tend to occur when products are new, and especially if the products are applied wet, such as paints, adhesives or sealants. Long-term emissions (i.e. for periods greater than several months) tend to occur from thicker materials such as building fabric materials, floor coverings and furniture.

Soft materials and furnishings can adsorb VOCs from the air when local emission rates and local concentrations are high and then re-emit the VOCs to the indoor air later.

4.1.5.4 Principles behind the maximum contaminant limit specified

The maximum contaminant limits for TVOC specified in the IAQ Verification Methods is:

- 500 μg/m³ averaged over 1 hour.

This limit was adopted from the NHMRC[7] recommended Interim National Indoor Air Quality Goals that were rescinded in March 2002 (but are still available) (NHMRC 1996).

4.1.6 Formaldehyde

4.1.6.1 Description

Formaldehyde (CH_2O) is a colourless strong-smelling gas. It is one of the most commonly encountered indoor VOCs. Formaldehyde is typically generated indoors due to off-gassing from a variety of common building materials such as particleboard, fibreboard and plywood. In general, concentrations of formaldehyde indoors typically exceed outdoor concentrations.

Formaldehyde is present in the outdoor air at natural background levels of about 0.03 ppm with concentrations up to 0.08 ppm in outdoor urban air. The contribution of formaldehyde air contaminants in indoor air from the outdoor air appears to be minimal.

Formaldehyde is an industrially significant substance with the widespread downstream use of formaldehyde-based inputs including synthetic resins, industrial chemicals, preservatives, and in the production of paper, textiles, cosmetics, disinfectants, medicines, paints, varnishes and lubricants.

4.1.6.2 Health effects

Formaldehyde is a VOC that can cause irritation of the eyes, nose, throat and lower respiratory tract, and an inflammatory response in the airways. The evidence of a linkage of formaldehyde with allergies, asthma, and respiratory effects is most extensive.

Formaldehyde is considered to cause cancer in humans (IARC 2006).

[7] National Health and Medical Research Council

4.1.6.3 Sources

Formaldehyde occurs naturally in the environment and is emitted by processes such as combustion, decay and is emitted naturally by all timber species. Formaldehyde is also present in exhaust fumes, wood smoke, and is produced by domestic appliances such as combustion heaters. The outdoor air is a source of formaldehyde, but the primary sources are the indoor environment itself, building materials, insulation materials, finishing materials, combustion appliances, smoke, and a large variety of consumer products.

The superior bonding properties and low cost of formaldehyde polymers make them common resins used in the production of many building materials. Formaldehyde polymers are used in the manufacture of floor coverings, and formaldehyde resins are also used in the textile industry as binders, fire retardants, or to impart stiffness, wrinkle resistance, and water repellence to fabrics.

Fertilisers and pesticides used for indoor plants can contain aldehydes. Gas-fired stoves and heaters can also emit formaldehyde. Formaldehyde is used in numerous workplaces, such as biological laboratories, hospitals, and hobby and craft areas.

4.1.6.4 Principles behind the maximum contaminant limit specified

The maximum contaminant limits for formaldehyde specified in the IAQ Verification Methods is:

- 0.1 mg/m^3 averaged over 30 minutes.

This limit was adopted from the WHO guidelines as the recommended level to prevent sensory irritation in the general population (WHO 2010).

4.1.7 Particulate matter

4.1.7.1 Description

Airborne particles are generally referred to as particulate matter or simply ‘PM’. Particulates can include dust, dirt, soot, smoke, liquid droplets and aerosols and can vary in size and visibility. Particles are classified based on size and aerodynamic diameter:

- Coarse particles are those between 10 and 2.5 micrometres (µm) in diameter
- Fine particles are smaller than 2.5 µm
- Ultrafine particles are smaller than 0.1 µm.

Particles can also be classified according to their chemical composition. The health impacts of particulate air contaminants are dependent on both their size and their chemical composition (WHO 2006). Research into the health and performance impacts of indoor $PM_{2.5}$ levels is ongoing.

4.1.7.2 Health effects

Even relatively low concentrations of particle pollution can cause health impacts in some individuals (WHO 2013). The concentration and size of the particles are also important, and these can vary greatly between sources, regions and seasons. Respiration of particles challenges the body's natural defence mechanisms and overexposure may strain these mechanisms, causing an adverse reaction.

Inhalable particles are typically defined as:

- PM_{10} for particles with an aerodynamic diameter of 10 µm or smaller
- $PM_{2.5}$ for particles with an aerodynamic diameter of 2.5 µm or smaller.

In general terms, the smaller the particle the greater its impact on human health. $PM_{2.5}$ are respirable particles, i.e. they bypass the body's natural defence mechanisms more readily and can make their way deep into the lungs.

Respirable particles may give rise to:

- irritation of the eyes, nose, throat and respiratory tract
- coughs
- bronchitis
- asthma and other lung conditions
- respiratory diseases and allergic responses
- exacerbation of respiratory and cardiopulmonary diseases
- lung cancer.

Some particles are small enough to pass into the bloodstream through the finest blood vessels of the lungs where they can trigger heart attacks (HEI 2013). Research into the health and performance impacts of $PM_{2.5}$ levels is ongoing.

4.1.7.3 Sources

Sources of particulate matter may include dust, mists, fumes, smoke, and other particulate by-products of combustion. Natural sources include bushfires, dust and sandstorms, pollens and sea spray salt. Human caused sources include electricity generation, motor vehicle emissions, industrial processes, incinerators, mining and stone crushing, agricultural processes, construction activities, unpaved roads and wood heaters.

The NEPM sets a standard for PM_{10} of 50 µg/m^3 (24-hour average) for outdoor air particulates. When these levels are exceeded, it tends to be from local factors such as dust storms, bushfires, conditions associated with a prolonged drought, widespread agricultural stubble burning, and domestic wood heater use in the region. The highest recorded PM_{10} average over 24 hours in NSW was 2427 µg/m^3, nearly 50 times the acceptable standard, recorded on 23 September 2009 during the Red Dawn dust storm event.

Generation sources of particulate matter indoors include the activities occurring within the building, such as materials and surface abrasion, printing and paper handling, cooking and food-preparation, human and animal bio effluent, and combustion-based heating equipment. Particles also enter the building with the outdoor air. Dust can build up on floors, furniture, carpets and soft furnishings, and be disturbed during maintenance and cleaning activities (sweeping and vacuuming) where there is often a re-suspension in the indoor air of dust particles that had previously settled onto surfaces. Particles that settle on hard floors can also be resuspended into the air by vibration and movement. Carpet fibres can filter and store particles for removal by periodic cleaning and maintenance.

4.1.7.4 Principles behind the maximum contaminant limit specified

The maximum contaminant limits for PM_{10} and $PM_{2.5}$ specified in the IAQ Verification Methods are in Table 4.2.

Table 4.2 Maximum contaminant limits for PM_{10} and $PM_{2.5}$ specified in the IAQ Verification Methods

Particle size	Averaging period	Contaminant limits
$PM_{2.5}$	1 year 24 hour (99th percentile)	10 µg/m³ 25 µg/m³
PM_{10}	1 year 24 hour (99th percentile)	20 µg/m³ 50 µg/m³

These limits were adopted from the WHO guidelines as the lowest levels at which total, cardiopulmonary and lung cancer mortality have been shown to increase (WHO 2006).

4.2 Controlling air contaminants

4.2.1 Avoidable and unavoidable contaminants

It is useful to characterise indoor air contaminants in term of avoidable and unavoidable sources. Unavoidable sources include those contaminants associated with occupant metabolism and activities. Avoidable sources may include emissions from materials, equipment and processes.

If the dominant need for ventilation is from an avoidable source of air contaminants, then the reduction or elimination of the source will provide the most effective method of air quality control. There are a range of controls available in relation to indoor air contaminants.

4.2.2 Hierarchy of contaminant controls

Ventilation represents only one method of controlling indoor air contamination. Controlling air contaminants at the source is far more effective for managing IAQ than attempting to control by general ventilation. Source control of potential air contaminants is the most effective strategy for eliminating or minimising contaminant concentrations indoors. Source control methods include:

- Elimination – Take the source away (e.g. exclude specific materials or products, designate chemical storage to specified external areas only etc.).
- Segregation – Separate the occupants and the sources of pollution (e.g. reduction in emission rates by intervention of barriers, enclosures, air pressure differentials, or personal protective equipment).
- Substitution/modification – Use modified or alternative materials or processes with a lower air contaminant generation profile such as low-emission building materials, low-emission office equipment, alternative industrial processes, change in combustion design or change in energy source.
- Local exhaust – Is used to remove pollutants at or near the source (with or without a capture hood) to prevent their dissipation through the building or enclosure more generally.
- Air cleaning – Can be used to remove particles or gaseous air contaminants or both, generated either locally or in an area or region, from the air using an air cleaning device.
- Education – To change or modify occupant behaviour or ensure correct operation and maintenance by the system operator or user. Education can include consumer information on products and materials, information on health, soiling, productivity, and nuisance effects of materials, information on legal rights and liabilities related to indoor quality, as well as real time IAQ data displayed from the building control system.

4.2.3 Air contaminant balance

Any consideration or analysis of indoor air contaminant concentrations generally devolves to a steady state consideration of the mass-balance of all contaminant outputs and inputs within the boundaries of the analysis.

The boundaries of the analysis are generally the walls, floors and ceiling of the space under consideration. The analysis must consider all the interactions within the volume encompassed by the boundaries and all movement across them.

The contaminant inputs are all the air contaminants being added to the space through outdoor air, indoor occupants and materials, indoor activities and processes, and the HVAC system or its components.

The contaminant outputs are all the air contaminants that are being removed from the space through:

- exhaust or spill air
- the actions of air filters and cleaners

- the absorption of contaminants into indoor materials
- particle settling
- species degradation and chemical reactions within the space air.

4.3 Indoor air contaminant control strategies

The most common design strategies that are utilised to control indoor air contaminant in buildings are:

- limit the use of materials and products that emit specific air contaminants
- remove unflued combustion heating from all internal areas of the building
- ventilate all unflued combustion cooking devices or areas in the building
- seal the building from uncontrolled infiltration and exfiltration of air
- manipulate contaminant transport with directional airflow
- locally exhaust-ventilate any fixed contaminant generation points
- optimise air distribution systems for contaminant control
- remove contaminants from the air with air cleaners
- ventilate the space with clean outdoor air
- manage the construction with an IAQ plan
- manage the facility with an IAQ plan.

Further detail on each of these strategies is provided in this section of the handbook.

4.3.1 Limit contaminant emitting materials

Many building materials, finishes and furnishings can emit air contaminants such as formaldehyde gas and other VOCs into the indoor air. In some cases, emissions occur for many years after manufacture or installation. One of the most effective ways to limit these air contaminants is to limit the use of the materials and products that emit them.

It is difficult for material specifiers and other decision makers to identify low-emission materials when there are no clear standards, goals or guidelines and inadequate information available on the air contaminants that may be emitted by a product. In many cases, sourcing the manufacturer's product data is the first step in the process. Manufacturers do produce safety data sheets (SDS), also called material safety data sheets (MSDS) outlining the properties of their products, the materials used and the associated hazards, including instructions for handling, storage and disposal. These sheets do not generally indicate the air contaminant emissions profile of a product, but material and ingredient lists can be used to identify potential air contaminant issues.

There are however an increasing number of schemes and organisations that do specify emission limits of VOCs (and other air contaminants) for building materials and finishes, for interior furnishings and for indoor equipment. This is resulting in an increasing number of low-emission products and materials coming to the market that are available for designers and contractors to use in the construction of buildings.

Appendix E provides a list of some data sources for more information on selecting low-emission materials for buildings.

4.3.2 Limit indoor combustion devices

Indoor combustion devices can generate several air contaminants including nitrogen dioxide, carbon monoxide, respirable particles, nitrosamines, and polynuclear aromatic hydrocarbons. These can be generated in many indoor locations, such as:

- restaurants
- cafeterias
- homes
- hotels
- enclosed carparks
- buildings with attached garages
- recreational facilities that use equipment with internal combustion engines.

The application of indoor combustion devices for space or water heating, or the use of internal combustion engines indoors should be reconsidered in a design targeting low-air contaminant characteristics. Options include the removal of internally located unflued combustion heating devices from the design and the provision of exhaust ventilation to all unflued combustion cooking devices and all cooking areas. The use of electricity or solar thermal energy for space and water heating produces no indoor air pollutants directly, whereas heating by an unflued combustion device can increase indoor levels of nitrogen dioxide, carbon monoxide, other combustion gases and particles. Some heaters can emit formaldehyde as a product of inefficient gas combustion.

Manufacturers of unflued gas heaters produce “low-nitrogen oxides” heaters for the Australian market. Even these heaters can lead to high nitrogen dioxide concentrations indoors under circumstances where the building ventilation rate is low, or the heating capacity of the heater is high relative to the building volume. The emissions performance of unflued gas heaters also tend to reduce over time, with older plant generating higher levels of air contaminants than it did when new.

4.3.3 Seal building to control infiltration and exfiltration

Air contaminants can enter the building with any uncontrolled infiltration of outdoor air through gaps or cracks in the building structure. The building fabric should be considered for air tightness and the implications for air infiltration and IAQ impacts. All holes, openings and gaps in the structure should be sealed, refer to the building sealing requirements in the NCC (Volume One Part J5, Volume Two H6P1 and Part 13.4 of the Housing Provisions). Sealing the building helps the ventilation designer to control the air pathway. Ambient wind profiles should also be considered regarding their effect on the building pressure profile.

Alert

In addition to the building sealing requirements, the NCC also contains requirements for condensation management for certain residential buildings (NCC Volume One Part F8, Volume Two Part H4 and Part 10.6 of the Housing Provisions). Improving air-tightness by sealing the building in order to improve indoor air quality needs to be considered in the context of the NCC condensation management requirements.

The ABCB also has a handbook, Condensation in Buildings, to assist in understanding condensation risk and the requirements contained in the NCC. The handbook can be accessed from the ABCB website.

4.3.4 Manipulate contaminant transport with directional airflow

Ventilation systems can comprise of supply, return and exhaust systems and how these systems interact with each other, and the outside, determines the building ventilation balance. The establishment of air pressure differentials between various enclosures within a building may be used to limit air movement and contaminant transport between them. Air flows from a higher to a lower pressure. In building ventilation, it is common to exhaust air from areas likely to generate air contaminants with makeup air supplied via adjacent occupied but cleaner enclosures. This induces an air flow pattern that inhibits cross-contamination of air and entrained contaminants from (low-pressure) polluted areas to (higher pressure) cleaner areas, i.e. air flows from clean to less clean areas. This strategy creates directional airflows.

Correctly sealing the building fabric and controlling indoor and outdoor air flows via mechanical ventilation provides good opportunities for air contaminant control. For pressure differential control, well-sealed enclosures are needed to establish clear air pathways. This type of ventilation design requires considering the air tightness between inside and outside, between enclosures, and the air movement forces at play.

4.3.5 Ventilate with local or general exhaust

Air contaminant control can be effectively achieved by applying local exhaust ventilation, where:

- air contaminants are dangerous or objectionable
- contaminant generation rates are high
- contaminants are generated from fixed point source(s).

Local exhaust involves the collection of air contaminants, as they are generated and as close as practicable to the source of generation. Systems use exhausted enclosures, cabinets, hoods and grilles as appropriate to capture the contaminants and discharge the collected effluent to atmosphere in a safe way. Zero or negligible mixing occurs with the indoor air. A clear pathway is needed for makeup air to replace exhausted air.

For a general exhaust system, the indoor air is removed from an enclosure and is replaced by relatively clean makeup air. The makeup air performs a dilution function that reduces general air contaminant concentrations. Exhausted enclosures or areas are maintained at a lower pressure relative to adjacent enclosures to assist with air contaminant control.

The effectiveness of a general exhaust system depends on the air mixing achieved, the exhaust airflow rate and the distribution and generation rate of the air contaminant sources. General exhaust is usually applied to enclosures in which specific contaminants are known to be generated and their generation rate is relatively well understood, e.g. bathrooms, laundries, carparks etc.

4.3.6 Air distribution design

The effectiveness of the air distribution layout in any ventilation system influences air contaminant transport and control. Depending on the air mixing achieved by the ventilation system the air quality may not be uniform throughout a ventilated space. Locating supply and return/exhaust registers too close together can result in short circuiting leading to an uneven distribution of outdoor air and an insufficient removal of airborne contaminants.

Poor supply and return air distribution can create under ventilated areas. Proper placement of air distribution supply and return registers with respect to partitions, furniture and each other is essential for good air distribution within the enclosure. Similar effects apply to the sizing, location and orientation of openings for natural ventilation systems, with cross-flow arrangements typically providing superior ventilation performance.

The efficiency of a mechanical ventilation system regarding air mixing and removing contaminants from the breathing zone may be expressed as the air change effectiveness (ACE) or the ventilation effectiveness (VE).

4.3.6.1 Air change effectiveness

ACE is an air distribution system’s ability to deliver ventilation air to a building, zone or space. The system ACE indicates how well the air is distributed within the breathing height. When ACE equals one, the air distribution system delivers air equivalent to a system with perfectly mixed air in the space. An ACE value less than one indicates the air distribution within the zone is less than perfect mixing.

4.3.6.2 Ventilation effectiveness

VE is a description of an air distribution system's ability to remove internally generated pollutants from a zone. VE is a ratio or measure of the cleanliness (or contaminant level) of the air in the breathing zone, compared to the cleanliness (or contaminant level) of the air in the return or exhaust air stream.

4.3.6.3 Calculating ventilation effectiveness

If there is complete mixing of the air and pollutants the VE is 1.0. If the air quality in the breathing zone is superior to the air quality in the exhaust/return air, the VE is greater than 1.0. If the air quality in the breathing zone is inferior to the air quality in the exhaust/return air, the VE effectiveness is less than 1.0.

ASHRAE 62.1 defines the range of "Zone Air Distribution Effectiveness (Ez)" values for air distribution systems based on configuration and operating temperatures, and provides a procedure for calculating the Ez. This calculation estimates the relative efficiency that different ventilation system arrangements can achieve, in delivering outdoor air to the breathing zone. Since supply air temperatures are involved, a unique Ez can be defined for systems in both heating and cooling modes (ASHRAE 2022).

4.3.6.4 Using carbon dioxide as a measure of ventilation effectiveness

While carbon dioxide concentrations are related to the perception of human bio effluent and odours, they are not a good overall metric of IAQ, as many important contaminant sources do not depend on the number of occupants and are therefore not correlated with carbon dioxide concentrations (ASHRAE 2022).

Nevertheless, in an occupied building as ventilation rates decrease, concentrations of carbon dioxide will increase, along with the concentrations of other contaminants generated indoors. Monitored indoor carbon dioxide concentrations are useful as an indicator of outdoor air ventilation rate per person but must acknowledge that outdoor air ventilation rates depend on:

- space type
- occupant density
- occupant characteristics (e.g. age, body mass, health, and activity levels)
- ventilation operation
- outdoor carbon dioxide levels.

Indoor carbon dioxide levels can be calculated for a building ventilation scenario using software tools (e.g. CONTAM Quick Indoor CO_2 (QICO2)).

Differences between indoor and outdoor monitored carbon dioxide levels can be used as an indicator for both occupancy and ventilation. Carbon dioxide monitors can be used to estimate outdoor airflow rates with levels of 900-1000 ppm typically considered equivalent to about 10 litres of outdoor air per second per person, for the base case. Uncertainties include sensor calibration and location, sample duration and timing, and varying outdoor carbon dioxide levels.

OzSAGE provided the following advice on carbon dioxide concentrations in relation to infection risk during the COVID-19 pandemic:

- Around 600 ppm or below is best practice
- Below 800 ppm indicates a low relative risk of infection
- Between 800 ppm to 1,500 ppm indicates a moderate relative risk of infection
- Above 1,500 ppm indicates a high relative risk of infection.

4.3.7 Air cleaning and contaminant removal

Air cleaning or contaminant removal can comprise a single device or a more complex system. Air cleaners, when correctly applied, can reduce the intake and recirculation of particulates, odours or gases and keep the building, the indoor air, and the HVAC system cleaner.

Adequate air cleaning is always considered good practice in mechanical ventilation and integrating air cleaning with mechanical ventilation is considered a significant advantage over natural ventilation systems. Air cleaning devices come in a range of configurations including integrated (duct or air handling unit (AHU) mounted) and stand-alone (portable or fixed) recirculating devices. Air cleaners also come in a range of technologies including particulate filters, gas phase cleaners and electronic air cleaning devices, sometimes with a mix of technologies within a single air cleaning device.

Air cleaners can be applied to outdoor air, return air and supply air streams as well as stand-alone recirculating devices. Portable cleaners generally include a fan and one or more of the air cleaning technologies.

Table 4.3 outlines the air contaminants specified in the NCC IAQ Verification Methods that can be targeted by different air cleaning technologies.

Table 4.3 Air cleaning technologies and NCC specified air contaminants

Air cleaning technology	Contaminants targeted	Comments
Panel or bag mechanical air filters	Particles - PM_{10} and $PM_{2.5}$	Wide variety of efficiencies depending on the particle sizes. Resistance increases and off-gassing possible as the filter loads. Easy maintenance and replacement options.

Air cleaning technology	Contaminants targeted	Comments
Electrostatic precipitators	Particles- PM_{10} and $PM_{2.5}$	Efficiency decreases and off-gassing possible as the filter loads. Maintenance and cleaning are essential.
Gas-phase air cleaners	Gases – formaldehyde, VOCs, nitrogen dioxide	Generally configured for one or more specific gaseous contaminants only. High resistance to airflow implies side stream or stand-alone configurations The lifetime for removing pollutants may be short and there is the potential for air contaminants to off-gas when fully loaded.
Catalytic converter	Gases – carbon monoxide, carbon dioxide nitrogen dioxide, ozone, VOCs	A specific catalyst designed to remove a specific gaseous air contaminant. Usually used in conjunction with another air cleaning device. The lifetime of the catalyst for removing pollutants may be short.
Ultraviolet germicidal irradiation (UVGI)	Biologicals	Normally line of sight effective against viruses, bacteria and protozoa. Bacterial and mould spores and biofilms tend to be resistant to ultraviolet (UV) radiation and require more light or longer time of exposure, or both, to be killed. Creates particulates and can generate ozone.
Photocatalytic oxidation (PCO)	Gases	Effectiveness depends on the catalysts used which are limited in their lifetime. Creates particulates and can generate ozone as a by-product.
Ozone generators	Particles, gases, biologicals	Not generally recommended because they produce ozone by design, a lung irritant, and an air contaminant targeted by the NCC Verification Methods.

Table 4.3 is based on material from the ASHRAE Position Document on Filtration and Air Cleaning (ASHRAE 2021).

Designers should seek specific standards and guidelines relevant to a particular application, for example the Australian Health Facility Guidelines, Australian Standards on cleanrooms, controlled environments, laboratories and medical gases and other industry-specific guidelines.

The type and level of filtration applied can affect minimum outdoor airflow rates and system operating pressures. All air cleaning technologies require ongoing maintenance. Designers should ensure that adequate access is provided around air filtration and cleaning systems to facilitate their regular inspection and maintenance.

AIRAH DA 15 Air Filters and Cleaning Devices contains good information on air cleaners and how they work (AIRAH 2019).

4.3.7.1 Panel or bag mechanical air filters

Particulate filters come in a range of designs and efficiencies. The mechanisms employed for particle entrapment within specific filter product designs include straining, impingement, interception, diffusion and electrostatic attraction. Common particulate filter types include inertial, fibrous, electrostatic and sieving filters and some designs are a hybrid of 2 or more types (e.g. electrostatic and fibrous).

Particulate filters are typically supplied in a panel or pleated bag (pocket) format that the air is passed through. Panel or bag filters are constructed out of sheets of fibrous media, generally manufactured to maximise the face area of the filter media that impacts the air stream. Particles are trapped through a variety of actions, and they build up on the media surfaces over time. As a particulate filter becomes loaded with contaminants the air resistance of the filter is generally increased, potentially resulting in a drop in system airflow. Designers should take account of these variations in pressure drop to ensure that the air delivered to the enclosure always contains the minimum outdoor airflow rate needed for adequate air contaminant control.

Panel and bag particulate air filters are generally disposable and replaced during maintenance. Coarse pre-filters can be used to protect or extend the operational life of high efficiency filters.

4.3.7.2 Electrostatic air filters

Electrostatic precipitators use the forces of electrostatic attraction to trap charged particles contained in any air that is directed through it. The devices incorporate a series of electrically charged plates and grids, arranged to first impose an electrical charge on the particle using electrically charged ‘ionisation plates’ and then attract and catch the charged particles on the oppositely charged ‘accumulator plates’.

Particles agglomerate and build up on the accumulator plates. Captured material needs to be periodically removed during maintenance to reinstate capture efficiency and to prevent secondary off-gassing of contaminants into the air stream.

4.3.7.3 Odour and gas phase air cleaners

Air cleaning devices that are designed to remove gaseous or odorous contaminants from the air using sorbent materials are typically referred to as gas phase air cleaners (GPAC) when they are applied to building ventilation systems. Different terms may be applied in industrial applications. GPAC devices come in a range of designs, including absorptive and adsorptive types, and a range of efficiencies for specified gaseous air contaminants.

Absorptive filters are usually wet wash systems using water or some other solution to remove contaminants from air as it is passed through a spray or shower. These systems are generally restricted to industrial applications and exhaust air treatments.

Adsorptive filters can include chemisorptive and physisorptive properties to remove contaminants from an air stream. Activated carbon, used with specific chemical adsorption materials, is the most used material. GPAC performance is usually targeted at one or a limited number of gaseous pollutants and generally a device will not reduce an air contaminant they were not designed to adsorb. GPAC applications in building ventilation systems are often deployed in a side-stream configuration and typically target VOCs in indoor air. Carbon monoxide and other organic gases are not typically targeted by this technology because of their small molecular size.

Catalytic converters can be included with GPAC in an air cleaning system to target specific gases that have smaller molecules such as carbon monoxide, carbon dioxide, nitrogen dioxide, and ozone. Catalysts generally need to be replaced or rejuvenated after a period of use.

ASHRAE Standard 145 provides 2 test methods for determining and validating the performance of GPAC devices. Part 1 covers the performance of sorbents used in GPAC and part 2 covers the air cleaning device itself.

4.3.7.4 Ultraviolet germicidal irradiation

Ultraviolet germicidal irradiation (UVGI) is a disinfection or sterilization method that uses ultraviolet (UV-C) light at sufficiently short wavelength to break down or degrade organic material and inactivate microorganisms. It is used in a variety of applications including food, air and water purification.

An air cleaning UVGI system is designed to expose the air stream or surface to germicidal UV-C shortwave radiation. Exposure comes from germicidal lamps that emit germicidal UV-C electromagnetic radiation at the correct wavelength, irradiating the passing air or the protected surface.

The types of UVGI systems developed for building and air-handling applications include surface-disinfection systems (coils and drains), in-duct systems, room recirculation system, and upper air systems. For each UVGI application the intensity of the radiation versus the length of exposure time for irradiation needs to be considered. The first step in the design of an in-duct or surface-disinfection UVGI system is to characterise the application. This includes describing the air stream (air volume, velocity, temperature and humidity), identifying the specific surfaces/areas to be treated, and possibly targeting specific microorganisms (characterising the likely air contaminants).

ASHRAE Standard 185 provides test methods for evaluating the efficacy of UV-C lights for their ability to inactivate airborne microorganisms. Part 1 covers duct or airflow irradiation and Part 2 covers surface irradiation.

4.3.7.5 Electronic air cleaners

There are a range of alternative electronic air cleaning devices that use specific technologies designed to remove contaminants form the air (ASHRAE 2021). These devices include PCO cleaners and ozone generators.

- PCO cleaners – These devices use a UV lamp in conjunction with a specific catalyst to generate radicals that convert gaseous air contaminants into harmless products.
- Ozone generators – These devices use UV lamps or an electrical discharge to intentionally generate ozone within the air stream. The ozone then oxidises any contaminants in the air passing over or around the lamps.

Technologies that generate electrical fields and/or ions, often called 'electronic filters', have been documented to range from relatively ineffective to very effective in reducing particles. However, many electronic air cleaners emit significant ozone.

Many air-cleaning devices use a combination of filters (e.g. particle removal and gas-phase air-cleaning technologies) and a fan. The devices are often stand-alone (portable) with limited coverage and air distribution.

4.3.7.6 Air cleaner efficiency ratings

The benefit of the air cleaning device depends on the effectiveness it has for removing the contaminant of concern, generally described as the filter efficiency. Typically, the air cleaning efficiency or effectiveness of an air cleaning device is determined for a type of air contaminant using a standardised test method. It is this efficiency (or efficiency range) that is used in the analysis of air contaminant control.

There are well developed standards covering test methods for determining and classifying the efficiency of particulate air filters including electrostatic air filters, these include:

- ISO 16890.1
- ASHRAE 52.2
- AS 1324.2.

These tests target operational efficiencies at specific particle size ranges and airflow rates. Aerosols are often used as the test challenge. ISO 16890 classifies filter performance by rating filter efficiency against the specific particle size groups: ePM_{10}, $ePM_{2.5}$ and ePM_1.

There are also tests developed specifically for GPAC devices (ASHRAE Standard 145) and UV-C lamps (ASHRAE Standard 185). There are no test measurement standards for the effectiveness of PCO cleaners or ozone generators (ASHRAE 2021).

For filters and air cleaners that are portable and self-contained, the rate of contaminant removal from air passing through the filter can be expressed as clean air delivery rate (CADR). This is approximately equal to the product of airflow rate and the contaminant removal efficiency. The air cleaning effect is typically most pronounced in the immediate vicinity of the device.

Some air cleaning devices are marketed with little evidence to support their actual operating effectiveness or their actual efficiency at removing specific air contaminants. To be relied on for an air contaminant control strategy, air cleaning devices need to be able to demonstrate the following key performance factors.

- They can remove the specified gaseous or particulate air contaminant from the air, with a level of efficiency that is known (tested) and repeatable over time.
- The test method used is transparent, repeatable and publicly available.
- The air flow rates, and operating characteristics used in the testing of the device are consistent with the parameters under which the air cleaner is typically applied.
- The action of the device does not create new or secondary air contaminants (e.g. some air cleaning treatments can produce intermediate species (by-products) that become airborne or can produce ozone as a by-product of their operation).

Independent testing to a publicly available peer-reviewed test specification is preferable to (and provides greater assurance than) internal manufacturer or supplier performed tests with bespoke test methods.

4.3.8 Ventilate with clean outdoor air

Outdoor air in Australia is generally accepted as being suitable for building ventilation from a regional perspective, see Chapter 2 of this handbook. Local air contaminant generation sources, such as coastal sand, traffic fumes, agricultural activities, industrial plants or refuse storage and management systems, may reduce the cleanliness of the air locally.

Where contaminant sources reduce the local quality of the outdoor air, the location of the air intake can be changed to reduce or eliminate contaminant intake or air cleaning can be applied to outdoor air streams to reduce contaminants.

For short-term pollution events, such as local bushfire smoke or dust storms, design arrangements can allow temporary reduction of outdoor air intake airflows, to minimise indoor air contamination.

It is good practice to not use plantrooms as outdoor air plenums and to provide all AHUs with a direct supply of outdoor air. This prevents or reduces the risk of cross-contamination from other plant within the room or from any maintenance and service activities that may occur.

4.3.9 Construction, commissioning, training and labelling

4.3.9.1 Construction IAQ Management Plan

A Construction IAQ Management Plan is a step-by-step approach to minimising the potential for introducing indoor air contaminants during construction and renovation projects. The aim is to reduce IAQ problems that may result from construction practices, promoting the comfort and wellbeing of building occupants and construction workers.

The Construction IAQ Management Plan is developed during the design phase of a project and implemented from the outset of the construction. The intention of the plan is to minimise factors that contaminate indoor air, such as dirt and dust entering HVAC systems and ductwork, improper storage of materials on-site, and poor housekeeping.

The following emission control strategies, to be applied during construction, can be included in the plan.

- Accelerate emissions of “wet” products and materials by using high ventilation during and after their application.
- During high emission periods, protect workers and increase ventilation.
- Delay installation of adsorbent indoor materials and furnishings, such as carpet, furniture, or ceiling tiles until emissions from other construction contaminants (e.g. wet product emissions) have dissipated. Otherwise, these materials may adsorb the contaminants and later release them during occupancy.
- Protect air ducts and HVAC plant from construction dust and debris and keep them clean.
- Delay occupancy of the building until contaminant emissions have subsided.
- Provide high outdoor ventilation rates to the building for a significant period after occupancy.

The Construction IAQ Management Plan can include the following requirements:

- Avoid using the building HVAC systems during construction.
- Protect all HVAC equipment from both dust and odours and seal all duct and equipment openings with plastic.
- Protect stored on-site and installed absorptive materials from moisture damage.
- Identify, isolate, and ventilate any containers housing toxic materials.
- Isolate any exhaust fumes from vehicles and tools.
- Use dust extraction for all cutting, drilling and grinding.
- Isolate areas of work to prevent contamination of clean or occupied spaces, for example, provide temporary barriers and maintain negative air pressure relative to other spaces.
- Conduct activities with high air contaminant emission potential out-of-hours, to allow time for air contaminants to flush out.
- Sealing of concrete surfaces for long-term dust control.
- Cleaning of entire workspace including hidden spaces and any supply or return air ceiling or floor voids.
- Use vacuum cleaners with high efficiency particulate air (HEPA) filters and use wetting agents for dust.

- Allow adequate time for ventilation flush-out and test indoor air contaminant levels prior to occupancy.

Because products often off-gas at their maximum rate when they are new or recently installed it is good practice to include flushing out the building as part of the Construction IAQ Management Plan.

Immediately after the construction is complete, buildings should be flushed-out with outdoor air ventilation to help remove the high levels of air contaminants common in fresh construction. The flush-out should be done after construction is finished and with all interior finishes installed. Prior to building occupancy and after flush-out, filtration media in the air handling systems should be renewed.

If occupancy is required prior to completing the flush-out, the space should only be occupied following delivery of the maximum ventilation rate possible (e.g. 100% outdoor air). During each day of the flush-out period, ventilation should begin at least 3 hours prior to occupancy and continue during occupancy.

As an alternative to flush-out, where low-emission construction and finishing materials have been used, baseline air contaminant testing can be conducted after construction ends and prior to occupancy. This can be used to demonstrate the maximum contaminant limits for acceptable air quality are not exceeded.

4.3.9.2 Commissioning

Commissioning is a comprehensive process for the planning, delivery, and verification of buildings and their systems. Itis very important that all ventilation systems and their controls are fully and correctly commissioned prior to handover. Commissioning activities need to be integrated with design and construction activities. Commissioning of the ventilation system should be integrated with commissioning of the whole building.

The AIRAH DA 27 provides comprehensive information on building commissioning (AIRAH 2011). Also refer to SA TS 5342 Technical Specification for building commissioning (SA TS 5342 2021).

Properly documented commissioning processes provides each system’s baseline operational data necessary to effectively manage the ongoing performance of the building and its systems.

4.3.9.3 Training

The training of operators and owners in the correct operation, monitoring and maintenance of the ventilation systems is important to ensure ongoing system performance.

Training should include information and guidance on the building air contaminant and ventilation control strategies as well as operational strategies that can be used to optimise IAQ.

4.3.9.4 Labelling

The labelling of air handling and ventilation plant with commissioning (performance) and operational information can significantly aid the provision of scheduled preventative and performance-based maintenance programs. Labels can be electronic and linked to building information management systems and computer aided maintenance management systems.

4.3.10 Operational planning

Building designers and contractors can help implement IAQ-friendly operational strategies that promote management practices consistent with the air contaminant control strategies and ventilation design assumptions for the project.

4.3.10.1 Operational IAQ Management Plan

The ventilation designer can play a role in the ongoing operation of the facility by providing a building Operational IAQ Management Plan. This helps the facility manager or building operator address IAQ issues during the life of the building. An Operational IAQ Management Plan can address issues such as the correct operation of the ventilation system as well as operation and maintenance strategies for the ongoing control of indoor air contaminants within the building.

4.3.10.2 Housekeeping

Building management and housekeeping is very important in relation to IAQ. Managing pollution sources known to be in specific areas within a building such as garbage collection areas, storage areas, kitchen/tearoom or photocopy/printing areas will assist in maintaining clean indoor air.

4.3.10.3 Consumer products

The use of some consumer products indoors can lead to the release of gaseous compounds and volatile organic vapours. Among the compounds of principal concern are aldehydes and polynuclear aromatic hydrocarbons, nitrosamines and hydrocines, polychlorinated biphenyls and a variety of organic substances. Solvents are used for a variety of purposes in surface-cleaners and furniture-cleaners, disinfectants, polishes, adhesives, personal grooming products, air odourisers and de-odourisers, insecticides, and pesticides.

The instigation of low-emission procurement guidelines for consumer products will assist in maintaining clean indoor air. See Appendix C for potential data sources and relevant certification schemes.

4.3.10.4 Maintenance protocols

The general expectation is that systems in buildings can perform to the standard to which they were designed, installed and constructed. Australian jurisdictions differ in the way these expectations are regulated.

Preventive maintenance means the routine inspection, cleaning, adjustment, and repair of building structures and systems, including the HVAC, and local exhaust ventilation. Preventive maintenance plays a major role in maintaining IAQ, by assuring the building systems are operating effectively and efficiently.

Regular maintenance of the HVAC system and appropriate management of HVAC hygiene are also essential aspects of IAQ. Filters and outdoor air intakes are particularly critical, and deserve special consideration by the system designer.

Maintenance and cleaning of the building and furnishings, methods used, and chemicals employed, are also relevant to managing odours and IAQ. This includes the procedures and products used when cleaning floor, wall, window and ceiling surfaces. These are areas the ventilation designer has little control over, however advice can be given to building owners and managers through building operation and maintenance documentation.

The most important contribution the designer can make to ongoing maintenance programs is to design the systems with maintenance in mind. This includes provisions for maintenance, and providing sufficient access to and around the plant and systems to allow maintenance to be safely and effectively delivered. This is a requirement of government WHS/OH&S laws and regulations and relevant to the entire design and installation process (SWA 2011).

4.4 Design strategies for controlling air quality

Much of the building fabric, its furnishings and equipment, its occupants and their activities produce air contaminants. This section of the handbook discusses some of the strategies to reduce air contamination by design. This includes:

- leveraging multiple disciplines in an integrated design approach
- targeting ventilation and air distribution system design to promote VE
- documenting the system design standards and calculations to give a clear understanding of the design intent and the underlying assumptions
- providing safe and easy access and required facilities (light, power, water and drainage) to encourage the provision of on-going maintenance
- location of air intakes and air discharges with regard to local air contamination effects
- address the infiltration of contaminants at building entry ways and other openings in the building fabric.

AIRAH DA 26 provides a detailed discussion on HVAC design and operational strategies to manage IAQ (AIRAH 2004).

ASHRAE also produced a detailed guideline for the design, construction and commissioning of buildings to optimise indoor air contaminant control and IAQ (ASHRAE 2009). The guideline lists the primary design objectives as follows.

- Objective 1 – Manage the design and construction process to achieve good IAQ.
- Objective 2 – Control moisture in building assemblies.
- Objective 3 – Limit entry of outdoor contaminants.
- Objective 4 – Control moisture and contaminants related to mechanical systems.
- Objective 5 – Limit contaminants from indoor sources.
- Objective 6 – Capture and exhaust contaminants from building equipment and activities.
- Objective 7 – Reduce contaminant concentrations through ventilation, filtration and air cleaning.
- Objective 8 – Apply more advanced ventilation approaches.

In the guideline, each objective is provided with an overview, major strategies and detailed information on how to achieve them.

4.4.1 Integrated design targeting IAQ

Opportunities and outcomes for a project targeting indoor air contaminant control are enhanced when IAQ is viewed in conjunction with holistic, collaborative strategies for IEQ.

Synergies exist between project team members, including the client, architect, interior designer, services engineers and contractors, and other building system designers. Design teams can work together to optimise the opportunities an integrated approach offers the building IAQ, delivering high performance, comfortable and safe building interiors.

An integrated design process could adopt the following strategies for targeting IAQ.

- Document the client's IAQ goals for the project and incorporate them into design and contract documents.
- Consider IAQ early in the project schedule, as early as the concept or pre-design stage where possible.
- Facilitate team members to share and discuss project IAQ goals avoiding duplication of work and harmonising effort.
- Investigate opportunities for improved IAQ in the project; discuss IAQ goals for ventilation and filtration systems, discuss interior finishes, discuss façade air permeance and building sealing.
- Coordinate the implementation of a construction IAQ Management Plan with all contractors during the construction process.

- Check all proposed substitutions of plant or materials for conformance with the original product's specified contaminant emission and performance characteristics.
- Ensure the building and all systems are fully commissioned and documented and meet the design intent.
- Provide the facility manager with education and support tools documenting best practices for operations and maintenance relative to IAQ.
- Evaluate system performance and outcomes with a post occupancy evaluation of the indoor air quality and ventilation.
- Document lessons learned on the project for application to the next project.

4.4.2 Ventilation effectiveness targeting air contaminants

VE is a function of several design and installation factors including:

- air distribution characteristics (pressure, flow, speed)
- return air characteristics
- location of inlets and outlets
- location of pollutant generation sources
- temperature of supply air relative to the enclosure temperature (see 4.3.6).

Compared to a standard mixing system, systems such as high-level supply/low-level exhaust, task ventilation and displacement ventilation may be applied to improve the VE of a system and hence improve the air quality in the enclosure served.

Task ventilation describes a design approach where ventilation air is delivered directly to the breathing zone of the occupant at a task. Ventilation controls are generally local, and the combination of efficient air delivery and individual control can generate a high level of acceptability with occupants. Well-designed task ventilation systems can achieve a high VE.

Displacement ventilation provides buoyancy driven flow rather than more conventional forced flows. Displacement air is introduced at low level in the enclosure and at a temperature slightly below the room ambient. Laminar flows are maintained with local heat sources creating a general upward movement delivering good ventilation and air contaminant removal to the breathing zone. Air contaminants are entrained upwards without mixing or passing through the breathing zone of other occupants. The contaminated air is removed at high level in the conventional manner. Well-designed displacement ventilation systems can achieve a high VE.

4.4.3 System documentation

4.4.3.1 Documenting assumptions

Enclosure use, occupancy numbers, enclosure size and layout, contaminant generation rates, occupant activities, infiltration and exfiltration rates, are only some of the design assumptions that may have changed between the design development and system installation phase. Ventilation system design assumptions need to be revisited at system installation stage to ensure that all assumptions remain valid. This can only occur when assumptions are properly recorded and documented.

4.4.3.2 Documenting design intent

A primary focus for designers should be the documentation of the design intent of their systems which they have developed based on the client's project operating requirements. Factors like occupancy numbers and operating hours, thermal comfort and IAQ performance, operation and maintenance policy, energy efficiency, energy monitoring and verification requirements all need to be documented.

Designers should also communicate the basis of design and provide a design narrative and operational sequences to facilitate system integration with other building stakeholders and disciplines. BIM (building information modelling) software platforms can be leveraged to facilitate documentation development and delivery.

4.4.3.3 Documenting operations and maintenance

Every system should be provided with comprehensive system information in the form of operating and maintenance (O&M) manuals developed by the designers and installers.

4.4.4 System maintainability

In relation to system operation and maintenance, designers need to consider the safety implications of the designs they develop. This is so the safety risks for operators and maintenance service providers are minimised as far as is reasonably practicable – this duty is known as safety-in-design. Installers must then deliver on the safety-in-design intent to minimise the safety risks. This includes identifying and resolving any safety risks that have not been mitigated by the designer (SWA 2011).

Ongoing maintenance can have a large impact on the IAQ provided by an operational ventilation system. Designers need to consider the maintainability of systems which should be designed and installed for easy and safe access to all components that need to be inspected or tested. This includes access for inspections to determine the HVAC hygiene level and access to clean or replace system components when required.

4.4.5 Location of air intakes and discharges

The ventilation systems should be designed to minimise the entry of air contaminants into the building. There are many limitations on the location and separation of air intakes and exhausts, including the consideration of the effects of wind, adjacent buildings and structures and local air quality may have on ventilation systems and indoor air quality. Designers can use Computational Fluid Dynamics (CFD) modelling, Gaussian dispersion analysis, wind tunnel analysis or tracer gas assessment to model exterior contamination patterns. Refer to ASHRAE Fundamentals Chapter 24 Airflow around buildings for further information (ASHRAE 2021).

4.4.6 Addressing entry ways

There are several ways that entry ways into buildings and spaces can be designed to restrict or reduce the entry of air contaminants including:

- the provision of entryway dirt capture systems such as permanently installed grilles, grates, rollout mats and slotted systems
- automatic sliding doors or self-closing doors combined with entry lobbies to create a break between the exterior and interior environments
- revolving door to restrict the movement of outdoor air into the indoor environment through exterior entry ways
- air curtains to restrict the movement of outdoor air into the indoor environment through openings in the fabric.

5 Applying the IAQ Verification Methods

5.1 Benefits of performance-based ventilation solutions

There are many opportunities and potential benefits to be unlocked through adopting a performance-based approach and using the IAQ Verification Methods in terms of:

- innovative and hybrid approaches to building ventilation
- flexibility in design and application
- opportunities to maximise the IAQ provided by ventilation systems
- opportunities to reduce energy use associated with building ventilation
- opportunities to recognise and benefit from low-emission materials use
- cost savings in design, installation and throughout the life cycle of the ventilation system
- improvements to the sustainability outcomes of the overall building operation
- increases to the buildability of the ventilation systems
- reduction of the spatial design requirements and impact on other building services.

Performance-based ventilation solutions may not be appropriate in all applications. In some cases, particularly when uncertainties apply, the results of a performance-based design may be too conservative, too inflexible, or too expensive, when compared to a DTS Solution.

5.2 Risks of performance-based ventilation solutions

There are some potential practical difficulties with implementing performance-based ventilation utilising the IAQ Verification Methods. These include:

- the difficulty of accurately estimating contaminant generation rates for each air contaminant in the space
- the performance approach may be more time consuming (particularly at the design stage) when compared to the DTS approach
- a Performance Solution may be more expensive, at least in term of design input, than the standard approach
- the performance approach may increase risk exposure for designers, owners and operators, if the building solution does not perform as anticipated
- a Performance Solution may require significant ongoing monitoring and review protocols.

The use of the NCC IAQ Verification Methods may not be appropriate in some situations, including for example where there is insufficient information about the intended operation and use of the building.

5.3 Developing a performance-based ventilation solution

5.3.1 Performance drivers

A performance-based design of a ventilation system may be undertaken because of technical ventilation issues including the following.

- **Outdoor air contamination** – outdoor air is too contaminated to use for dilution ventilation and an alternative is required.
- **Outdoor air condition** – outdoor air is too hot or too cold or too humid to economically use for dilution ventilation and an alternative is required.
- **Outdoor air reductions** – optimisation of overall outdoor air quantities may result in reductions in capital costs and ongoing operating costs providing a financial incentive for the performance-based approach.

Other possible drivers include a desire for innovation, sustainability, or cost savings, or in response to specific building characteristics. These could include location issues, building security considerations, or where hybrid ventilation designs cannot comply with DTS Provisions.

5.3.2 Design objectives

The following ventilation design objectives typically apply to ventilation system design:

- prevent the accumulation in indoor air of contaminants (e.g. particles, gases, aerosols) injurious to health or detrimental to comfort
- provide an adequate supply of oxygen to combustion appliances
- control nuisance due to odours
- maintain oxygen content of indoor air to levels necessary for human respiration.

5.3.3 Design criteria

As part of the assessment to determine compliance with the NCC IAQ Verification Methods, the design inputs used to meet the ventilation design objectives should consider:

- the uses of the enclosure and the activities likely to be accommodated
- the population density, and the age and health of the occupants

- the percentage of occupants to be satisfied with the ventilation and air quality outcomes (100%, 90%. 80%, etc.)
- the type and location of any combustion appliances
- the proportion of time the ventilation requirements need to be met, (all the time, 95%, 90% etc.)
- any air cleaning or treatment applied.

Note the NCC IAQ ventilation Verification Methods specify maximum air quality contaminant values that must be satisfied all the time.

5.4 Design inputs for performance-based ventilation systems

5.4.1 Design inputs for occupied space ventilation systems

The critical pollutants for occupied spaces (in Class 2, 3, 5, 6, 9b, or 9c buildings or a Class 4 part of a building) nominated by the NCC IAQ Verification Method F6V1, are carbon monoxide, carbon dioxide, nitrogen dioxide, ozone, particulate matter and total volatile organic compounds.

For air contaminant modelling of the occupied spaces the essential design inputs include:

- the operation schedule for the building and the building services systems
- the population number, gender, age and type
- the definition of all IAQ enclosures or IAQ zones in the building
- enclosure use, and activities and process that are contained within each
- enclosure size and layout, including internal partitioning
- the materials and finishes used in the enclosure, and their air contaminant emission profiles
- contaminant generation rates from all occupant and non-occupant related sources
- mechanical supply, return and exhaust air/spill air flowrates
- details of any air cleaning devices employed in the design
- infiltration and exfiltration rates
- the external climate conditions, including temperature, moisture content, wind and pressure, and addressing any local microclimates.

Assumptions like occupancy numbers and operating hours, thermal comfort and IAQ performance, operation and maintenance policy, energy efficiency, energy monitoring and verification requirements should all be documented by the designers. A list of the design assumptions made during the design development and system installation phase should be created. Ventilation system design assumptions should be revisited at system installation stage to ensure that all assumptions remain valid.

5.4.2 Design inputs for carpark ventilation systems

The critical pollutant for a Class 7a building, nominated by the NCC IAQ Verification Method F6V2, is the carbon monoxide emitted from the exhaust pipes of vehicle engines. Emission of carbon monoxide is greater than other contaminants from the vehicles, particularly when they are idling or moving. Emissions are highest when the engine is cold, i.e. recently started. Concentration rates of carbon monoxide in the space are directly related to the vehicle movement rates. Carparks often have 2 or more peak usage times during the day.

The main elements of a carpark ventilation model that determines contaminant concentration levels are:

- the number of vehicles active in the space – vehicle usage rates determine generation rates for the air pollutant
- the vehicle activity in the space – entry, exits and driving distances
- the vehicle fleet type using the carpark– age, size, fuel type (petrol, diesel, electric, hybrid)
- the internal geometry of the structure, floor plan, parking layout, single or multiple compartment – all affect internal air movement and contaminant transport
- the parking management strategy (e.g. self-parking, concierge parking, stack parking), and the location of any carpark workers
- the natural or mechanical ventilation system used – the air flow rates, the methods of operation, the control of any air movement devices, and any air treatment devices
- the local weather conditions – particularly for systems with natural ventilation elements
- the concentration of carbon monoxide in the local outdoor air used for ventilation
- the location of external openings in the building, and the supply and exhaust grille locations
- the location and type of any recirculation or air movement devices in the carpark and any makeup air taken from adjacent spaces
- any additional activities that may occur in the carpark area, including storage areas, vehicle servicing, vehicle cleaning etc.

Analysing the vehicle usage rates and usage profile for the building allows estimates to be made of the overall contaminant emission rates into the space. Analysing the ventilation rates and arrangements allows estimates of the overall contaminant removal rates to be made. Combining these analyses provides estimates of the spatial and temporal concentrations of the carbon monoxide emissions. Analysis of the actual carbon monoxide levels in the outdoor air from the intended location may provide additional data to estimate the overall contaminant concentration within the enclosure. Sample measurements may help to ascertain this. Refer to Appendix C for a list of measurement methods.

Estimating the vehicle usage rates and the resulting air contaminant generation rates requires consideration of the following:

- the vehicle population and their distribution within the carpark
- the classification of the building served by the carpark users (e.g. residential, commercial, retail, mixed-use)
- the vehicle fleet mix anticipated, including fuel type and engine size
- estimates of vehicle entry and exit movements (when and how many cars)
- estimates of vehicle driving travel distance to park and leave (internal driving distances)
- estimates of more highly used zones within the carpark and the resultant high/low air contaminant concentration regions
- queuing time at the exit gates and any other internal queuing areas.

Accurately estimating carbon monoxide contaminant generation rates for Class 7a enclosures could be achieved by accessing and assessing the following data:

- empirical data on typical existing vehicle fleets within similar carparks (location, use, area, size)
- empirical data on vehicle usage and emission profiles within similar carparks
- empirical data on the outdoor air ambient carbon monoxide concentrations in the proposed area
- utilising conservative contaminant generation rates as specified in AS 1668.2-2012 (Standards Australia 2012a)
- aligning vehicle movements with those expected by traffic engineers
- accounting for non-uniform power output of vehicles within graded/ramped carpark areas
- utilising available emission modelling tools/databases and aligning data to relevant Australian Design Rules (ADR) pertaining to emission standards, which in most cases are based on many empirical tests for a range of driving cycles.

Refer to Appendix D for information on vehicle emission models available to assist in the determination of air contaminant generation rates by different types and sizes of vehicles in different driving formats.

Analysing the ventilation achieved by the system (natural, mechanical, or hybrid) will also depend on:

- location of the carpark (underground, ground level, elevated)
- external air temperature and wind rose data
- external topography of the surrounding natural and built environment
- position of access openings and any ventilation openings; and ultimately
- pressures developed at the ventilation openings.

Other issues that need to be considered include:

- management protocols for the facility (hours of operation)
- operational protocols (self- or staff-parked vehicles) used in the facility
- non-routine usage of the carpark (e.g. seasonal peaks in retail carparks)
- air monitoring and control systems deployed for the building.

One way for a carpark ventilation building solution to use the IAQ Verification Method is to demonstrate and validate the system performance through simulation, using fluid flow analysis or CFD.

CFD simulation can predict the air transport paths, the emission generation rates and the resulting concentrations of carbon monoxide. Refer to Appendix D for additional information on vehicle emission models and CFD modelling tools.

5.5 Verifying a building solution against the Verification Method

A design can be verified against the criteria in the Verification Methods using mathematical calculations, CFD analysis, or bespoke software solutions. In some cases, post-installation testing can be used to provide additional assurance that the ventilation systems are meeting the Performance Requirements.

5.6 Modelling IAQ and air contaminant transport

IAQ modelling is a tool used in estimating and predicting indoor air pollutant concentrations. It relates indoor air contaminant concentrations to various influencing factors such as building geometry, ventilation arrangements, air contaminant sources and contaminant sinks. IAQ models predict an air contaminant's concentration as a function of its concentration in the outdoor air, the indoor sources and their generation rates, and the indoor sinks for the contaminant and their removal/adsorption rates.

Performance-based ventilation design addressing IAQ, and air contaminant transport modelling involve evaluations of both bulk air and detailed air properties in buildings. Multizone network modelling is commonly used for bulk airflow analysis in building ventilation design and assessment.

In a multizone model, airflow movements and air contaminant transport are calculated between the rooms of the building, and between the rooms and the outdoors. The "well-mixed indoor air" assumption is used to simplify the analysis. The building is subdivided into zones having similar airflow properties and air contaminant sources and sinks. When characteristic airflows, sources and sinks are not uniform, the well-mixed assumption is no longer valid. In this case, a CFD tool can be used to calculate or estimate the detailed properties of the indoor air.

Models that can be used to predict contaminant and airflow behaviours range from simple regression analysis to comprehensive deterministic models and more complex numerical models. The fundamentals underlying the development of an IAQ model are based on the mass balance analysis of the air contaminants of interest within a particular indoor space.

5.6.1 Principles of simulation

An IAQ model provides a means to accurately predict the concentration of an air contaminant (such as peak concentration or average dosage) in time and space for defined building or space usage conditions.

The 'model' is the mathematical expression of the complex physical phenomena of a system, in this case the quality of the indoor air. The 'simulation' is the process of using the model to analyse and predict the behaviour of the system under real-life conditions.

The study of indoor air contaminant transport has evolved into a unique discipline requiring knowledge in the fundamental principles of fluid mechanics, species transport, heat transfer, building physics, and systems engineering. Accurately and reliably predicting ventilation airflows and air contaminant transport within buildings and interiors is a complex task.

In recent years there has been extensive activity in the development and use of CFD software and other computer software programs, platforms and plugins, for simulating room air movement and air contaminant transport applications. These simulations range from the prediction of air jet diffusion, air velocity and temperature distribution within rooms, to the spread of air contaminants within enclosures and systems, to fire and smoke spread inside entire buildings.

Modelling air contaminant transport within indoor environments requires knowledge of computational tools and techniques only recently developed. In these tools, knowledge of fundamental principles of ventilation and details of the building and its systems, including HVAC, is coupled with CFD or some other simulation technique in order to accurately assess and predict contaminant concentrations within the space.

CIBSE AM 11 provides a good overview of building performance modelling, including ventilation modelling (CIBSE 2015).

5.6.2 Air contaminant modelling

Provision of acceptable indoor air quality depends largely on 2 factors: contaminant-source control and effective ventilation. Modelling these 2 factors requires a thorough understanding of the building construction, the ventilation system, the occupants and their activities, and the emission characteristics of building materials, finishes and furnishings.

The extent of indoor air contaminant transport can be estimated using numerical models for heat transfer, mass transfer and momentum. These fundamental models are used to estimate concentrations of indoor air contaminants based on ventilation rates, contaminant generation rates, dilution rates, pollutant decay rates, sink rates and air mixing factors.

Modelling approaches combine the mass rate estimates of air contaminant generation within a space with mathematical models of pollutant transport and fate to estimate the spread of air pollutant concentrations. These models range from simple mathematical constructs to complex computer-based simulations.

IAQ models require a combination of processes to be modelled simultaneously including:

- air contaminant generation, transport, treatment and adsorption rates
- outdoor air ventilation, infiltration and exfiltration rates
- mechanical exhaust and spill air rates
- internal air movement (due to mechanical or natural pressures, temperature etc.).

The 2 main modelling approaches used for predicting indoor air flows and contaminant levels are microscopic models and macroscopic models. The possible pros and cons of each approach is provided in Table 5.1.

Table 5.1 Pros and cons of macroscopic and microscopic models

Pros and cons	Microscopic models	Macroscopic models
Ordinary differential equations	No	Yes
Partial differential equations (e.g. Navier-Stokes)	Yes	No
Prediction of spatial distribution of indoor parameters	Yes	No
Computer time and power required	High	Low
Accuracy	High	Good
Prediction of flow conditions (e.g. velocity)	Yes	No
Depth and granularity of analysis	High	Low

Note: Macroscopic models may have lower accuracy when applied to complex or interconnected enclosure geometries.

ASHRAE provide a methodology for modelling air contaminant transport through building ventilation through the “Indoor Air Quality Procedure” of ASHRAE 62.1. The standard also outlines a series of equations that can be used to determine required zone outdoor airflow or the breathing zone contaminant concentration with recirculation and filtration for single zone systems (ASHRAE 2022).

5.6.3 Microscopic modelling techniques

Microscopic modelling is generally based on CFD techniques. CFD is a general-purpose simulation technology whose applications include:

- aerodynamics
- hydrodynamics
- meteorology
- biomedical engineering
- the movement of effluents outdoors
- smoke movement within buildings
- ventilation airflow patterns
- air contaminant transport.

CFD numerically models the physical processes that occur within a fluid, by the solution of a set of non-linear partial differential equations that express the fundamental physical laws that govern those processes, e.g. the laws governing the conservation of mass, momentum and energy. The space or volume under analysis is divided into smaller volumes by a grid of intersecting lines. The points of intersection are termed nodes, and the results of the models are strongly dependent on the resolution of nodes used. Even basic models may include millions of nodes. The size or density of the grid used will determine the granularity of the data produced.

A system of equations is formulated at each node. The driving forces for indoor air movements are the pressure differences caused by wind, thermal buoyancy, and mechanical ventilation systems/devices or combinations of these. Air contaminant sources and sinks can be modelled and, in conjunction with the velocity field, pollutant concentrations estimated at each node. Modelling concentration levels for multiple air contaminants from multiple emission sources can be extraordinarily complex, and the first step in any design should be to remove or minimise as many indoor air contaminant sources as practicable.

CFD uses computer code or programming to solve the relevant science-based mathematical equations, using specific information about the design and application in question. CFD is used to predict what will happen, quantitatively, when fluids flow, often with the complications of:

- simultaneous flow of heat
- mass transfer
- change of phase (e.g. melting, freezing, boiling)
- chemical reaction
- mechanical movement
- displacement or dilution
- interaction with the surrounding surfaces.

Simulation and CFD-based predictions are never 100 percent reliable, because the:

- input data may involve too much estimation and assumptions that are not reflected in the final constructed building
- available computing power may be too small for the high numerical accuracy required in complex analyses
- scientific knowledge base may be inadequate and precise mathematical models may not be available to represent the dynamics of the specific application.

In general, the reliability of CFD-based predictions is greater for:

- laminar flows rather than turbulent ones
- single-phase flows rather than multi-phase flows
- chemically-inert rather than chemically-reactive materials
- single chemical reactions rather than multiple ones
- simple fluids rather than those of complex composition.

Microscopic modelling typically provides more granularity in data output than macroscopic modelling techniques.

5.6.4 Macroscopic modelling techniques

5.6.4.1 Single zone modelling

The simplest construct is the well-mixed single-zone model (the well-mixed box model), which incorporates the following concepts:

- the air in the space being modelled is bound by floor, walls and ceiling
- any air contaminant emitted is uniformly mixed throughout the space
- the space receives outdoor air at a given rate through natural infiltration and/or mechanical means
- there is an outflow of air by exfiltration and/or mechanical means at the same rate
- air contaminants sink mechanisms such as adsorption or particle deposition can be included
- air filtration and air cleaning can be incorporated
- different contaminant emission rate functions can be considered (the simplest is a constant rate)
- the duration of emissions rate can be set to reflect the time the source emits air contaminants into the zone.

The effect of local exhaust, which removes emitted pollutants before they mix into the indoor air, can also be accounted for by applying fractional terms to the emissions rate.

Based on these parameters, the distribution and concentration of air contaminants in a defined space can be estimated over time based on the relationship between source strength, ventilation and concentration.

$$\text{concentration}\ (\text{mg/m}^3) = (\text{emission rate}\ (\text{mg/h}) - \text{removal rate}\ (\text{mg/h})) \div \text{ventilation rate}\ (\text{m}^3)$$

A single zone model is the simplest of the macro modelling approaches and requires the fewest inputs and assumptions. An example of a single zone mathematical model is the following equation:

$$C_{ss} = \frac{(1-\epsilon).\,G}{Q + \alpha.\,V}$$

The input parameters to include:

V = room volume (m^3)

Q = outdoor air supply rate (m^3/min)

G = contaminant emission rate (µg/min)

α = loss parameter (/min), and

ϵ = the fraction of emissions directly vented or capture efficiency.

The model can be used with these inputs to predict the steady state concentration of the contaminant (C_{ss}, µg/m^3) within the room/zone/enclosure.

5.6.4.2 Multiple zone modelling

Depending on ventilation conditions, a single room, a floor, or a whole building may be represented as a single compartment or as multiple zones for air quality modelling.

A single-compartment model may not provide an adequate description or granularity of the contaminant distribution and concentration (e.g. the breathing zone in carparks) when:

(1) contaminant sources or sinks are not uniformly distributed throughout the compartment, or

(2) the rate of air mixing or VE in the compartment is low.

A multiple zone model provides a methodology to account for spatial differences in the air pollutant concentration, within a single space.

Because perfect mixing in a space does not often occur, and because air contaminant sinks and sources are generally distributed throughout the space, concentrations of the air contaminant will often vary between locations in a room. In many IAQ simulations it is the concentration in the breathing zone that is of most interest.

A compartment is defined as a region within which spatial variations in air contaminant concentrations can be neglected over the time scale of interest. In view of the uncertainties associated with many of the modelling parameters, the concept of breaking a single space into separate compartments for analysis has been widely used in IAQ modelling.

5.6.4.3 Multi-compartment models

Most multi-compartment models have been described by first-order linear ordinary differential equations. An example of a multi-compartment model could be in the form:

$$\frac{dx_1}{dt} + a_1x_1 = a_2x_2 + a_3x_3 + a_4x_4 + \cdots. + a_nx_n + 1$$

$$\frac{dx_2}{dt} + b_1x_1 = b_2x_2 + b_3x_3 + b_4x_4 + \cdots. + b_nx_n + 1$$

$$\frac{dx_n}{dt} + \cdots \ldots = \cdots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots ..$$

The terms a_1, b_1, etc., represent the sum of first-order air contaminant losses from the compartment due to exhaust streams, filtration or contaminant removal from any air stream, and sinks due to first-order chemical reactions. In cases where higher-order chemical reactions are important, the model equations will be non-linear and will generally be solved numerically.

In the case of particulate air contaminants, the parameters would contain loss terms to account for surface deposition. The gain of air contaminants in some compartments that may result from the intrusion of air from other compartments also needs to be accounted for in the model.

5.6.5 Boundaries in a model

The concepts of general flow and thermal boundary conditions are essential in predicting air flow patterns and air quality in IAQ simulations. For any IAQ modelling approach the boundary conditions need to be established. These include the following.

- The physical boundaries of the space including, walls, floors, ceiling, roofs, air barriers and openings and any associated radiative, convective and conductive heat transfers.
- Surfaces and surface coatings should also be considered, i.e. black walls and aluminium walls.
- The space geometry including the volumes, ceiling height and occupied zones.
- Infiltration and exfiltration occurring at the boundaries of the simulation.
- Outdoor air intake and room air exhaust airflows.
- The pressure relationships with adjacent spaces and the outdoors.

Boundary conditions should be realistic and accurately represented. Small changes to boundary conditions may significantly affect the patterns of air flow and air contaminant distribution.

5.6.6 Contaminant sources and sinks

Indoor air contaminants may be of outdoor or indoor origin.

Outdoor pollutants may enter a building through infiltration or ventilation air. Pollutants of indoor origin may arise from point or diffuse sources. Regardless of their source, air pollutants will typically be transported and dispersed in 3D, throughout the space.

Some pollutants may be removed by air cleaning devices (through which outdoor air, supply air or recirculated air flows), by exfiltration or exhaust ventilation to the outdoors, or by chemical change. In the case of particles, surface generation characteristics and removal through particle settlement rates are also important.

A useful categorisation of sources for air contaminants is:

- point sources
- line sources
- area sources.

The IAQ simulation should include source and sink models that detail the air contaminant sources and their generation rates; and the air contaminant sinks and their sink rates.

Source models can include both empirical models and mass transfer-based models:

- empirical source models involve fitting measured concentrations and profiled emissions with an appropriate equation, such as a power-law relationship
- mass transfer-based models involve solving fundamental equations governing the emission process, for example from dry and wet building materials to the air.

Occupants are usually treated as sources of both air contaminants (e.g. carbon dioxide) and heat. The occupant is often assumed not to move during the simulation. Understanding the emission characteristics of different indoor sources over time is a critical element of IAQ modelling.

Contaminant sinks are absorptive materials, typically dry and soft material like textiles, furnishings, acoustical ceiling tiles and gypsum board that readily absorb the VOCs emitted by source materials. The interaction of indoor air contaminants with indoor materials is known but poorly understood. Sink materials may re-release absorbed air contaminants over a prolonged period and themselves become sources.

Other sinks include the action of air cleaning devices and potentially the biological activity of living plants.

5.6.7 Building classifications

In some cases, the classification of the building will help to determine the different types of air contaminant that may be expected during typical conditions of use. For instance, for Class 7a carparks the only contaminant that is required to be verified is carbon monoxide as this is the dominant contaminant for these buildings. Building classifications can help ventilation system designers identify potential air contaminants from:

- the expected type of building occupant
- the activities typically undertaken in the building type
- the types of materials typically used and stored in particular buildings.

5.6.8 Ventilation and infiltration

For mechanically ventilated buildings, it is the ventilation parameters of the building HVAC system (i.e. flow rates, temperature, velocity, and throw) that are input into the model.

For naturally ventilated buildings, the ventilation parameters are largely due to pressure and temperature gradients, and these depend on:

- building shape and size
- size, location and orientation of openings
- configuration of surrounding buildings and topography
- local wind speed and direction
- indoor and outdoor temperatures
- relative humidity.

5.6.9 Local and general exhaust

Local and general exhaust streams are typically modelled using a fractional term to simulate their effectiveness at removing the targeted air contaminant.

5.6.10 Air cleaning devices

Air cleaning devices are generally modelled based on their efficiency, their effectiveness and the rate of air flow passing through them. Devices can be once through or recirculating, full flow or side stream, and many devices need to include bypass factors.

Ongoing maintenance of air cleaning devices is essential for their continued effectiveness. The actual rated efficiency at the applied air flow is generally available from the manufacturer of the device.

5.6.11 Complexities of simulation

The starting point in developing and using an indoor air contaminant model is usually a statement of the mass balance concerning the pollutant of interest and the ventilation system arrangements. Solutions to mass-balance equations invariably contain parameters that must be evaluated independently.

Geometric parameters, such as definitions of volumes and surface areas, can be measured directly, obtained from building plans or transferred electronically from BIM. Accurate values of the ventilation parameters are usually more difficult to determine.

The most difficult parameters to evaluate and define for the model are usually those associated with the rate at which the air contaminant is being released or being removed (i.e. the strengths of the contaminant sources and sinks). Simulating ventilation air flows and indoor air contaminant concentrations within buildings has many complexities including the following.

- **Multi-compartment models** - Widely used compartmental IAQ models are broadly classified into 2 categories, single compartment and multi compartment. Analysing multiple individual compartments in a building all served by a single ventilation system can result in a complex interlinking of, and interaction between, multiple compartments with differing air contaminant profiles.
- **Models for sinks** - For some buildings and systems, sinks have to be incorporated into the model to account for the action of adsorptive and absorptive surfaces and materials, reactive gases, and any contaminants removed by air cleaners and the like. Models for the adsorption of air contaminants and re-emission later are complex to develop and verify experimentally.
- **Models for sources** - Models to simulate contaminant sources with different or varying rates of contaminant releases, e.g. instant, exponential decay, constant, need to be developed. Source models need to be developed for every source of every air contaminant under investigation.
- **Modelling air mixing** - When the air in the room is not well mixed, the dilution by ventilation air is not necessarily uniform because the rates of dilution are not the same in all parts of the room. A portion of the ventilation air stream often tends to bypass some parts of the room. For instance, when both the inlet and exhaust ducts are on the ceiling, the lower half of the room (and especially the corners) tend to be bypassed and the air in these areas is diluted more slowly than predicted. A mixing or VE factor (a multiplier for the ventilation rate usually ranging in value between 1.4 and 0.6) can be used to account for mixing rates that are lower than would exist if the room air were continually well mixed (see 4.3.6).
- **Simulating laminar and turbulent flows** - Most applications of CFD for room air flow and heat transfer simulation have employed the K-epsilon (k-ε) turbulence model which was originally developed for high-Reynolds number (i.e. fully turbulent) flows. More research

and development work is needed, particularly in the areas of more efficient computational schemes, irregular and adaptive grids, turbulence modelling and wall functions.

There are some models available that employ the use of low Mach number approximations and turbulence models for sub-grid scale (SGS). SGS modelling is used to represent the effects of unresolved small-scale fluid motions (small eddies, swirls, vortices) in the equations governing the large-scale motions that are resolved in computer models computations. These methods have been compared with full-scale experiments with acceptable accuracy.

Many of these complexities are simplified when powerful software-based analytical tools and simulation platforms are used in the air contaminant analysis.

5.7 IAQ modelling software tools and platforms

Air contaminant concentrations within a space can be manually calculated from the space air volume, dilution air flow rate, and the air contaminant generation and removal rates within the space. As designers consider calculating the concentration of multiple contaminants in multiple compartments over a protracted time span then manual calculations become complex and time consuming. Computer modelling and simulation tools and platforms can significantly reduce the time and complexity of the analysis.

IAQ models are developed to aid in understanding and predicting indoor air contaminant concentrations and dosages as functions of outdoor air-contaminant concentrations, indoor-outdoor air-exchange rates, and indoor air contaminant sources and sinks. Modelling IAQ can be undertaken for hypothetical situations and so can be used to find solutions and explore the effectiveness of various mitigation options in the design phase of a building. Modelling can also assess temporal and spatial variation in concentrations.

In the absence of measurements, the accuracy of the model output for a particular application is inherently unknown. For the modelling of outdoor air contaminants, well known models have been validated independently, and their performance is understood. For IAQ models, 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.

5.7.1 Modelling software

There are several software programs readily available to simplify the process, including freeware and proprietary software.

In many computer software programs ventilation and airflow models (for describing natural, mechanical, infiltration or exfiltration airflows) are combined with a separate set of air contaminant models, detailing:

- temporal and spatial variations of the indoor sources and sinks
- physio-chemical transformations
- indoor activities and background concentration of contaminants in outdoor air.

These models are then combined to predict the indoor pollutant concentrations in ventilated buildings.

These programs and tools can combine microscopic and macroscopic simulation techniques for multiple air contaminants within single and multiple compartments or zones to build a complete ventilation, air contaminant and IAQ model for the building in operation.

Appendix D provides a non-exhaustive list of some software tools available to designers intending to model air contaminant transport in buildings and air contaminant concentrations in occupied zones.

5.7.2 Interpretation and graphical visualisation of results

The results and outputs of the simulation are generally provided through a graphical user interface (GUI) program. This interface typically provides a dynamic visualisation and analysis of the air transport calculations and resulting air contaminant concentration levels.

All models and resulting simulations should be the subject of sensitivity analysis and independent peer review (see Appendix D).

5.7.3 Validating IAQ models

IAQ models can be validated in accordance with ASTM D 5157, a guideline that provides quantitative and qualitative tools for evaluation of IAQ models (ASTM 2019). These tools include methods for assessing the overall model performance as well as identifying specific areas of deficiency. Tools include statistical formulae for assessing the general agreement between predicted and measured values, as well as values for various statistical indicators that can be used when judging model performance.

5.8 Monitoring air contaminant levels

5.8.1 Monitoring

A performance-based approach to the management of ventilation and IAQ may include a proactive monitoring program to inspect, analyse and evaluate the performance of the building ventilation system on a regular basis.

Measurements are used to verify the operational performance of the system and the results of these measurements are monitored and recorded to provide assurance that the system is operating as designed. Measuring performance is also important for system commissioning, system diagnostic analysis, design evaluation and ongoing research and development.

The key to any monitoring system is to establish a baseline datum from which to compare ongoing operation and performance. Baseline data is generally based on the commissioning data which is itself derived from the system design and installation documentation.

Monitoring instruments can include advanced useful features such as an internal data logger and alarm relay outputs which inform when exceedances are reached.

5.8.2 Personal monitors

Miniaturised air samplers are available that collect gaseous and particulate samples from the immediate vicinity of people, even as they conduct their normal activities. They all use sensitive chemical or physical analytic methods.

These sometimes wearable devices can be battery-powered non-passive samplers or be diffusion- and permeation-controlled passive samplers. Passive devices are smaller and lighter and generally only applicable for gas or vapour sampling.

Alternatively, sensors can be fixed wall or desk mounted devices monitoring a range of IAQ/IEQ parameters and providing data feedback to central control and visualisation systems, generally wirelessly.

5.8.3 Remote monitors

Sampling and monitoring equipment can be placed in remote locations outside the space being evaluated and draw air-sample streams to them.

5.8.4 Monitoring ventilation rates

Ventilation systems for buildings can vary considerably. Residential and small commercial buildings are often naturally ventilated. Naturally ventilated spaces are primarily ventilated by the controlled opening of windows and doors and the uncontrolled infiltration of outdoor air and exfiltration of indoor air through cracks in the building envelope (i.e. gaps around doors and windows, wall and floor joints, etc.).

Measurement of the natural ventilation and infiltration/exfiltration rates, and the meteorologic factors that affect them (outdoor temperature, relative humidity, wind speed, and wind direction), can be an integral part of fixed-location field monitoring.

Larger commercial buildings are often ventilated by mechanical systems. Mechanical ventilation systems vary considerably in design and complexity. The methods chosen to measure ventilation rates should be suitable for the systems under consideration. The methods commonly used to determine the ventilation rate for mechanical systems include:

- pressure-measuring devices (such as inclined manometers and U-tubes)
- velocity meters (such as pitot tubes, hot-wire flowmeters, heated-thermistor flowmeters and heated-thermocouple flowmeters)
- mechanical gas-flow indicators (such as rotating and deflecting-vane anemometers)
- tracer-gas techniques
- heat-balance techniques.

5.8.5 NABERS IE sampling and measurement protocols

The NABERS[8] Indoor Environment (IE) for offices rating is calculated by comparing the performance of the IEQ of a building or tenancy (or both) against other office buildings using benchmarks of performance. The IEQ of a building is assessed against up to 5 different parameters, one of which is IAQ (DPIE 2021).

The NABERS IE assessment of IAQ utilises a range of quantitative measurements taken on-site. These include measurements to quantify:

- VE (measuring carbon dioxide)
- particulate matter measuring PM_{10}
- formaldehyde (handheld or laboratory analysis)
- total volatile organic compounds (handheld or laboratory analysis)
- carbon monoxide (measured at outdoor air intake).

The base building assessment includes on-site measurements of carbon dioxide, carbon monoxide, and PM_{10}. Whereas whole building assessments includes additional measurements for TVOCs and formaldehyde. Carbon monoxide measurement is not required for tenancy assessments.

NABERS uses carbon dioxide as a proxy to measure the VE based on AS 1668.2, where the minimum ventilation rate should be no less than 10 L/s per occupant. Under NABERS this equates to a difference between measured indoor and outdoor carbon dioxide that is less than 400 ppm. That is, if outdoor levels of carbon dioxide are found to be 350 ppm, then indoor levels must remain below 750 ppm. Scores are determined based on the percentage of locations at which these conditions are met.

The protocols and instruments used and the NABERS specification could potentially be used to develop an air sampling and monitoring methodology to prove the criteria in the IAQ Verification Method have been met.

[8] National Australian Built Environment Rating System

5.8.6 Real time IAQ monitoring and certification

Continuous monitoring can be combined with independent verification of IAQ data to provide third party certification of IAQ.

For example the free and publicly available RESET Air Standard defines requirements for collecting IAQ data via continuous electronic monitoring of an interior space or building. IAQ parameters are continuously recorded in the cloud where data analysis algorithms compile daily averages calculated from hours of occupancy and compares them against IAQ limits. To achieve certification to a particular IAQ standard, air contaminants and other conditions must be maintained within the limits specified in the standard.

5.9 Testing air contaminant concentration levels

5.9.1 Measurement options

There are 2 basic options used to measure airborne contaminants:

- **Air sampling over time** – where materials are collected (typically on a filter or other medium) and subsequently analysed in an environmental laboratory located away from the sampling location.
- **Measurements using real-time instruments** – where measurements are made, and results obtained on-site. Photometers, optical particle counters and condensation particle counters can be used for real-time measurements. The specific instrument of choice depends on the application and the desired results.

5.9.2 Sampling options

Sampling techniques fall into the following 3 broad categories.

- **Continuous sampling** - real-time instantaneous sampling results allowing observation of fluctuations in concentration over specified periods.
- **Integrated sampling** - an average sampling result over a specified period providing a mean concentration of the air contaminant.
- **Spot sampling** - a single sample taken at specified intervals; suitable when knowledge of air contaminant concentration variation over short periods is not important.

Spot sampling typically consists of admitting an air sample into a previously evacuated vessel, drawing a sample into a deflated bag for later analysis, or drawing a sample through a sample collector to extract (and quantify) a contaminant from the air.

ISO 16000.1 is intended to aid the planning of indoor air contaminant monitoring (ISO 2004). The sampling strategy for indoor air monitoring should clarify for what purposes, when, where, how often and over what periods of time monitoring is to be performed. These should be consistent with the concentration limits and exposures listed in the IAQ Verification Method. ISO 16000.1 deals with these factors and offers suggestions on how to develop a suitable sampling strategy.

5.9.3 Measuring contaminant levels

Measurements should be taken using hand-held equipment or using the laboratory analytical methods as outlined in Appendix C.

Handheld instruments such as real-time organic gas (carbon monoxide, carbon dioxide, nitrogen dioxide) infrared analysers with output logged over time are generally suitable measuring devices.

The main instruments and methods of measuring particulate concentration are based on either gravimetric, optical, or microbalance principles. The main methods of measuring particulate size distribution are scanning mobility particle sizer and electrical low-pressure impactor.

Appendices

Appendix A Abbreviations

The following table, Table A.1 contains abbreviations and chemical formulas used in this handbook. Table A.2 contains symbols and units used in this handbook.

Table A.1 Abbreviations and chemical formulas

Abbreviation/chemical formula	Meaning
AAQ	Ambient Air Quality
ABCB	Australian Building Codes Board
ACE	Air change effectiveness
ADR	Australian Design Rules
AG	Australian Government
AHU	Air handling unit
AIRAH	Australian Institute of Refrigeration, Air conditioning and Heating
AS	Australian Standard
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEES	Building for environmental and economic sustainability
BIM	Building information models
BPL	Building product library
CADR	Clean air delivery rate
CFD	Computational Fluid Dynamics
CO	Carbon monoxide
CO_2	Carbon dioxide
COHb	blood carboxyhaemoglobin
COVID-19	Coronavirus disease 2019
CH_2O	Formaldehyde
CHPS	Collaborative for high performing schools
CML	Chemical and material library
DA	Design application (relates to AIRAH DA manuals)
DTS	Deemed-to-Satisfy

Abbreviation/chemical formula	Meaning
ePM	Particulate matter efficiency
GUI	graphic user interface
GPAC	gas phase air cleaners
HEI	Health Effects Institute
HEPA	High efficiency particulate air
HVAC	Heating, ventilation and air-conditioning
IAQ	Indoor Air Quality
IARC	International Agency for Research on Cancer
IE	Indoor environment
IEQ	Indoor Environment Quality
IGA	Inter-government agreement
ISO	International Standardization Organisation
MERS	middle east respiratory syndrome
MERV	Minimum efficiency reporting values
MSDS	Material safety data sheet
NABERS	National Australian Built Environment Rating System
NATA	National Association of Testing Authorities (Australia)
NCC	National Construction Code (Australia)
NEPC	National Environment Protection Council (Australia)
NEPM	National Environment Protection Measure (Australia)
NHMRC	National Health and Medical Research Council (Australia)
NO_2	Nitrogen dioxide
NO_x	oxides of nitrogen
NZS	New Zealand Standard
O_3	Ozone
O&M	Operating and maintenance
OH&S	Occupational Health and Safety
PCO	Photocatalytic oxidation
PM	Particulate matter

Abbreviation/chemical formula	Meaning
$PM_{2.5}$	Particulate matter less than 2.5 micrometres diameter
PM_{10}	Particulate matter less than 10 micrometres diameter
SARS	severe acute respiratory syndrome
SDS	safety data sheet
SGS	sub-grid scale
SVOC	semi volatile organic compounds
SWA	Safe Work Australia
TVOC	total volatile organic compounds
UV	ultraviolet
UVGI	ultraviolet germicidal irradiation
VE	Ventilation effectiveness
VOCs	Volatile organic compounds
WHO	World Health Organisation
WHS	Workplace Health & Safety

Table A.2 Symbols and units

Symbol	Meaning
°C	degrees Celsius
α	loss parameter (/min)
ϵ	fraction of emissions directly vented or capture efficiency
C_i	indoor air contaminant concentration
C_o	outdoor air contaminant concentration
C_{ss}	steady state concentration of the contaminant (μg/m^3)
G	contaminant emission rate (μg/min)
m^2	square metre
ppm	parts per million
Q	outdoor air supply rate (ventilation) (m^3/min)
S	measure of contaminant source generation within the space
V	room volume (m^3)

Appendix B Compliance with the NCC

B.1 Responsibilities for regulation of building and plumbing in Australia

State and territory governments are responsible for regulation of building, plumbing and development/planning in their respective state or territory.

The NCC is a joint initiative of the Commonwealth and state and territory governments and is produced and maintained by the ABCB on behalf of the Australian Government and each state and territory government. The NCC provides a uniform set of technical provisions for the design and construction of buildings and other structures and plumbing and drainage systems throughout Australia. It allows for variations in climate and geological or geographic conditions.

The NCC is given legal effect by building and plumbing regulatory legislation in each state and territory. This legislation consists of an Act of Parliament and subordinate legislation (e.g. Building Regulations) which empowers the regulation of certain aspects of buildings and structures and contains the administrative provisions necessary to give effect to the legislation.

Each state and territory adopts the NCC subject to the variation or deletion of some of its provisions, or the addition of extra provisions. These variations, deletions and additions are generally signposted within the relevant section of the NCC and located within appendices to the NCC. Notwithstanding this, any provision of the NCC may be overridden by, or subject to, state or territory legislation. The NCC must therefore be read in conjunction with that legislation.

B.2 Demonstrating compliance with the NCC

Compliance with the NCC is achieved by complying with the NCC Governing Requirements and relevant Performance Requirements.

The Governing Requirements are a set of governing rules outlining how the NCC must be used and the process that must be followed.

The Performance Requirements prescribe the minimum necessary requirements for buildings, building elements, and plumbing and drainage systems. They must be met to demonstrate compliance with the NCC.

There are 3 options available to demonstrate compliance with the Performance Requirements. These are:

- a Performance Solution
- a DTS Solution, or

- a combination of a Performance Solution and a DTS Solution.

All compliance options must be assessed using one or a combination of Assessment Methods, as appropriate. These include:

- Evidence of suitability
- Expert Judgement
- Verification Methods
- Comparison with DTS Provisions.

A figure showing hierarchy of the NCC, and its compliance options is provided in Figure B.1. It should be read in conjunction with the NCC.

To access the NCC or for further general information regarding demonstrating compliance with the NCC visit the ABCB website.

Figure B.1 Demonstrating compliance with the NCC

Appendix C Data sources for low-emission materials

C.1 Introduction

This Appendix provides a list of documents, websites and organisations which may be useful sources of additional information on the following topics:

- low-emission materials and products databases
- sources of air contaminant emission data
- a list of online resources for low-emission materials and products
- test methods for quantifying air contaminant emissions.

None of these lists are intended to be exhaustive and are provided for information only.

C.2 Evaluating and selecting low-emission products

Off-gassing of contaminants from materials and products can be minimised by selecting materials that contain smaller amounts of solvents or require less material for application. These low-emission materials, practices or products are well suited for projects targeting indoor air contaminant control.

Traditionally building materials are evaluated and selected based on performance, aesthetics, and cost. When projects focus on air contaminant control, materials selection parameters must be expanded to include an evaluation of their air contaminant emissions profile and potential effect on IAQ. Low-emission materials are products that produce a lesser or reduced amount of air contaminants when compared to competing products that serve the same purpose.

The growing popularity of “green” buildings and “green” building programs, such as the Green Building Council of Australia’s Green Star rating system, PassivHaus, and WELL, has expanded the demand and availability for low-emission building materials and products in Australia and world-wide. For building designers and ventilation engineers these low-emission materials provide greater opportunities to improve the air quality of building projects.

Assessing the emissions of materials is a complex process, which can be further confounded by varying and sometimes contradicting claims from product manufacturers. However, there are product resources and tools available to help designers make appropriate, informed materials evaluations and selections.

C.2.1 Emissions from materials

Certain types of building materials and internal finishes have historically been prone to emitting VOCs and other air contaminants. Manufacturers now communicate more about the presence of VOCs in products like paints, adhesives, carpets and composite wood products. For many of these products (e.g. carpet) materials and manufacturing processes have been changed to create low-emission products.

Low-emission products promote good indoor air quality, typically through reduced emissions of VOCs or formaldehyde. Examples of building materials that can come in low VOC-emission formats include, solvents, paints, adhesives, carpeting, and particleboard. Low-emission products should also be fit-for-purpose, durable, and have low maintenance requirements. They should not contain any highly toxic compounds or ozone depleting substances

The characteristics of low-emission products can vary significantly depending on the material type. The evaluation of low-emission products requires a working knowledge of:

- the health and environmental impact issues associated with different air contaminant emissions from different material types
- government, industry, and third-party standards for low-emission green products
- available low-emission products in the marketplace, including their performance characteristics, appearance, and costs.

Information on the air contaminant emissions of materials and products is available from a range of sources including:

- safety data sheets
- third party certification schemes
- green product standards
- green product directories.

C.2.2 Safety data sheet

WHS/OH&S regulations require manufacturers and suppliers of products containing hazardous chemicals to provide an SDS/MSDS (see 4.3.1).

SDSs contain information regarding potentially significant levels of airborne contaminants, storage and handling precautions, health effects, odour description, volatility, expected products of combustion, reactivity, and procedures for spill clean-up.

C.2.3 Third-party certification

Users should be wary of environmental claims (both positive and negative) that have not been substantiated by independent sources

Third-party certification is the certification of a specific product or process that is performed by an organisation independent from manufacturers or suppliers of the product or process. Certification is often used to substantiate the environmental attributes of a specific product, such as the VOC emissions.

C.2.4 Green product standards

To consistently assure the environmental performance (including air contaminant emissions) of certain material types, several public agencies and private organizations have developed green product standards. These standards define specific criteria for various material types, and many include the assessment and rating of the type and level of air contaminants that are emitted from a product. In some cases, a trademarked "green" label or tag can be used for complying products.

Green product standards can range from government regulations and guidelines to industry guidelines (e.g. the Carpet Institute of Australia's Environmental Certification Scheme for carpets), to third party certification standards (e.g. Green Seal standards for paints).

C.2.5 Green product directories

Typically hosted on a website, information is used to profile individual products from specific manufacturers. Green product directories provide listings of available products with the environmental attributes claimed by the manufacturers.

Examples include:

- Green Building Products (greenfinder.com.au)
- GreenSpec - Green Building Design, Products and Materials in the UK
- Green Product Directory – Build It Green.

C.3 Online resources

There are a range of organisations that have developed assessment, testing and certification systems for low-emission materials, often as part of a broader environmental or sustainability assessment. The following websites provide a range of resources to enable the selection of low-emission materials.

BEES[9] Online implements a powerful technique for selecting cost-effective, environmentally-preferable building products, developed by the National Institute of Standards and Technology (NIST) Engineering Laboratory. The NIST website contains further information on BEES.

[9] Building for environmental and economic sustainability

The Cradle to Cradle Products Innovation Institute, administers the publicly available Cradle to Cradle Certified™ Product Standard which provides designers and manufacturers with criteria and requirements for continually improving what products are made of and how they are made. The mark provides consumers, regulators, employees, and industry peers with a clear, visible, and tangible validation of a manufacturer's ongoing commitment to sustainability. There are courses for architects, designers and students to help shift mindsets and strengthen professional credibility and distinction available on the Institute's website.

The Collaborative for High Performing Schools (CHPS) website offers a searchable high performance building product database, in partnership with the US Environmental Protection Agency and Californian Department of Resources Recycling and Recovery. The database includes the CHPS low-emitting materials list, other environmental attributes, and life cycle and multiple attribute claims.

Under the Carpet Institute of Australia's Environmental Certification Scheme for carpets, manufacturers must comply with the Code of Practice for Environmental Management which provides performance standards for raw materials, carpet manufacturing, in-service use and final disposal. The scheme has 4 levels of certification with incrementally more demanding performance criteria. ECS Level 4 is the top grading.

The Declare Database developed by the International Living Future Institute lists building products whose ingredients have been fully disclosed and vetted against the organisation's Red List of the "worst in class" toxic chemicals pervasive in the environment.

UL ECOLOGO certification is based on multi-attribute, life-cycle-based sustainability standards. All products certified to an ECOLOGO Standard must meet or exceed each of the listed criteria before receiving the Mark. ECOLOGO Certification is classified as ISO Type 1 ecolabel and has been successfully assessed by the Global Ecolabeling Network, further demonstrating its credibility.

Global GreenTag certified products pass the world's toughest standards for health, eco performance and safety. Recognised by major green rating schemes, GreenTag is a one-stop certification to choose or evidence product selections.

The GreenGuard Certification Program recognises building materials, finishes, interior furnishings, furniture cleaning products, and electronic equipment with low chemical and particle emissions. Its database of more than 130,000 certified products has been integrated into Underwriters Laboratories Sustainable Product Database.

Green Label Plus is an independent testing program that identifies carpet, adhesives, and cushions with very low emissions of VOCs to help improve indoor air quality. It is an outgrowth of, and enhancement to the Carpet and Rug Institute Green Label Testing program.

Green Seal offers third-party certification based on leadership sustainability standards that help protect the natural world and human health. The Green Seal standards consider the total environmental impact of a product and reduce that impact while maintaining the same performance and quality you would expect.

Paint products bearing the Green Wise label have been tested and certified by Coatings Research Group Incorporated (CRGI) to meet environmentally determined performance standards established by CRGI's ISO-accredited facility for specific product types and to meet or exceed specified VOC limits.

Indoor airPLUS is a voluntary partnership and labelling program that helps new home builders improve the quality of indoor air by requiring construction practices and product specifications that minimize exposure to airborne pollutants and contaminants.

The Pharos Project evaluates building products and components, profiles chemicals and materials for health and environmental hazards and rates product certifications and standards.

The Pharos website contains a range of resources including the following.

- The Pharos Building Product Library (BPL) combines manufacturer transparency and independent research to provide in-depth health and environmental information about a wide range of building products.
- The Pharos Chemical and Material Library (CML) is an online catalogue of chemicals, polymers, metals, and other substances. It identifies key health and environmental information, restricted substance lists, and characterizes the process chemistry used to produce substances.
- The Pharos Certifications and Standards Library provides information on certifications and standards used to measure the environmental and health impacts of building materials, including VOC content and emissions.

The CompAIR volatile ingredients calculator helps users identify building products that release less chemicals into the air. Since some VOCs are hazardous, selecting products with lower or no Volatile Ingredients can help avoid damaging worker and occupant health.

The Quartz Project is an open data initiative that promotes the transparency of building products. The goal is to drive market transformation towards less toxic, lower-impact materials for better buildings and healthier communities.

C.4 Making material selections

Given the many tools and resources available for evaluating and identifying low-emission materials, it is useful to develop an organised process for making product selections. Selecting low-emission materials requires research, critical evaluation, and common sense. Specifiers are advised to collect the following information when preparing to evaluate low-emission materials.

- Critical performance criteria required of the material to be selected.

- Appropriate product emission information, including the test method used and any certification.
- MSDSs for the products.
- Maintenance expectations for the material or system.

Building products that may contain VOCs include floor coverings, underlays and adhesives, paints and other finish coatings, sealants, adhesives, and products that use adhesives extensively, such as furniture and other composite wood products. For machine made carpet, VOCs are relatively low and decay quickly because most of the volatiles are 'driven off' in when the finished carpet passes through the curing oven.

C.5 Specification guidelines

Once a low-emission material has been evaluated and selected for a project, it is important to include clear and binding specification language in the construction documents.

C.6 Test methods for quantifying air contaminant emissions

C.6.1 Test methods for office equipment

For office equipment the air contaminants tested can include NCC nominated indoor pollutants TVOC, ozone and particulate. Compliance is demonstrated by the provision of test certificates for equipment. Certificates should be issued by NATA[10] or ISO/IEC 17025 accredited laboratories.

- ISO/IEC 28360-1:2021 - Information technology — Determination of chemical emission rates from electronic equipment — Part 1: Using consumables.
- ECMA-328 2013 Determination of Chemical Emission Rates from Electronic Equipment.
- RAL UZ 171:2012 Basic Criteria for Award of The Environmental Label - Office Equipment with Printing Functions (Printers, Copiers, Multifunction Devices).
- UL 2823 GREENGUARD Test Method for Electronic Equipment.

C.6.2 Test methods for materials emissions

Emissions rating for construction products require chemical emissions from representative samples to be tested under simulated real-world conditions. Tests are performed by accredited laboratory facilities to accepted published standards. Certificates should be issued by NATA ISO

[10] National Association of Testing Authorities

17025 accredited laboratories. The air contaminants tested can include the NCC nominated indoor pollutants; formaldehyde and TVOCs.

VOCs are emitted from products throughout their lifetime. Rate of emission testing involves testing the product in a specified chamber, and measuring the emissions released during a specified period.

Standardised test methods are available for textiles and floor coverings, paints and varnishes, and engineered wood products. Engineered wood products include particleboard, plywood, medium density fibreboard, laminated veneer lumber, high-pressure laminate, compact laminate and decorative overlaid wood panels. The following is a list of some of the common test methods used:

- AS/NZS[11] 2098.11 Methods of test for veneer and plywood Method 11: Determination of formaldehyde emissions for plywood.
- AS/NZS 4266.16 Reconstituted wood-based panels - Methods of test - Formaldehyde emission - Desiccator method.
- AS/NZS 4357.4 Structural laminated veneer lumber - Determination of formaldehyde emissions.
- ASTM D3960 Standard Practice for Determining Volatile Organic Compound (VOC) Content of Paints and Related Coatings.
- ASTM D5116 Standard guide for small-scale environmental chamber determinations of organic emissions from indoor materials/products.
- ASTM D5197 Standard Test Method for Determination of Formaldehyde and Other Carbonyl Compounds in Air (Active Sampler Methodology.)
- ASTM D6007 Standard Test Method for Determining Formaldehyde Concentrations in Air from Wood Products Using a Small-Scale Chamber.
- ASTM D6196 Standard Practice for Choosing Sorbents, Sampling Parameters and Thermal Desorption Analytical Conditions for Monitoring Volatile Organic Chemicals in Air.
- ASTM D6803 Standard Practice for Testing and Sampling of Volatile Organic Compounds (Including Carbonyl Compounds) Emitted from Paint Using Small Environmental Chambers.
- ASTM D7339 Standard Test Method for Determination of Volatile Organic Compounds Emitted from Carpet using a Specific Sorbent Tube and Thermal Desorption/Gas Chromatography
- ASTM D7706 Standard Practice for Rapid Screening of VOC Emissions from Products using Micro-Scale Chambers.

[11] New Zealand Standard

- ASTM E1333 Standard Test Method for Determining Formaldehyde Concentrations in Air and Emission Rates from Wood Products Using a Large Chamber.
- EN 717-1:2004 Wood-based panels. Determination of formaldehyde release. Formaldehyde emission by the chamber method.
- ISO 10580 Resilient, textile and laminate floor coverings - Test method for volatile organic compound (VOC) emissions.
- ISO 11890-1 Paints and varnishes - Determination of volatile organic compounds (VOC) and/or semi volatile organic compounds (SVOC) content – Part 1: Difference method.
- ISO 11890-2 Paints and varnishes - Determination of volatile organic compounds (VOC) and/or semi volatile organic compounds (SVOC) content – Part 2: Gas-chromatographic method.
- ISO 12460-1 Wood-based panels — Determination of formaldehyde release — Part 1: Formaldehyde emission by the 1-cubic-metre chamber method
- ISO 12460-2 Wood-based panels — Determination of formaldehyde release — Part 2: Small-scale chamber method
- ISO 12460-3 Wood-based panels — Determination of formaldehyde release — Part 3: Gas analysis method
- ISO 16000-2 Indoor air — Part 2: Sampling strategy for formaldehyde
- ISO 16000-3 Indoor air – Part 3: Determination of formaldehyde and other carbonyl compounds in indoor air and test chamber air – Active sampling method.
- ISO 16000-4 Indoor air — Part 4: Determination of formaldehyde — Diffusive sampling method
- ISO 16000-6 Indoor air – Part 6: Determination of VOCs in indoor and test chamber air by active sampling on Tenax TA sorbent, thermal desorption and gas chromatography using MS/FID.
- ISO 16000-8 Indoor air — Part 8: Determination of local mean ages of air in buildings for characterizing ventilation conditions
- ISO 16000-9 Indoor air – Part 9: Determination of the emission of volatile organic compounds from building products and furnishing – Emission test chamber method.
- ISO 16000-10 Indoor air – Part 10: Determination of the emission of volatile organic compounds from building products and furnishing – Emission test cell method.
- ISO 16000-11 Indoor air – Part 11: Determination of the emission of volatile organic compounds from building products and furnishing – Sampling, storage of samples and preparation of test specimens.

- ISO 16000-25 Determination of the emission of semi-volatile organic compounds by building products – Micro-chamber method.
- ISO/IEC 17025 General requirements for the competence of testing and calibration laboratories)
- ISO 17895 Paints and varnishes - Determination of the volatile organic compound content of low-VOC emulsion paints (in-can VOC).
- EN 16516 Construction products - Assessment of release of dangerous substances - Determination of emissions into indoor air.

C.6.3 Test methods for outdoor air contaminants

The following test methods can be applied to outdoor air testing:

- AS 3580.5.1 Methods for sampling and analysis of ambient air – Determination of Oxides of Nitrogen – Direct Reading Instrument Method
- AS 3580.6.1 Methods for sampling and analysis of ambient air – Determination of Ozone – Direct Reading Instrument Method.
- AS 3580.7.1 Methods for sampling and analysis of ambient air – Determination of Carbon Monoxide – Direct Reading Instrument Method.
- AS 3580.9.8 Methods for sampling and analysis of ambient air – Determination of Suspended Particulate Matter – PM_{10} continuous direct mass method using a tapered element oscillating microbalance.
- AS/NZS 3580.9.10 Methods for sampling and analysis of ambient air – Determination of Suspended Particulate Matter – $PM_{2.5}$ low volume sampler – Gravimetric method.
- AS/NZS 3580.9.12 Methods for sampling and analysis of ambient air – Determination of Suspended Particulate Matter - $PM_{2.5}$ beta attenuation monitors.

Appendix D IAQ models and simulation software

D.1 Simulation software for air contaminant concentrations

Air contaminant concentrations in a ventilated space can be manually calculated from the space air volume, the ventilation air flow rate, and the contaminant generation rates within the space. Manual calculations can be laborious and complex, and the calculation process is simplified with the use of computer software or modelling platforms.

There are several software programs readily available to simplify the process. This Appendix contains several non-exhaustive lists outlining some of the tools available to the designer. None of these lists are intended to be exhaustive and all are provided for information only.

D.1.1 CONTAM

CONTAM is a multizone indoor air quality and ventilation analysis computer program provided by the NIST. The computer software is designed to help designers determine the following factors.

- **Airflows**: Infiltration, exfiltration, and room-to-room airflows in building systems driven by mechanical means, wind pressures acting on the exterior of the building, and buoyancy effects induced by the indoor and outdoor air temperature difference.
- **Contaminant Concentrations**: the dispersal of airborne contaminants transported by these airflows; transformed by a variety of processes including chemical and radio-chemical transformation, adsorption and desorption to building materials, filtration, and deposition to building surfaces, etc.; and generated by a variety of source mechanisms.
- **Personal Exposure**: the predictions of exposure of occupants to airborne contaminants for eventual risk assessment.

CONTAM can be useful in a variety of applications. Its ability to calculate building airflows is useful to assess the adequacy of ventilation rates in a building, to determine the variation in ventilation rates over time and the distribution of ventilation air within a building, and to estimate the impact of envelope air tightening efforts on infiltration rates.

The prediction of contaminant concentrations can be used to determine the indoor air quality performance of a building before it is constructed and occupied, to investigate the impacts of various design decisions related to ventilation system design and building material selection, and to assess the indoor air quality performance of an existing building. Predicted contaminant concentrations can also be used to estimate personal exposure based on occupancy patterns in the building being studied. Exposure estimates can be compared for different assumptions of ventilation rates and source strengths.

CONTAM is distributed as free software by NIST.

D.1.2 CONTAM Model/TRNSYS Simulation

In order to better address the interdependencies and the interactions between heat transfer, inter-zone airflow and indoor contaminant transport the NIST has developed an updated version of the multi-zone airflow and contaminant transport modelling tool, CONTAM, along with a set of utilities to enable coupling of the full CONTAM model with the TRNSYS simulation tool in a more seamless manner and with additional capabilities that were previously not available.

This coupled simulation capability enables users to apply the tool to couple CONTAM with existing energy analysis software to address the interaction between indoor air quality considerations and energy conservation measures in building design and analysis.

D.1.3 CHAMPS-Multizone

CHAMPS-Multizone (CHAMPS-MZ) is a simulation program for whole building combined heat, air, moisture, and pollutant simulation.

It is a software tool for free non-commercial use developed through a joint effort between Syracuse University (USA) and University of Technology Dresden (Germany). Its user community includes research institutes and consulting companies. The program is used for analysis and prediction of:

- combined building energy, moisture, and pollutants simulation in building zonal scale
- impact of outdoor climate and pollution on indoor environment and its energy consumption penalty
- building design parameters studies to assist and optimize building design process through building performance-based simulation.

The CHAMPS-MZ software has a solar radiation model, building envelope model, airflow network model, and zone and HVAC model to predict the combined energy and IAQ performances of a whole building. A GUI is included for users to input the design or control parameters.

D.1.4 IA-QUEST

IA-QUEST is both a database of material emission test results and an indoor air quality simulation program, provided by the National Research Council of Canada.

The database component provides information on the emission of specified VOCs and TVOC from common (Canadian) building materials. The simulation component calculates the concentrations of contaminants that would occur in a room with known ventilation rate and schedule due to emissions from materials contained within that space. The calculation of concentrations assumes a simple single-zone perfect mixing model. The emission characteristics of materials are obtained from the database packaged within the program.

Users need to input the following information to estimate indoor air concentrations of air contaminants arising from single or multiple building materials:

- volume of the space
- ventilation rate and schedule
- for each material (selected from database):
    - exposed/emitting surface area
    - entry and removal times to/from the space.
- the period of the simulation.

IA-Quest is distributed as free software by NRC.

D.1.5 I-BEAM

The I-BEAM or Indoor Air Quality Building Education and Assessment Model is a guidance tool produced by the USA Environmental Protection Agency. It is primarily designed for use by building professionals and others interested in indoor air quality in commercial buildings. I-BEAM updates and expands EPA's Building Air Quality guidance and is designed to provide comprehensive guidance for managing IAQ in commercial buildings.

I-BEAM consists of many individual modules which explain different aspects of IAQ including:

- conducting an indoor air quality building audit
- diagnosing and resolving IAQ related health problems
- establishing an IAQ management and maintenance program to reduce IAQ risks
- planning IAQ compatible energy projects
- protecting occupants from exposures to construction/renovation contaminants
- calculating the cost, revenue and productivity impacts of planned IAQ activities.

D.1.6 IAQ Tools

IAQ Tools is a proprietary software program that solves problems concerning a wide variety of airborne contaminants, ventilation design, filter design and selection, design for contaminant source control, tracer gas calculations, and air quality unit conversions. IAQ Tools has a variety of flexible calculation options that solve for ventilation rates, contaminant concentrations, or contaminant generation rates (steady state model).

IAQ Tools performs calculations for more than 30 different contaminants, including a wide variety of gases, airborne solid contaminants, bio-aerosols, and tracer gases.

D.1.7 TRNFlow

TRNSYS thermal multi-zone building models requires air flows between zones as input values. In natural ventilation systems these depend on the wind pressures and the inside and outside temperatures. To account for this situation TRNFlow – AIRFLOW SIMULATION IN BUILDINGS integrates the multi-zone air flow model COMIS into the TRNSYS thermal multizone building model. TRNFlow includes calculation of the air exchange considering window ventilation, infiltration/exfiltration, and airflow between rooms, mechanical outdoor and exhaust air, and multizone fluid simulation accounting for wind pressures, temperature differences and mechanical ventilation forces. The data for the air flow model is entered using the existing TRNBuild GUI.

D.1.8 DesignBuilder

DesignBuilder provides advanced modelling tools in an easy-to-use interface. This enables the whole design team to use the same software to develop comfortable and energy-efficient building designs from concept through to completion. In EnergyPlus the HVAC and building 3D models are simulated simultaneously to ensure the dynamic interaction between the building and systems is treated accurately.

D.1.9 Simulation Tool Kit for Indoor Air Quality and Inhalation Exposure (IAQX)

Researchers at EPA have developed indoor air modelling programs to assist with understanding indoor air pollution. They include:

- Simulation Tool Kit for Indoor Air Quality and Inhalation Exposure (IAQX)
- Indoor Semi-volatile Organic Compounds (i-SVOC)
- Parameters (PARAMS) Program Version 1.1 for indoor emission source modelling.

PARAMS implements 30 methods for estimating the parameters in indoor emissions source models, which are an essential component of indoor air quality and exposure models. IAQX and i-SVOC are used for dynamic modelling of the emissions, transport, and absorption of pollutants in the indoor environment.

D.1.10 Quick Indoor CO2 (QICO2) Tool

This tool is used for implementing the carbon dioxide concentration calculations. After providing the relevant inputs, or selecting from several predefined cases, the QICO2 tool allows the user to estimate indoor carbon dioxide concentrations in a ventilated space at steady-state, 1 h after occupancy and at a selected value of time to metric (tmetric). These calculated concentrations can be compared with measured carbon dioxide concentrations in a building or space to evaluate whether the intended or required ventilation rate is actually being achieved.

D.1.11 BIM Platforms and IAQ

As the complexity, capability and uptake of BIM software platforms continues to expand it is likely that they will include ventilation and IAQ models and simulation capabilities. This is a rapidly developing technical area.

The integration of building design and construction software, with geographic information system (GIS), wireless sensors, building control systems, online real-time data banks and cloud computing technologies offers innovative opportunities for indoor air quality management and real-time monitoring.

D.2 CFD software for air contaminant concentrations

CFD software is a powerful modelling tool that can simulate thermal and pressure gradients and air flows in indoor environments. CFD can quickly solve the mass, momentum, and energy conservation equations and model multi zone areas providing results that are significantly more detailed than those of multi zone mass balance models.

D.2.1 Class 7a Carpark ventilation

While single-zone models may provide the carpark ventilation system designer with general expectations and averages of how a system design may perform based on the net transfer of air contaminants, these models may not always provide the high degree of accuracy required for carpark ventilation system design. Microscopic models (i.e. CFD software) provide an increased degree of accuracy at a scale that can provide the designer with a high level of confidence of the expected performance of the ventilation system design.

There is a wide range of open source and proprietary CFD software programs available to assist in the analysis of ventilation and carbon monoxide transport and dilution within carparks.

D.2.2 ANSYS Fluid®

ANSYS fluids is a product suite for modelling fluid flow and other related physical phenomena. It contains both general purpose CFD software, ANSYS CFX and ANSYS FLUENT, and additional specialised products to address specific applications.

ANSYS CFD provides a tool to assess the levels of thermal comfort for building occupants, by examining parameters such as the air temperature and radiant heat loads, as well as a tool to ensure adequate ACE by solving and assessing the mean age of air. FLUENT is a commercial CFD program developed by Ansys Inc.

D.2.3 FloVENT®

FloVENT software predicts 3D airflow, heat transfer, contamination distribution and comfort indices in and around buildings, and is designed specifically for the design and optimisation of HVAC systems. FloVENT Version 10.1 is the latest version.

D.2.4 OpenFOAM®

OpenFOAM is a free, open source CFD software. OpenFOAM has an extensive range of features to solve anything from complex fluid flows involving chemical reactions, turbulence and heat transfer, to acoustics, solid mechanics and electromagnetics.

D.2.5 PHOENICS®

PHOENICS is a general-purpose software package that predicts quantitatively how fluids (air, water, steam, oil, blood, etc.) flow in and around, the associated changes of chemical and physical composition and the associated stresses in the immersed solids. In architecture, PHOENICS is used to predict the airflow in and around buildings, to improve the architectural design and thermal comfort.

D.2.6 SimScale®

SimScale cloud-based HVAC simulation performs CFD, heat transfer, and thermal analyses for testing and optimising heating and cooling equipment, and HVAC. The SimScale platform enables investigation of several design versions simultaneously.

D.2.7 simFlow®

simFlow CFD Software is a numerical modelling tool that combines a graphical user interface with the open-source OpenFOAM® libraries with functionality to handle phenomena such as compressible and incompressible fluid flow, turbulent flows, heat transfer, including conjugate heat transfer, multiphase flows, cavitation and chemical reactions.

D.2.8 STAR-CCM+®

Simcenter STAR-CCM+ is a CFD program with an entire engineering process for solving problems involving flow (of fluids or solids), heat transfer and stress. It can tackle problems involving multi-physics and complex geometries to help automate simulation workflows and perform iterative design studies with minimal user interaction.

D.2.9 HyperWorks®

HyperWorks provides a full suite of CFD tools for both the expert and novice users, to generate fast and accurate simulations of fluid flow and heat transfer systems from detailed component analysis to full systems performance.

D.3 Vehicle emission models for Class 7a carpark ventilation

There is a wide range of vehicle emission models available to assist in the determination of air contaminant generation rates by different types and sizes of vehicles. New vehicles in Australia must comply with Australian Design Rule 79/02 — Emission Control for Light Vehicles (2005) as amended.

The following provides a summary of some of the models available.

D.3.1 ARTEMIS

The European ARTEMIS (Assessment and Reliability of Transport Emission Models and Inventory Systems) project developed the Common Artemis Driving Cycles (CADC) based on statistical analysis of a large database of European real world driving patterns. Such driving cycles present a real advantage as they are derived from a large database, using a methodology that was widely discussed and approved. The cycles include 3 driving schedules: (1) Urban, (2) Rural Road and (3) Motorway. The Motorway cycle has 2 maximum speed variants.

D.3.2 CUEDC

In Australia, a Composite Urban Emissions Drive Cycle (CUEDC) was developed for light duty petrol vehicles in 2005. This followed the development of CUEDC cycles for diesel vehicles in 1998. The Petrol CUEDC was developed to be representative of “real world” Australian urban driving. There are 6 CUEDC cycles, one for each of the 6 ADR vehicle categories: MC, NA, NB, ME, NC, NCH.

D.3.3 COPERT

D.3.3.1 COPERT 5

COPERT 5 (COmputer Programme to calculate Emissions from Road Transport) is a software tool supported by the European Environment Agency and used world-wide to calculate air pollutant and greenhouse gas emissions from road transport. COPERT 5 uses vehicle population, mileage, speed and other data such as ambient temperature and calculates emissions and energy consumption for a specific country or region. Emission control technologies are included for the vehicle categories; additional user defined technologies can be included. Different methods are used to estimate emissions of the various pollutants. The latest version is COPERT version 5.6.1 (Sep 2022).

D.3.3.2 COPERT Australia

A dedicated Australian version of COPERT was developed to properly reflect the Australian fleet mix, fuel quality and driving characteristics and to provide vehicle emission estimates for the Australian situation. COPERT Australia predicts emissions for 226 individual vehicle categories, which are defined in terms of vehicle type (e.g. small passenger car, large SUV, heavy bus, rigid truck, articulated truck), fuel type (petrol, E10, diesel, LPG, hybrid), and ‘emission control technology level’ or ADRs. The software accounts for various other factors such as driving conditions (average speed), fuel quality, impacts of ageing on emissions (deterioration of engine and catalysts over time) and meteorology (ambient temperature and humidity). The National Pollutant Inventory recommends COPERT Australia for motor vehicle emission inventories and it has been used to estimate motor vehicle emissions for all states and territories in Australia.

D.3.4 HBEFA

The Handbook Emission Factors for Road Transport (HBEFA) provides emission factors for all current vehicle categories (i.e. cars, light duty vehicles, heavy duty vehicles, urban buses, coaches and motorcycles), each divided into different categories, for a wide variety of traffic situations. Emission factors for all regulated and the most important non-regulated pollutants as well as fuel consumption and carbon dioxide are included. The latest version is HBEFA 4.2 (published 2022).

D.3.5 MOVES

The USA EPA’s MOVES (Motor Vehicle Emission Simulator) emission modelling program estimates emissions for mobile sources at the national, county, and project level for criteria air pollutants. MOVES3 is the latest version.

D.3.6 PHEM

PHEM (Passenger Car and Heavy Duty Emission Model) is a vehicle simulation tool capable of simulating vehicle hot and cold emissions for different driving cycles, gear shift strategies, vehicle loadings, road gradients, vehicle characteristics (mass, size, air resistance, etc.). PHEM has been validated by emission measurements both from light and heavy-duty vehicles in the laboratories (chassis and engine test bed) and on the road (with PEMS) and under different test conditions. If fed with a detailed list of vehicle specifications PHEM is capable of modelling emission levels on a large variety of conditions not covered by the available measurements. The model received a major update to version 2.0.0.0 in 2016.

The PHEMlight model is a microscale model for simulating fuel consumption and pollutant emissions from road vehicles.

D.3.7 VECTO

VECTO (Vehicle Energy Consumption Calculation Tool) is a simulation software developed on behalf of the European Commission. The tool calculates energy and fuel consumption as well as CO_2 emissions of heavy commercial vehicles. VECTO is the basis of the EU regulation EU 2017/2400 and serves as a calculation program of the declared consumption values and CO_2 emissions for most heavy-duty vehicles sold from 1.1.2019.

D.3.8 VERSIT+

VERSIT+ is constituted by a suite of models, used to predict emission factors and energy use factors that are representative for vehicle fleets in different countries. Emission factors are differentiated for various vehicle types and traffic situations and consider real-world driving conditions.

D.4 Inputs and assumptions

Building ventilation simulation or IAQ modelling typically uses a computer to solve the relevant science-based mathematical equations, using information and data about the specific design circumstances under analysis. The data is typically selected from defaults within the programming, calculated by internal models and algorithms or input by the simulator.

The main components of the simulation process are:

- the person who describes the problem
- the scientific knowledge that is expressed mathematically
- the computer software (code) which embodies this knowledge and expresses the stated problem in scientific terms
- the computer hardware which performs the calculations dictated by the software
- the person who inspects and interprets the results of the simulation.

As with any calculation, model, analysis or simulation, the accuracy of the data that is output from the analysis is entirely dependent on the accuracy of the data that is input, i.e. bad data in means bad data out.

All inputs and assumptions used in the analysis should be documented for future reference. Some software can check the data input and alert to any potential (out of range) errors before it provides calculations or analysis. Interpretation of results should also be documented, and a sensitivity analysis conducted.

D.5 Sensitivity analysis

Sensitivity analysis is the investigation of the potential changes to, and errors in, the input data and assumptions of any model and the impacts that those changes and errors can have on the conclusions that can be drawn from the results of the simulation.

Sensitivity analysis is performed by carrying out multiple simulation runs while varying specific building, ventilation and contaminant transport model parameters, to determine the effect of those specific changes or actions on air contaminant concentration levels.

The results of the analysis can highlight which air contaminant control parameters are the most important and their effect on ventilation strategies in different applications and conditions can be quantified.

Inputs such as climate conditions, building thermal performance, fabric infiltration, occupation densities and uses, cooling and heating loads, configurations of openings and ducts, and ventilation rates can all be varied to show the effect changes will have on air contaminant concentration levels.

D.6 Procuring simulation services

The lack of regulation in the building simulation industry can make it difficult to engage a quality consultant to complete a simulation task. Common problems clients face include:

- lack of understanding of the type of simulation required
- the outcome needed and the steps necessary to achieve that goal
- poorly defined modelling scope creating difficulty in comparing quotes
- lack of confidence in the skill of the modeller and poor quality of the simulation.

The AIRAH Building Simulation Procurement Guidelines (AIRAH 2014) provides advice for the client, developer, architect, engineer, building owner, facility manager, managing agent, etc. intending to engage a consultant to complete a building simulation, including some guidance on what to look for in a consultant simulator.

Appendix E References and information

E.1 Referenced standards

The following standards are referred to in this handbook.

- AS 1324.2–2003 Air filters for use in general ventilation and airconditioning, Part 2: Methods of test (Standards Australia 2003).
- AS 1668.2–2012 The use of Ventilation and airconditioning in buildings, Part 2: Mechanical ventilation (incorporating amendments 1 and 2) (Standards Australia 2012a).
- AS 1668.4–2012 The use of ventilation and airconditioning in buildings, Part 4: Natural ventilation of Buildings (Standards Australia 2012b).
- ASHRAE 52.2-2017 Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size (ASHRAE 2017).
- ASHRAE 62.1-2022 Ventilation and Acceptable Indoor Air Quality (ASHRAE 2022).
- ASHRAE 145.1-2015 Laboratory Test Method for Assessing the Performance of Gas-Phase Air-Cleaning Systems: Loose Granular Media (ASHRAE 2015a).
- ASHRAE 145.2-2016 Laboratory Test Method for Assessing the Performance of Gas-Phase Air Cleaning Systems: Air Cleaning Devices (ASHRAE 2016).
- ASHRAE 185.1-2015 Method of Testing UV-C Lights for Use in Air-Handling Units or Air Ducts to Inactivate Airborne Microorganisms (ASHRAE 2015b).
- ASHRAE 185.2-2014 Method of Testing Ultraviolet Lamps for Use in HVAC&R Units or Air Ducts to Inactivate Microorganisms on Irradiated Surfaces (ASHRAE 2014).
- ASTM D5157-19 Standard Guide for Statistical Evaluation of Indoor Air Quality Models (ASTM 2019).
- ISO 16000-1:2004 Indoor air – Part 1: General aspects of sampling strategy (ISO 2004).
- ISO 16890-1:2016 Air filters for general ventilation – Part 1: Technical specifications, requirements and classification system based upon particulate matter efficiency (ePM) (ISO 2016).
- ISO 16814:2008 Building environment design – Indoor air quality – Methods of expressing the quality of indoor air for human occupancy (ISO 2008).
- ISO/IEC 17025:2017 General requirements for the competence of testing and calibration laboratories (ISO/IEC 2017).

- UL 2823-2013 GREENGUARD Certification Program Method for Measuring and Evaluating Chemical and Particle Emissions From Electronic Equipment Using Dynamic Environmental Chambers (UL 2013).

E.2 Referenced documents

The following documents are referred to in this handbook.

- AIRAH Design Application Manual DA15 Air filters and cleaning devices (AIRAH 2019).
- AIRAH Design Application Manual DA26 Indoor Air Quality (AIRAH 2004).
- AIRAH Design Application Manual DA27 Building Commissioning (AIRAH 2011).
- AIRAH Building Simulation Procurement Guidelines Manual (AIRAH 2014).
- ASHRAE Handbook - Fundamentals 2021 (ASHRAE 2021).
- ASHRAE Position Document on Indoor Carbon Dioxide (ASHRAE 2022).
- ASHRAE Position Document on Indoor Air Quality (ASHRAE 2020).
- ASHRAE Position Document on Filtration and Air Cleaning (ASHRAE 2021).
- ASHRAE Indoor Air Quality Guide 2009 – Best Practices for Design, Construction and Commissioning, (ASHRAE 2009).
- Australia State of the Environment 2021: air quality, Australian Government (AG 2021).
- CIBSE Application Manual AM 11 (2015) - Building performance modelling Chartered Institute of Building Services Engineers London (CIBSE 2015).
- Health Effects Institute (2013) Understanding the Health Effects of Ambient Ultrafine Particles. HEI: Boston, Massachusetts (HEI 2013).
- IARC Monographs on the evaluation of carcinogenic risks to humans Vol. 88 (2006) Formaldehyde, 2-Butoxyethamnol and 1-tert-Butoxypropan-2-ol, International Agency for Research on Cancer, WHO: Lyon, France (IARC 2006).
- IARC Monographs on the evaluation of carcinogenic risks to humans Vol. 105 (2012) Diesel and gasoline engine exhausts and some nitroarenes, International Agency for Research on Cancer WHO: Lyon, France (IARC 2012).
- NABERS The Rules - Indoor Environment for Offices Version 2.0 (2021) State of NSW and Department of Planning Industry and Environment (DPIE 2021).
- National Environment Protection (Ambient Air Quality) Measure, 1998 as amended, prepared by the Office of Legislative Drafting, Attorney-General's Department, Canberra (NEPM 1998).

- NHMRC recommended Interim National Indoor Air Quality Goals 1996, National Health and Medical Research Council, (NHMRC 1996 rescinded 2002).
- NCC 2022 Volume One Building Code of Australia Class 2 to 9 Buildings, Australian Building Codes Board, Canberra (ABCB 2022a).
- NCC 2022 Volume Two Building Code of Australia Class 1 and 10 Buildings, Australian Building Codes Board, Canberra (ABCB 2022b).
- NCC 2022 Housing Provisions Standard, Australian Building Codes Board, Canberra (ABCB 2022c).
- NEPC Methodology for setting air quality standards in Australia Part A (2011) National Environment Protection Council (NEPC 2011).
- SA TS 5342 Technical specification for building commissioning (2021) Standards Australia (SA TS 5342 2021).
- WHO Global air quality guidelines: particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide, World Health Organization (WHO 2021).
- WHO guidelines for indoor air quality: selected pollutants, World Health Organization (WHO 2010).
- WHO Air quality guidelines: Global update 2005. Particulate matter, ozone, nitrogen dioxide and sulphur dioxide. Copenhagen, WHO Regional Office for Europe. (WHO 2006).
- WHO Review of evidence on health aspects of air pollution – REVIHAAP Project Technical Report, World Health Organization (WHO 2013).
- WHS Model Work Health and Safety Act (2011) Safe Work Australia, Canberra (SWA 2011).
- Workplace Exposure Standards for Airborne Contaminants, Safe Work Australia, Canberra (SWA 2019).

E.3 Additional information sources

- ABCB abcb.gov.au
    - National Construction Code and related resources including handbooks.
- AIRAH airah.org.au
    - Australian HVAC&R Industry application manuals and best practice guides.
- ASHRAE ashrae.org
    - American (USA) and regional standards and guides.
- CIBSE cibse.org/knowledge

- Building services application manuals and guides.
- ISO iso.org/iso/home/standards.htm
  - International standards
  - Standards Australia Home | Standards Australia Store | Standards Australia
  - Australian Standards and related products, regional and international standards.