Sustainable Building Services

Sustainable Ventilation in Commercial Building Environments for the ‘New Normal’

SEPTEMBER 18 2022

CIBSE Ken Dale Award Report 2022

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CIBSE

Executive Summary

Ventilation and Indoor Air Quality (IAQ) has become one of the central topics in building design and operation since the onset of the COVID-19 pandemic.

This period post-pandemic, often referred to as the ‘new normal’, provides us with an opportunity to review and renew our approach to commercial buildings ventilation design based on recent learnings and guidance, while achieving our sustainability goals.

Typically climate change has seen a focus on the environmental aspects of sustainable building design, although the COVID-19 pandemic has increased awareness of the importance IAQ on occupant comfort and safety. As a result the ‘people’ aspect of sustainability has become more central in sustainable building design while still respecting the ‘planet’ and ‘profit’ pillars. This renewed focus on IAQ has expanded our knowledge on air pollutants including viruses, TVOCs and PMs and their effect on occupant comfort in excessive concentrations.

The overarching aim of this research is to summarise the latest best practice design guidance in HVAC building services, with a focus on ventilation, and analyse the impact of this guidance on selected case study buildings sustainability performance. Based on this, an objective to classify ‘adequate’ ventilation for future commercial building design for the ‘new normal’ was later added due to its importance across the research.

> *“More air does not always mean better Indoor Air Quality.*
> *Design for IAQ, not ventilation rates”*

Ventilation systems, and its distribution and associated effectiveness are reviewed along with important IAQ monitoring, and air filtration topics to provide background information on the research.

This supported a fundamental aspect of this study which was the review and discussion of HVAC - ventilation in particular - best practice guidance from several leading bodies issued during and post the COVID-19 pandemic.

The guidance provides general consensus that certain HVAC measures can be beneficial and are recommended, but specifics do vary across institution. Many of these recommendations were issued in sole consideration of virus risk transmission, and so not in greater consideration of the overall effect on building operation and sustainability (now incorporating IAQ and resilience), therefore some of these measures do not align with the future of ventilation design approach proposed in this report. In general, design ventilation flowrate specification, mechanical ventilation operation and the distribution system effectiveness, and the air filtration and cleaning strategy are pivotal design aspects with measures recommended for most buildings. A detailed analysis and discussion of these measures and their application is provided in this report.

The building certification and rating systems of WELL, LEED, BREEAM, and in less detail NABERS IE, and the Immune building standard were also reviewed for HVAC measures. Based on this summary analysis it is concluded that the main standards have prohibitive certification costs but accessible design information. As a result it is recommended that in general the WELL standard ‘Air’ features, LEED Material credits, and BREEAM IAQ Plan prerequisite be communicated to, and considered by, the design team without the need or cost for certification.

To further understand the applicability and sustainability impact of these distilled HVAC measures, and to test the proposed updated design approach methodology, both are analysed on 5 selected case study commercial buildings covering multiple climate zones;

1. Arup Office, 1 Albert Quay, Cork, Ireland – Commercial Office - Cool Humid (5A) climate zone
2. National University Singapore SDE4, Singapore – Educational Facility - Very Hot Humid (1A) climate zone
3. 161 Collins Street, Melbourne, Australia – Commercial Office - Mixed Humid (4A) climate zone
4. 20 Martin Place, Sydney, Australia – Commercial Office - Warm Humid (3A) climate zone
5. 70 Eagle Street, Brisbane, Australia – Commercial Office - Hot Humid (2A) climate zone

For each case study building an introduction, and summary of the HVAC system will be provided followed by analysis of the ventilation adequacy, and HVAC measures suitability and impact.

From the results of this research, I recommend that an updated ventilation specification methodology based on *BS EN 16798 Energy performance of buildings. Ventilation for buildings* adapted to include ventilation effectiveness, be included as part of an updated IAQ based design approach utilised for future commercial building ventilation design.

Table i - Research Classified Recommended Adequate Ventilation Rates for Commercial Buildings in the New Normal

Category	Rec. Ventilation Rate	
	l/s/p	l/s/m2
I	$\frac{15}{Ev}$	$\frac{1.5}{Ev}$
II	$\frac{10.5}{Ev}$	$\frac{1.05}{Ev}$
III	$\frac{6}{Ev}$	$\frac{0.6}{Ev}$
IV	$\frac{4.125}{Ev}$	$\frac{0.4125}{Ev}$

This design stage IAQ classification and specification can be further enhanced using an adapted Method 2 (BS EN 16798-1) limit values for substance concentration formula to calculate the estimated zone IAQ level - using CO2 as the chosen known contaminant. Values can be compared against recommended or benchmark values, and the calculation estimated design CO2 levels provide verifiable values (+/- 50ppm) that can then be used to validate achievement of the zone design target IAQ Category using the ventilation rates specified, and its effectiveness during operation, with significant deviations in site measured CO2 rates compared to design values highlighting any potential issues in ventilation delivery.

For greater building contamination dilution and resilience, enhanced effective air change (ACHe) rates are recommended based on American CDC guidance;

Table ii – Recommended Effective Air Change Rate based on BS EN 16798 Standard

Category	Rec. ACH
	ACHe
I	≥6
II	≥3
III	≥2
IV	≥1

This updated approach mainly effects early stage design but has implications over the whole building life cycle. It requires early consideration and communication of the ventilation strategy, and pollution source limitation measures, details of which should be recorded in the IAQ plan. Attention should be paid at construction stage that specified low-pollution materials are installed, and that planned construction pollution prevention measures are implemented. In operation, post occupancy evaluations and ongoing commissioning using the adapted Method 2 CO2 levels will help monitor and maintain desired IAQ levels, while effective maintenance procedures for filters and ventilation equipment are recommended and will maximise efficiency and results.

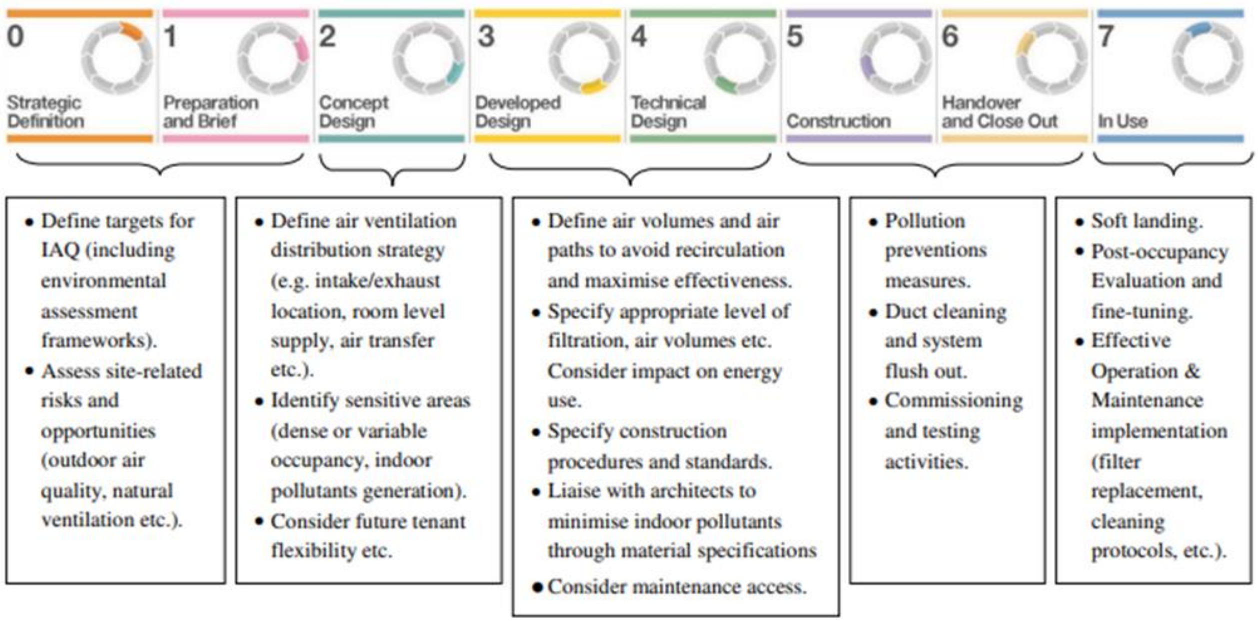

Figure i1 - Recommended Updated Design Approach Process Graphic

Once this updated approach is applied correctly, which can be assisted and confirmed using the CIBSE TM61 – 64 guidance as a basis, building resilience and operation will be optimised in case of any future public health emergency or similar.

This recommended approach is not being proposed as a perfect solution, and further research and development is required as noted in the case study analysis of this report. However, this report provides a strong literature and site based investigation into 'new normal' sustainable ventilation design. The main intention of this research and its recommended approach is to update the way in which we consider ventilation in buildings in the future, with the goal of designing for IAQ, not ventilation rates. It is important to strike a balance between the benefits of ventilation against issues such as energy, cost, and occupant comfort.

Acknowledgments

I owe so much to so many people who helped me throughout this research but I must thank a specific few for their time, generosity, and support over the last 2 years. To CIBSE for organising the Ken Dale Travel bursary and supporting my ever adapting research. To Arup, and in particular John Burgess, Nick Adams, Jodhi Atmaja, Siow Ting Ang, Stefan Sadokierski, Jen Cardwell to name a few; for the help, guidance, and advice across the globe in this study. To Professor Lam Khee Poh, Bertrand Lasternas and National University Singapore, Dimitri Soulos, Andrew Denton-Burke, Jacob Sawyer, and Ahmad Khan of Pembroke Real Estate and JLL respectively for their time, information, and assistance in the case study site visits.

Lastly, I would like to thank my family for their support and understanding as I spent long days and nights obsessing over this research and report.

CIBSE Ken Dale Travel Bursary

The Ken Dale Travel Bursary has been established by CIBSE to commemorate Ken Dale's contribution to the Institution and the building services profession. The bursary award is available to CIBSE members in the developmental stage of their career who wish to spend three to four weeks outside their own country researching aspects connected to their field of work and which will benefit CIBSE, their employer, their clients, and the profession. More information is available here.

About the Author

John Smyth is a Mechanical Design Engineer working with Arup in Cork, Ireland. He has a BE(Hons) Energy Engineering from University College Cork and a MSc Sustainable Energy Engineering from Waterford Institute of Technology where John won the CIBSE student award for thesis presentation on the sustainability of tall buildings in Ireland. Johns focus on sustainability has continued through his work in Arup where he has contributed to the design and analysis of energy efficiency and sustainability across a variety of projects.

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Preface

The research content, destinations and even the title for this CIBSE Ken Dale report have changed several times in what has been an unpredictable and extraordinary two years. However, the main goal of this research - to investigate the best practice design guidance in HVAC building services and analyse the sustainability impact of this guidance in international case study applications for the 'new normal' - has been relatively constant throughout, and it is my hope it is achieved in this report.

The COVID-19 pandemic has presented many challenges and opportunities for society and the engineering community in its relatively short timeframe, merely one of which is the way we design and operate our buildings in a world conscious of 'social distancing' and the risk of virus transmission in high occupancy environments.
The inspiration for this research was the rise of the COVID-19 virus pandemic in early 2020 and effect this may have on the future of building services design and operation. However, over the course of the research this has evolved to not just COVID-19 virus concerns but the broader spectrum of Indoor Air Quality (IAQ) and ventilation. My original, ambitious goal of inspecting and surveying best practice building services systems in person across multiple continents and climates was, out of necessity and for the better, revised to the more achievable and relevant research destinations and objectives as set out below in the relevant sections of this report.

Even in a time of global travel restrictions and lockdowns, there was always the aim to maintain an international aspect of this study in keeping with the principles of the CIBSE Ken Dale award. This was originally achieved virtually through international case study building contacts, countless zoom meetings and cloud data sharing whenever possible. However, even with the marked advancements in digital communication and the incredible support from an unmentionable number of people across my international research case study destinations, in my opinion the most useful results and conclusions presented in this report came from the hands on inspection, analysis and discussion from travelling to the international case study buildings which occurred in May 2022 as COVID restrictions subsided, an opportunity for which I am eternally thankful to CIBSE. Finally, this report is built upon the research of many others (too many to name but some will be referenced throughout the report) and the information and data provided by case study subjects, and I would just like to thank and dedicate this report to you all.

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Introduction

My original ambition was to produce a ground-breaking scientific report, full of technical analysis to an academic journal level, on the effect of the COVID-19 and other public health emergencies such as wildfires on the design and operation of buildings HVAC systems across the globe. However, I eventually realised there were many incredibly smart academics and industry leaders doing immense technical and theoretical 'heavy-lifting' research that was far beyond anything I could ever produce or even conceive. So rather than compete with this research I decided to collate, condense, and simplify where possible, the outputs of these 'heavy lifters' research and guidance notes in relation to ventilation systems specifically, and focus on its application - using the Ken Dale research award as the basis.

It should be noted that this research and the output recommendations changed almost weekly as our collective knowledge of COVID-19 updated, although I did attempt to remain current as much as possible. Also, we as a society began to look beyond just the COVID-19 virus to other contaminants as Indoor Air Quality (IAQ) in general, and the opportunity that this new rethinking of building systems has provided, which very much became the final emphasis of this report too.

As a result this study explored the impact and viability of selected guidance measures on 5 case study buildings across Ireland, Singapore, and Australia. This report provides a narration of the research conducted on the case study buildings, and my conclusions based on the results. The majority of my conclusions are my opinion and not fact, but I did aim to support them with credible and real-world research.
Also, pursuant to the instructions of the Ken Dale award committee to be 'bold and provocative', I challenge some of these guidance recommendations and go so far as to develop my own recommendations around the future of building ventilation design and operation.

A longer than planned background information section is provided, and I hope helpful, to inform the reader on the context and thought-process behind much of my research, but as much as possible I try to brief and use tables and graphics to communicate this information with references to where one might go for more knowledge on the topic generally provided if applicable.

You will still see pockets of scientific analysis and engineering based language (I am an engineer after all!) but I have tried to make this report accessible to all and to simplify much of my study so that anyone interested can understand it.

Due to my work as a sustainability and building services engineer there is a focus on sustainability in this report. The definition of sustainability within the built environment has evolved as society has developed over the years since the 1987 Brundtland report simply defining sustainability as that which 'meets the needs of the present without compromising the ability of future generations to meet their own needs'. A more recent and widely known interpretation of sustainability popularised by the US Green Building Council's (USGBC) green building certification system 'LEED' accounts for the Triple Bottom Line (TBL) of sustainability of "people, planet and profit" which considers more than just the environmental features of the built environment but its economic prosperity and social responsibility to its occupants and the public.

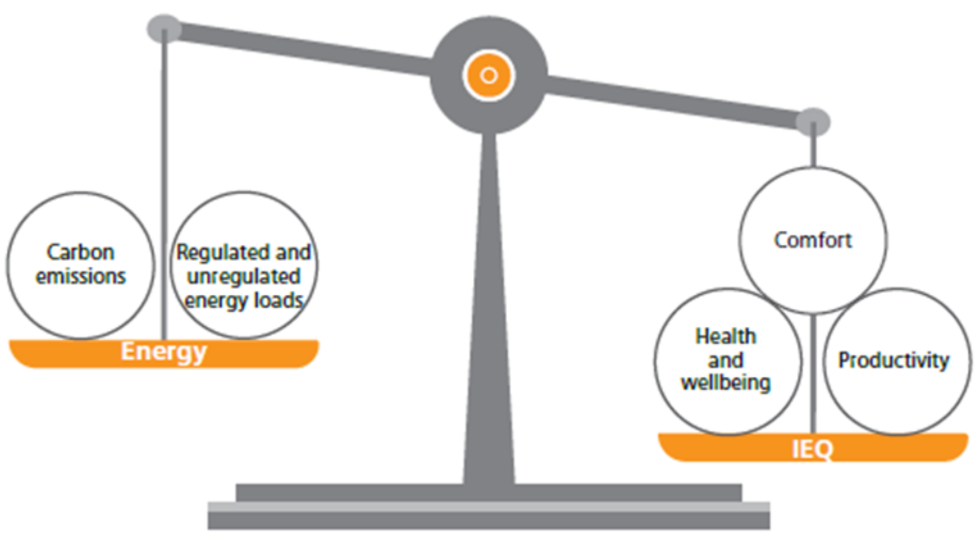

Figure 2 - The Balance of Energy with IEQ (CIBSE)

Growing concerns of irreversible climate change has seen a focus on the environmental aspects of sustainable building design in the last decade, although with the effects of the COVID-19 pandemic and increased awareness of the importance IAQ on occupant comfort and safety, 'people' has become more central in sustainable building design while still respecting the 'planet' and 'profit' pillars.

Building services play an essential role in building sustainability under all three pillars and one major aspect of this is ventilation – the process of supplying air to or removing air from a space for the purpose of controlling air contaminant levels, humidity, or temperature within the space[1].

The occurrences of public health emergencies such as the Australian wildfires (external) and the COVID-19 pandemic (internal) have put a renewed emphasis on the importance of air quality and adequate ventilation for building resilience and occupant wellbeing as we move forward. This era at the tail end of the COVID-19 restrictions with society re-opening in a post-pandemic world has been termed 'the new normal' with civilization, and the way we design and operate in it having changed irreversibly. Commercial building environments have been most notably affected by these public health emergencies with many facilities closing in line with guidelines and having to adapt to recommendations to safely reopen and operate in the new normal.

One of these recommendations is for 'adequate ventilation' which has been shown to not only improve occupant comfort and productivity, but to lower risk of occupant illness and air contamination according to recent scientific studies[2][3]. Similar findings are even shown in historic learnings from the influenza & tuberculosis epidemics in the 20th century[4]. This benefit of adequate ventilation raises the question of what qualifies as 'adequate', particularly in reference to indoor air contamination sources such as COVID-19, and how do we calculate or allow for it in our building designs. As a result, this study explores ventilation rates and calculation methodologies for commercial buildings with the objective to classify adequate ventilation, and analyse this for the given case study buildings from the research locations detailed below.
Ventilation in this study is taken to be controlled mechanical ventilation, and does not focus on infiltration or natural ventilation. For natural ventilation guidance ASHRAE 62.1:2013 provides a methodology to assess its effectiveness, and in UK and Ireland the CIBSE Applications Manual AM10, which follows a similar but more comprehensive approach, is recommended and is also referenced in Part F of the Building Regulations.

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[1] ANSI/ASHRAE Standard 62.1-2019 Ventilation for Acceptable Indoor Air Quality

[2] Tom Lipinski et al (2020) "Review of ventilation strategies to reduce the risk of disease transmission in high occupancy buildings", International Journal of Thermofluids, Published online 2020 Sep 13. doi: 10.1016/j.ijft.2020.100045

[3] Henry C. Burridge et al. (2021) "The ventilation of buildings and other mitigating measures for COVID-19: a focus on wintertime", Proceedings of the royal society A Mathematical, Physical and Engineering Sciences, March 2021, Volume 477, Issue 2247

[4] Richard A. Hobday, and John W. Cason (2009) "The Open-Air Treatment of PANDEMIC INFLUENZA", Am J Public Health. 2009 October;

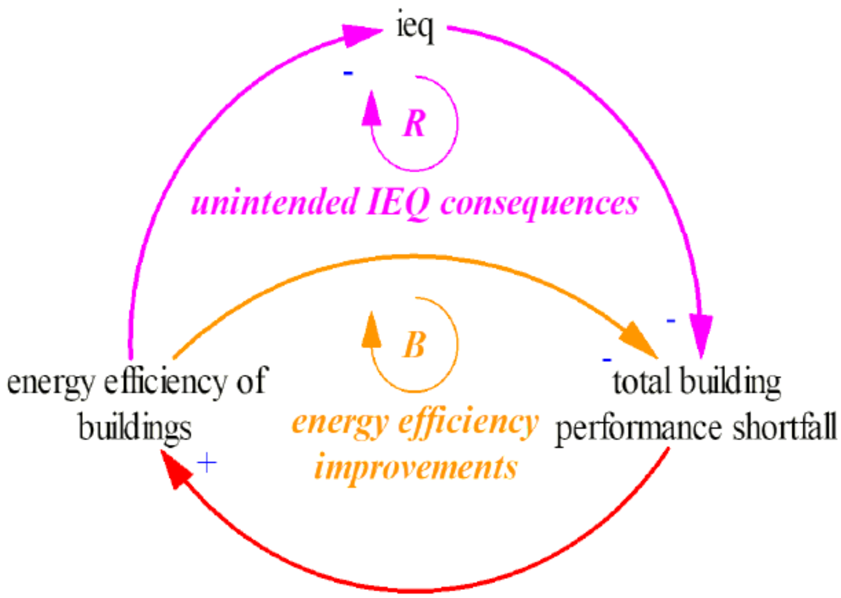


Figure 3 – Circular IEQ and energy efficiency (CIBSE)

In light of the COVID-19 pandemic and the beginning of the new normal, a myriad of new and updated HVAC design and operation guidance, including measures such as adequate ventilation, has been published. This modern design guidance considers a wider range of measures to reduce the risk of COVID-19 to building occupants and improve overall building resilience.

This study completes a high-level summary review of a selection of the latest HVAC guidance in particularly from the leading global building services institutions including ASHRAE, AIRAH, CIBSE, REHVA and ISHRAE. From this review the distilled main recommendations from across the guidance applicable to ventilation and IAQ are discussed and analysed on the given case study buildings. The analysis will follow the sustainability theme of this study with a focus on the economic, energy and IAQ impact of proposed measures.

Research Objectives & Methodology

The overarching aim of this research is to summarise the latest best practice design guidance in HVAC building services, with a focus on ventilation, and analyse the impact of this guidance on selected case study buildings sustainability performance.

There are vast amounts of incredible research and guidance documents available in the field of building services and ventilation in buildings, particularly in relation to the COVID-19 pandemic which brought a renewed emphasis onto building IAQ.

This report is not looking to regurgitate or replicate this extensive research but to summarise a selection of relevant guidance into actionable measures, and to analyse the impact of these applicable measures on case study buildings.
To achieve this aim 4 research objectives have been set out;

1. Classify ‘adequate ventilation’ and how it may be applied and communicated in commercial building design for the ‘new normal’.
2. Summarise the latest commercial building HVAC design and operation guidance from global institutions and distil actionable measures to improve indoor air quality and building performance for the ‘new normal’.
3. Analyse applicable measures identified on the case study buildings to examine their real-world application and results of their implication in commercial building environments.
4. Present and discuss recommendations to carry forward for the future of commercial ventilation design in the new normal.

To achieve these objectives the research method will be a combination of literature review, desktop studies and where possible onsite analysis of case study buildings.
The literature review will mainly consist of building ventilation standards and the latest HVAC guidance documents and research papers, with a focus on design for the new normal. Desktop studies will be conducted using available building information to present the case study buildings in a systematic format summarising building design, construction, activity, and HVAC systems relevant to the study.
Offsite analysis using modelling and first principles calculations of identified best practise guidance measures will also be included in these desktop studies.
Finally, where possible, the onsite analysis of HVAC measures utilising available building performance data to quantify the measures effect on energy and IAQ (where suitable performance data is available) will be completed.

This reports analysis will be applied to existing case study buildings in order to be able to collect actual building data, where available, but in theory the research should be applicable to new and existing buildings design and operation.
The study case study buildings are selected to be representative international commercial buildings with accessible building design and performance data for the research. Therefore, 5 case study buildings across 3 research destinations are selected as outlined below.

Research Destinations

The research timeframe between 2020 and 2022 was an understandably precarious period for international travel with a global pandemic and related travel restrictions. As a result the research destinations were changed several times during the study but the final locations and activity type of the 5 case study buildings are given below;

- Commercial Office, Cork, Ireland – Arup Cork
- Education Facility, Singapore – NUS SDE4
- Commercial Office & Retail, Australia
    - Brisbane
    - Sydney
    - Melbourne

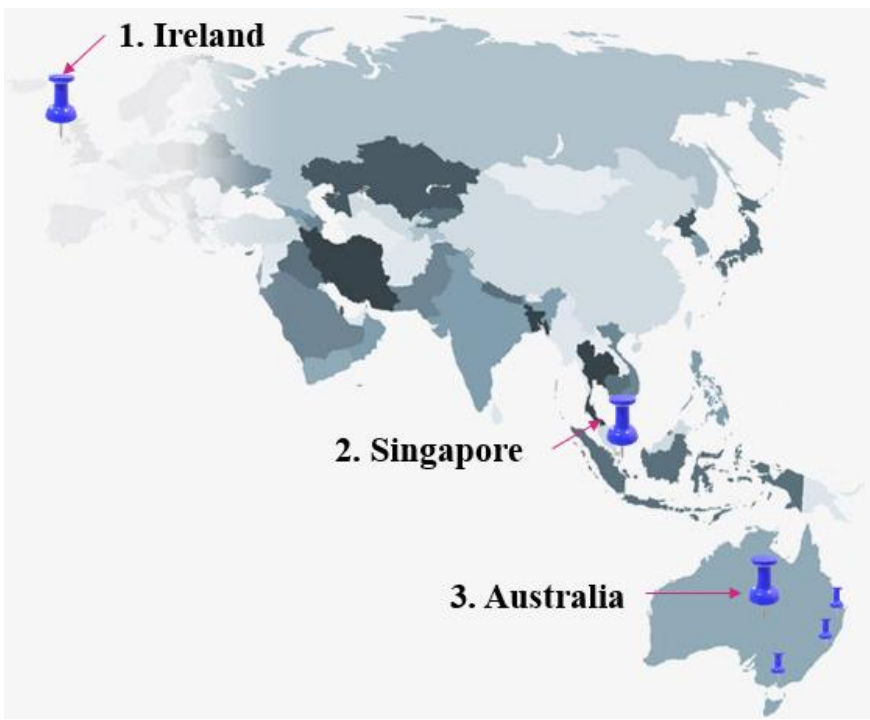


Figure 4 - Research Destinations Map

The case study locations were chosen for relevancy to the research topic but also accessibility to building data and flexible communication channels.
With the support of the CIBSE Ken Dale award and Arup, and despite the best efforts of the COVID-19 pandemic I was able to visit the international case study locations in May 2022.

Background

Overview

While some grasp of ventilation and HVAC systems is assumed by the author for this report, a detailed knowledge of ventilation systems, COVID-19 and contaminants in general, or the best practice guidance on HVAC systems is not required.
However, for completeness of this report, and better reader comprehension a brief insight into some topics relating to ventilation, COVID-19 and HVAC guidance are covered below.

It is important to note that there has been an abundance of discussion, research, and even twitter conversations on IAQ, COVID-19 and aerosols (and other contaminants) over the last few years and anyone interested in the subject should check out research by Trisha Greenhalgh et al. (2021) on ' Ten scientific reasons in support of airborne transmission of SARS-CoV-2'[5] and there many reference papers. However it is generally accepted that, and for the purpose of this study assumed that contaminants, including COVID-19, as aeroslised and floating in the air.
And although the original inspiration for this research, COVID-19 will not be the only focus of this report but a wider array of contaminants (e.g. wildfire smoke, CO2, VOCs, PMs etc.) are considered under the umbrella of Indoor Air Quality - IAQ.

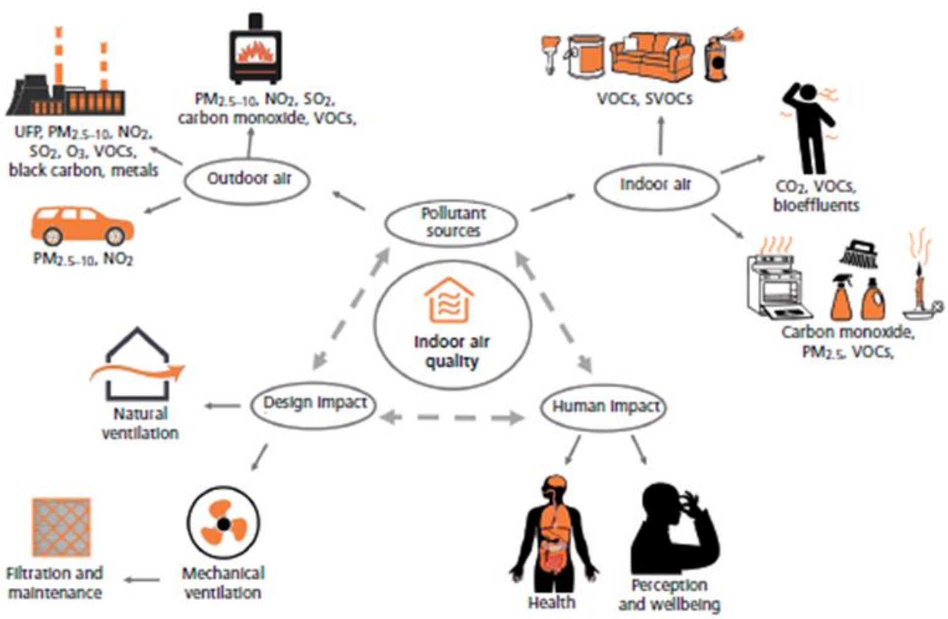


Figure 5 – IAQ Influences Mind Maps

[5] https://www.thelancet.com/article/S0140-6736(21)00869-2/fulltext

It is also important to point out that for COVID-19 and typically any contaminant, that the traditional contamination control pyramid adapted from the US CDC below is the best practice process for facilitates for infection and general contamination control. This research report is based on engineering controls, of which one main solution is ventilation, to reduce the environmental risks of airborne contamination.

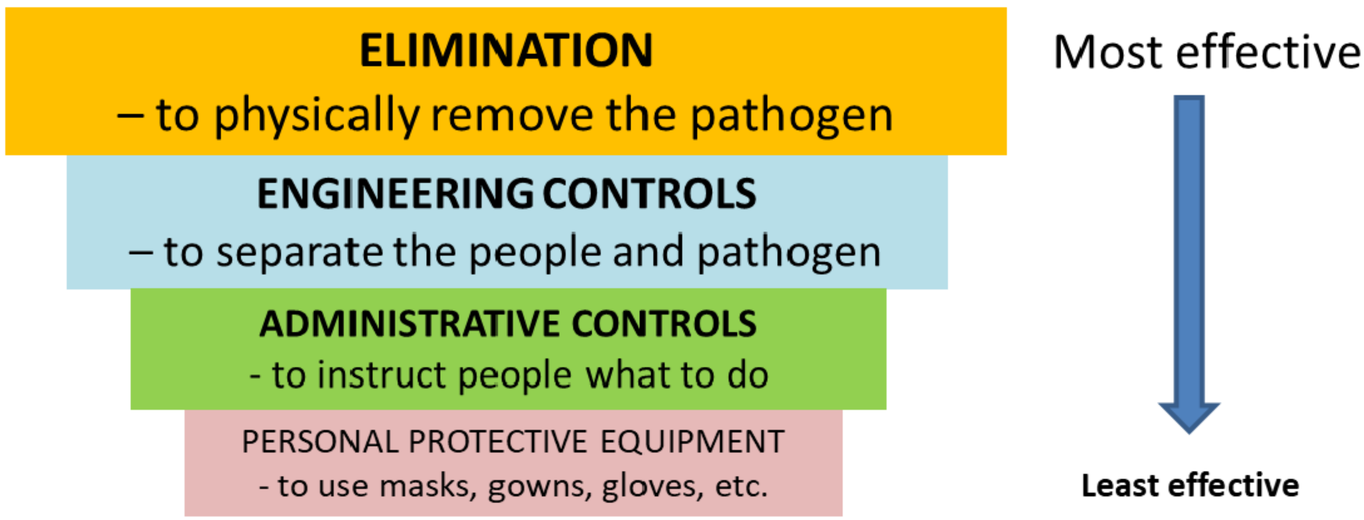


Figure 6 – Traditional Contamination Control Pyramid (US CDC)

While elimination of the contaminant and use of personal protective equipment (PPE) are self-explanatory, examples of administrative controls can be found in the British Council for Offices Briefing Note on Office Design and Operation After Covid-19 from April 2020 if you require further information.

In terms of ventilation based engineering controls, the first strategy is to manage IAQ through source control as highlighted in the latest CIBSE TM 61 2020 - Operational performance of buildings. The identification of key external and internal sources for pollution, material selection, and details of ventilation strategy such as position of air intakes are crucial to minimise pollution. Then the air change rates specified and achieved for ventilation and the ventilation schedules also play an important role in providing fresh air to occupants and diluting or removing pollutants from indoors.
Finally, appropriate filtration strategy can help protect building users from major outdoor sources of pollution and strike the right balance between indoor air quality and energy efficiency in the air distribution system.

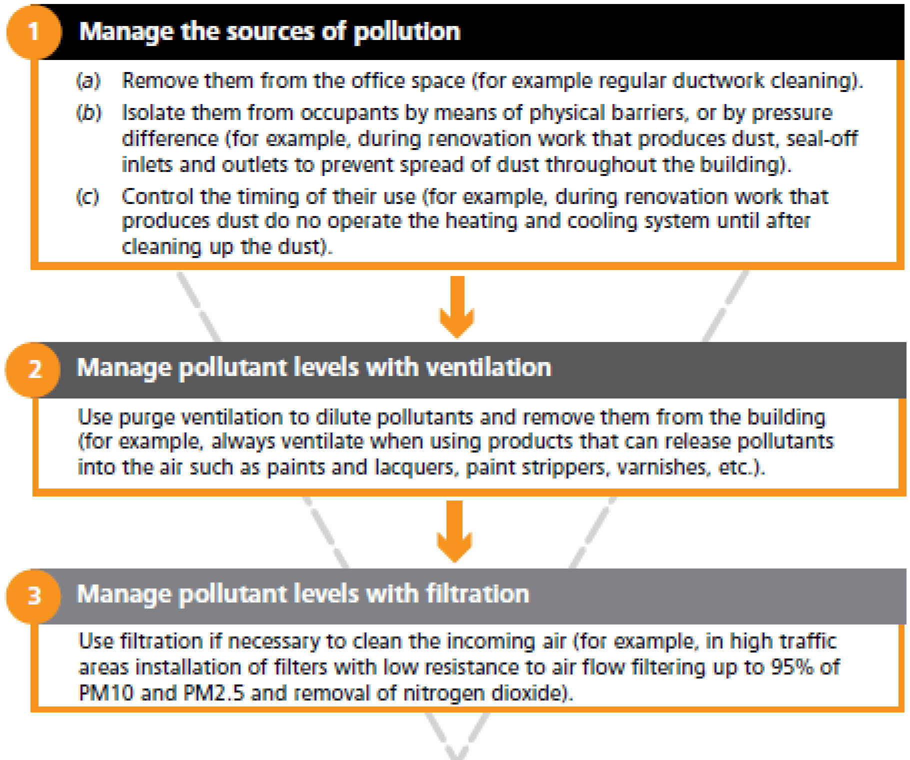


Figure 7 – Indoor Air Quality Management Hierarchy (CIBSE TM61)

Consequently, we will take a deeper look into the background of Air Pollutants, Ventilation and its systems, IAQ monitoring, and Air Filtration & Cleaning, before looking at the best practice guidance available for HVAC systems in this new normal.

Air Pollutants - COVID and Contaminants

Air pollutants are contaminants in the indoor or outdoor environment of any chemical, physical or biological agent that modifies the natural characteristics of the atmosphere according to the World Health Organisation (WHO). Some air pollutants or contaminants are now typically found in our outdoor and indoor environments but when accumulated in high enough levels for extended periods can be harmful to human health.

Such contaminants include Carbon Monoxide (CO), Carbon dioxide (CO2), Nitrogen dioxide (NO2), Ozone (O3) Particulate Matter (PM1, PM2.5), Radon, Volatile Organic Contaminants (VOCs) and certain aromatic hydrocarbons. More recently this has been revisited to include consideration of bacteria and viruses due to the COVID-19 pandemic. Bio-effluent pollutants which are referenced throughout are atmospheric pollutants that emanates from humans or animals (CO2, CH4). All of these pollutants vary in size from 100 µm to 0.001 µm.

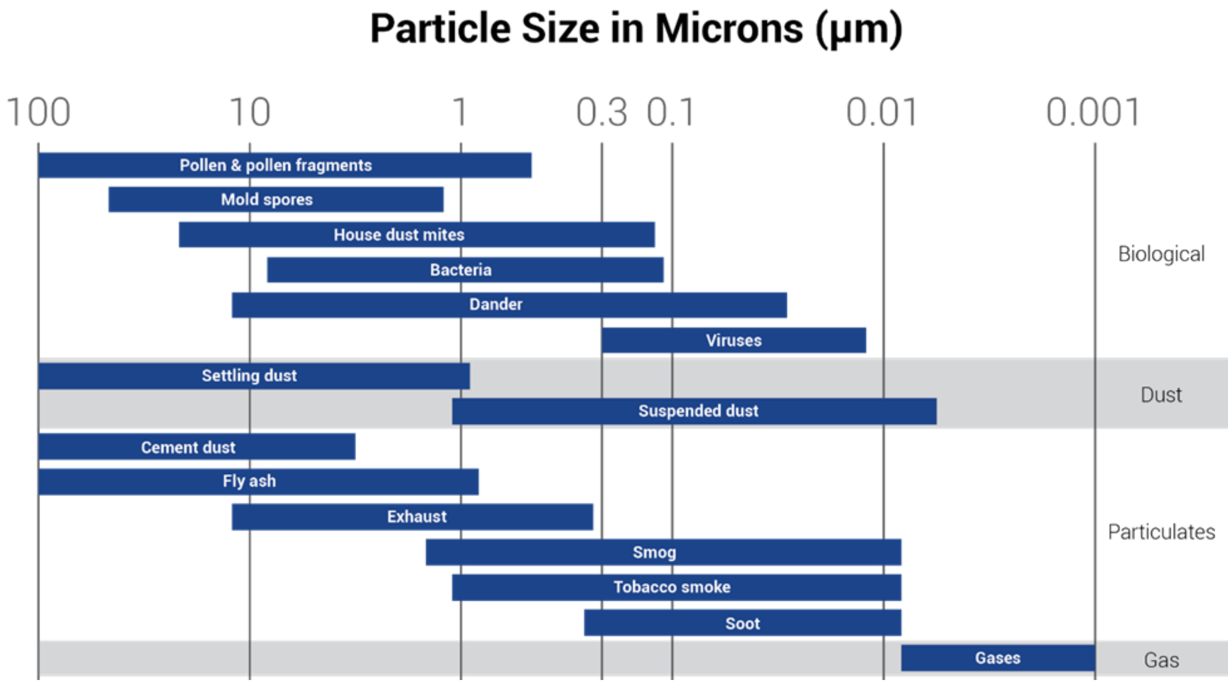


Figure 8 – Graph of Typical Contaminants Particle Size

Contaminants for our case can be divided into two main groups –

1. Outdoor air sources and,
2. Indoor air sources.

Sources of outdoor air pollution include road traffic, industrial processes, waste incineration and wildfire smoke to name a few. Pollution includes particulate matter, NO2, CO and radon, all of which can be brought into a building through natural or mechanical ventilation and via infiltration through the building fabric.

But there are also indoor air pollution sources typically found inside a building, including VOCs given off by wall and floor coverings for example, dust, damp, and mould; emissions from office equipment and industrial machinery and, of course, occupants themselves, who breathe out CO2 and can spread colds and viruses.

These Outdoor and Indoor air contaminants can be further categorised as two forms of air pollution;

1. Particle pollution
2. Gaseous pollution

Particle air pollution covers chemical compounds such as combustion particles and micro plastics consolidated under the Particulate Matter (PM) bracket. Biological particles such as bacteria, viruses, and spores/pollens are considered particle pollution. Gaseous air pollution includes any gases in the air such as VOCs, formaldehyde, NOx etc. This distinction and the understanding of these different contaminant types is important as it can influence our filtration strategy later in design.

Figure 9 – Common Commercial Environment IAQ Contaminants

Both these indoor and outdoor air contaminants can have serious effects on occupants comfort, productivity and most importantly health. Therefore you would expect their allowable concentrations to be strongly regulated and standardised correct? Unfortunately not with contaminant or pollution regulations inconsistent across several bodies but this is improving.

CO2 as a pollutant is primarily sourced from human respiration (also found in combustion devices) and therefore is strongly linked to occupancy density and ventilation. While ambient in the outside air it can accumulate in much higher concentrations in indoor environments and has been linked negative health effects although the extent of which is currently debated.

A study by UK Health Security Agency[6] found that previous research into the health effects of CO2 levels did not account for other confounding factors such as environment (temperature, humidity, noise etc.) and other air pollutants, and even the occupant's health status therefore a direct link is not established. However, although it is difficult to link CO_2 itself with health effects at exposures less than 5000 ppm, the existing guideline concentrations (usually reported for 8 h, for schools and offices), which suggest that CO_2 levels <1000 ppm represent good indoor air quality and <1500 ppm are acceptable for the general population, appear consistent with the current research. Additionally, it is clear that CO2 levels have been a gauge for indoor air and environment quality, and maintaining recommended concentrations can improve occupant comfort and health.

Similar to other contaminants the health effects of CO2 depend on the concentration level and exposure time in the environment. Unlike other contaminants however, occupants can adapt quite well and quickly to bio-effluents including CO2. This adaptability has lead to ventilation rate specifications based on 'adapted persons' i.e. an occupant in the environment for greater than 15 minutes and has adjusted to it as per EN 16798-1. This is discussed further in the ventilation section below.

Other pollutants such as PMs and TVOCs also have several recognised concentration level recommendations across several bodies.

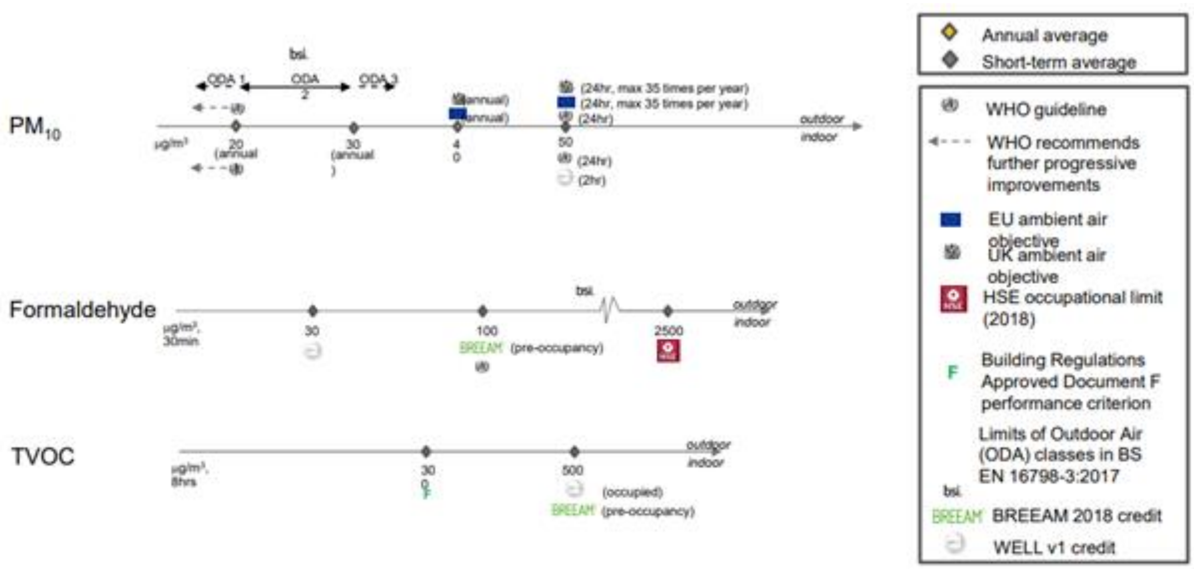


Figure 10 – Example IAQ Concentration Level Criteria (CIBSE)

[6] Low Level Carbon Dioxide Indoors—A Pollution Indicator or a Pollutant? A Health-Based Perspective - https://www.mdpi.com/2076-3298/8/11/125

Many (including CIBSE) increasingly refer to WHO guidelines for air pollution standards, especially since of late they have shown to be leaders in viruses and COVID-19 related research and guidance.

Pollutant		WHO Exposure	WHO Exposure	Critical Outcomes
Airborne Particles		Guidelines	Guidelines	
	chemical compounds			
PM1	fine combustion particles <1micron	n/a (usually about 70% PM2.5)	n/a (usually about 70% PM2.5)	PM1 is the most penetrating particle size range and can pass into the bloodstream. Traffic emission particles are Group 1 carcinogens the most toxic causing cancer and there is no safe level of exposure. Children are vulnerable.
PM 2.5	fine combustion particles <2.5micron	10μgM3 annual mean	125μgM3 24 hour	
PM10	fine combustion particles <10micron	20μgM3 annual mean	500μgM3 annual mean	
	plastic particles and fibres	n/a more research needed	n/a more research needed	penetration into food chain and body tissues
	bioparticles			
	Pathogens bacteria and virus e.g..	Chicken pox, flu, measles		infection can cause serious illness and fatality
	moulds, spores, pollens, allergens e.g..	legionella, aspergillus, anthrax		infection can cause serious illness and fatality
Pollutant		WHO Exposure	WHO Exposure	Critical Outcomes
Gases in Air		Guidelines (other)	Guidelines (other)	
NO2	Nitrogen oxide	40μgM3 annual mean	200μg 24 hour mean	long term respiratory system damage
SO2	Sulphur dioxide	20μgM3 annual mean	500μgM3 10-minute average	long term respiratory system damage
O3	Ozone	100μgM3 8 hour mean		long term respiratory system damage
CH2O	Formaldehyde	0.1mg/M3 30-minute average		nasopharyngeal cancer and myeloid leukaemia
PAH's	Polyaromatic Hydrocarbons	risk 0.012μgM3 1/1000000	risk 1.2μgM3 1/10000	lung cancer
VOC's	Volatile Organic Compounds	need individual data	need individual data	many VOC's proven carcinogens
H2S	Hydrogen Sulphide	HSE 5ppm 8 hours TWA	HSE 10ppm 15 minutes TWA	can cause fainting leading to fatality

Figure 11 – WHO Pollutant Guidelines Summary

Briefly focusing on viruses, specifically COVID-19 which as the initial instigator for this research, COVID-19 or coronavirus or SARS-CoV-2 can spread in indoor and outdoor settings in a number of ways as indicated by the figure.

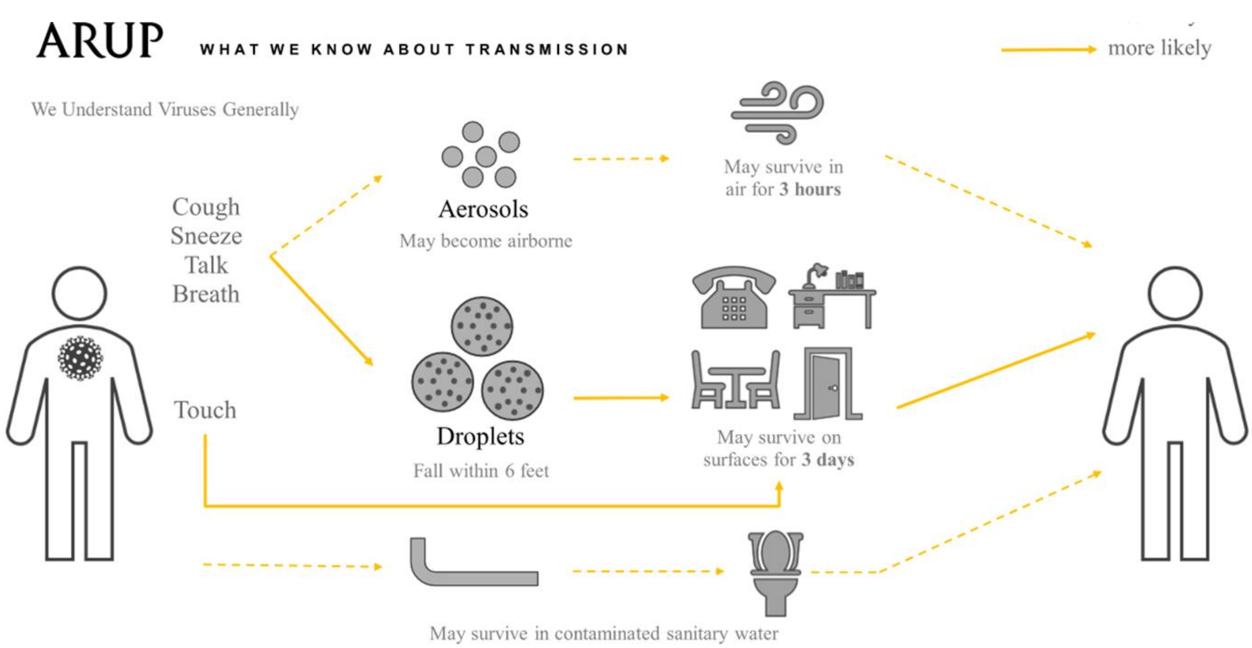


Figure 12 – COVID-19 Virus Transmission Routes (Arup)

"Covid-19 spreads primarily from person to person through small droplets from the nose or mouth, which are expelled when a person with Covid-19 coughs, sneezes or speaks" (World Health Organization)

This report will not go into intricate details on COVID-19 and its transmission but for those with a greater interest in the subject a great paper in the journal of hospital infection by J.W Tang et al. titled 'Dismantling the myths on the airborne transmission of Sars-Cov-2' is a well written source for facts on the topic.

However, the behaviour of the virus through airborne transmission, of primary concern for HVAC systems, has been the subject of a number of studies which generally agree that the virus can remain viable in the air for a long period and travel some distance away from an infected individual via ventilation systems. Consequently, it can be assumed that airborne transmission through a ventilation system can infect those in areas also served by the same ventilation system, although this has not yet to be rigorously established but taking an abundance of caution we will accept it as possible.

A recent study by H. Parhizkar et al. (2021)[7] on quantifying human and environmental viral load relationships amidst mitigation strategies in a controlled chamber recruited 11 participants diagnosed with COVID-19 to individually occupy a controlled chamber and conduct specified physical activities under a range of environmental conditions over 3 day period. The study indicated that increased ventilation and filtration are associated with lower environmental viral loads, and higher relative humidity is associated with lower aerosol viral loads and higher surface viral loads, consistent with an increased rate of particle deposition. Data from near field aerosol trials with high expiratory activities suggest that respiratory particles of smaller sizes (0.3µm -1µm) best characterize the variance of near field aerosol viral load. A study published by Dr. Brent Stephens on March 1 2012 for The National Air Filtration Association (NAFA) Foundation titled "HVAC Filtration and the Wells-Riley approach to assessing risks for infectious airborne diseases" suggest larger particles may contain greater viral transmission risk as indicated from the following excerpt;

[7] Quantifying human and environmental viral load relationships amidst mitigation strategies in a controlled chamber with participants having COVID-19, H. Parhizkar et al. 2021

'These previous studies all confirm that aerosols generated during coughing by influenza patients and subsequently remaining suspended in indoor environments indeed contain the influenza virus and that much of that viral RNA is contained within particles in the respirable size range (i.e., <4μm). However, whereas ~100% of the number of particles emitted during the aforementioned coughing and breathing studies were smaller than 4μm size, only 40-70% of the influenza virus RNA is typically detected on particles in this size range (Blachereet al., 2009; Lindsley et al., 2010; Lindsley et al., 2010a), suggesting that the virus content of aerosols may actually be skewed toward larger particles' [8]. This has a significant effect on filtration effectiveness and strategy noting we need to consider from at least 0.3μm to >4μm suggesting up to particulate matter sizes up to 10μm (PM10) . We look more into this in the filtration section below.

But the importance of ventilation in reducing the virus risk is well established with several reported outbreaks where airborne transmission is given as the mechanism. For example, the Guangzhou Restaurant study by Li et al.[9], and Korean Call Center study by Park et al.[10] have reported very low per capita ventilation rates with values in the range 0.5-2 l/s/person estimated; much lower than typical building guidance 'adequate' ventilation recommendations.

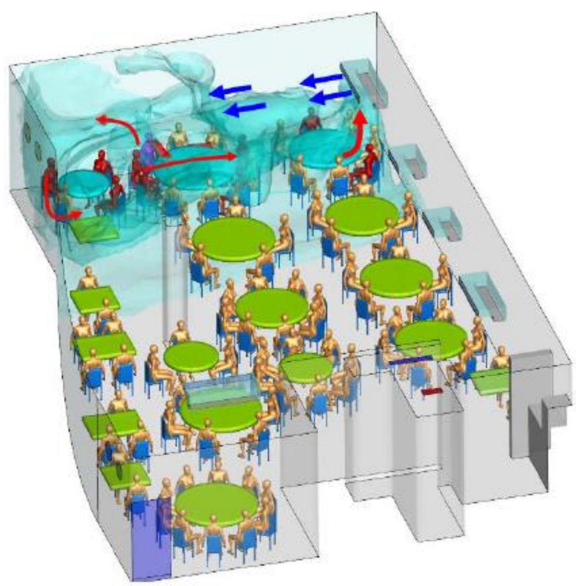


Figure 13 – Graphic of Guangzhou Restaurant Study by Li et al

[8] HVAC filtration for controlling infectious airborne disease transmission in indoor environments: Predicting risk reductions and operational costs. Parham Azimi and Brent Stephens. Build Environ. 2013 Dec; 70: 150–160. 10.1016/j.buildenv.2013.08.025

[9] Lu J, Gu J, Li K, Xu C, Su W, Lai Z, Zhou D, Yu C, Xu B, Yang Z. COVID-19 Outbreak Associated with Air Conditioning in Restaurant, Guangzhou, China, 2020. Emerg Infect Dis. 2020 Jul;26(7):1628-1631. doi: 10.3201/eid2607.200764. Epub 2020 Apr 2. PMID: 32240078; PMCID: PMC7323555.

[10] Park SY et al.,. Coronavirus Disease Outbreak in Call Center, South Korea. Emerg Infect Dis. 2020 Aug;26(8):1666-1670. doi: 10.3201/eid2608.201274. Epub 2020 Apr 23. PMID: 32324530; PMCID: PMC7392450.

But what is the 'adequate' ventilation rate required to minimise the amount of virus, or other contaminants of concern in a building? That is part of the research aim of this study which we will investigate later. This report will not completely focus on virus transmission risk however, which has had a great deal of research of late. I will note that current evidence suggests that airborne transmission risk depends on the concentration of virus in the air in a room, the rate at which occupants in the space inhale the virus, and the duration of exposure according to Buonanno, Morawska and Stabile's 2020[19] research paper. As a result, using complex mathematical models such as Wells-Riley approach, and some simplifying assumptions, the risk of airborne transmission can be estimated. Branch Pattern produced an excellent virus transmission risk calculator with user guide for anyone looking for more indept information.

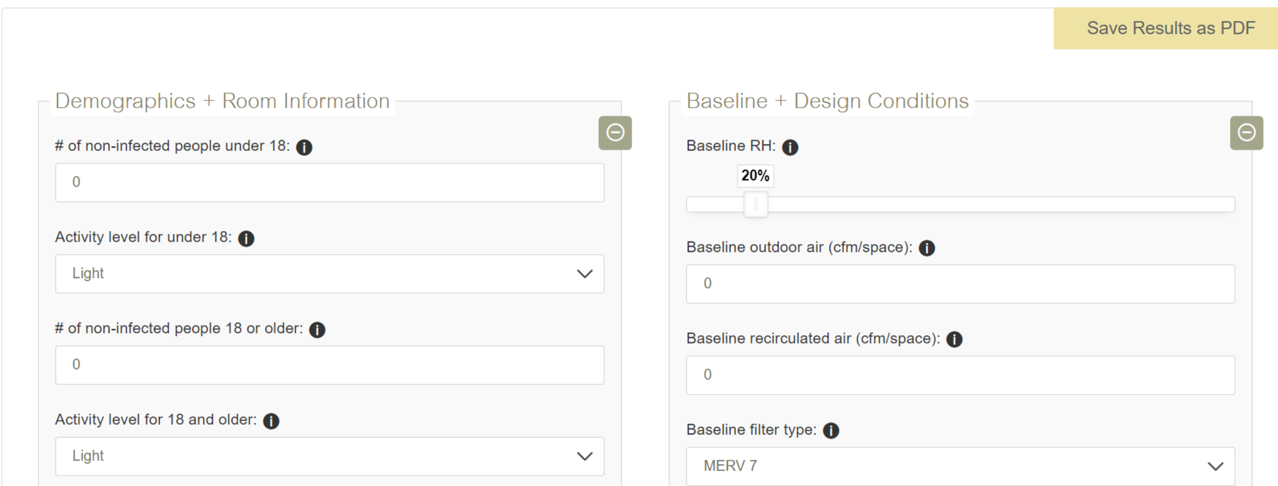


Figure 14 - Branch Pattern Virus Transmission Risk Calculator

One interesting output from the risk calculator is that in a well-mixed room under steady-state conditions with a constant viral emission rate the concentration of virus is approximately inversely proportional to the absolute ventilation rate (volume flow per unit time) in the room. As such doubling the ventilation rate would roughly halve the viral dose inhaled under the same emission and inhalation conditions.

Therefore, where there is an internal source of pollution – such as COVID-19 or even CO2 – dedicated 100% outdoor-air systems are widely advocated as a means of reducing virus risks and indoor pollution levels. Dedicated outdoor-air systems (DOAS) would normally include some form of heat recovery to reduce the heating, cooling, and humidification energy consumption. However, particularly as a result of the pandemic, there is increased concern about the potential risks of cross-contamination between exhaust and supply airstreams so there has been an abundance of research and guidance related to this.

As a result I focus a section of this study on this ventilation heat recovery guidance.

It is important to note that COVID-19 is not the only air contaminant, or even virus, that is directly connected to ventilation systems. Even as early as the 1940s 'adequate ventilation' was being promoted as a measure to fight against tuberculosis (TB). A study of ventilation improvements during a TB outbreak in university buildings[11] showed when CO_2 was reduced to <1000 ppm it was independently associated with a 97% decrease in the incidence of TB among contacts.

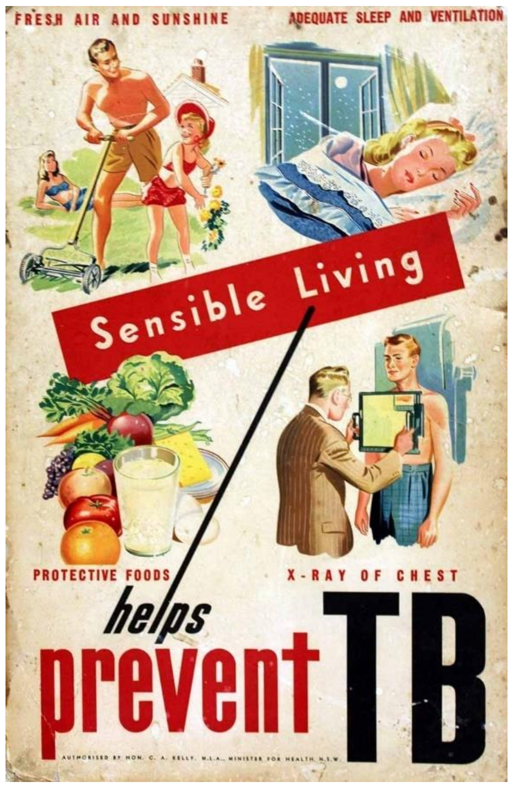


Figure 15 – 1900s TB Poster Promoting Adequate Ventilation

Back then, and even now, there remain many unknowns with virus transmission, but this research will take COVID-19 and other aeroslised viruses as occupant based indoor contaminants that require ventilation and/or air cleaning to be removed.

Staying with the 'on trend' topics - wildfire smoke is an outdoor contaminant with growing global awareness due to their increased frequency and intensity across the globe, and being increasingly deadly wildfires across America and Australia.

[11] Effect of ventilation improvement during a tuberculosis outbreak in underventilated university buildings, Du et al.,2020 - https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7217216/

Wildfire smoke is a mixture of mainly small particle pollution and gaseous pollutants (e.g. carbon monoxide), and is estimated to cause over 339,000 premature deaths a year globally – far more than those who lose their lives directly in these blazes.
Moreover, in 2019 and 2020 wildfires and the resulting smoke were responsible for the temporary closure of businesses and schools across Australia and California respectively. But even in Europe there are on average 65,000 wildfires every year, and research has shown that smoke from forest fires can linger in the atmosphere for weeks as it spreads, and can even become more toxic with time. Therefore, it should be a consideration for nearly every building design in the future based on our current climate degradation direction, no matter what the location. In response to the increasing wildfire smoke hazard ASHRAE initiated the Guideline 44P *Protecting Building Occupants from Smoke During Wildfire and Prescribed Burn Events* which is still in development but is a useful resources for those looking for more information.

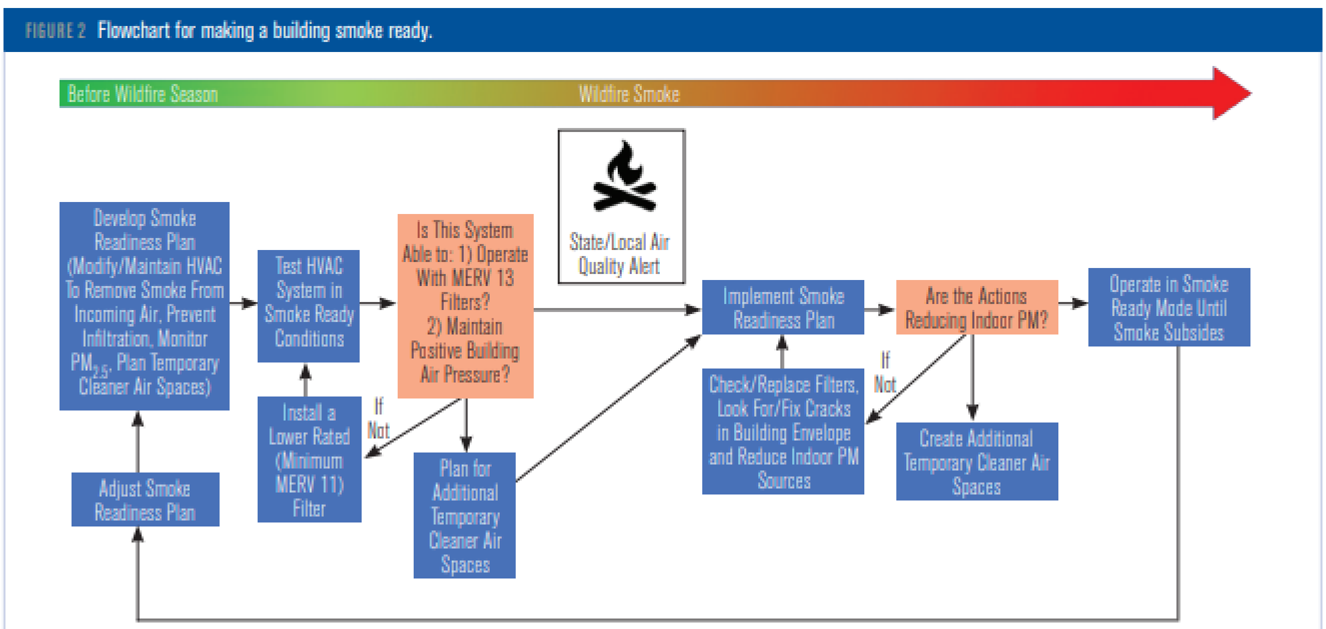


Figure 16 – Flowchart for Making a Building Smoke Ready (ASHRAE Guideline 44P)

A more familiar contaminant is carbon dioxide or CO2. The amount of CO2 in indoor air can be a good indicator of air quality, at least for indoor air contaminant sources. The outdoor CO2 level is about 400 parts per million (ppm) but this varies depending on location and is ever increasing as our economies continue to grow on fossil fuels. The indoor level is the outdoor level plus whatever accumulates indoors from any carbon dioxide sources there. The two primary CO2 sources indoors are combustion and breathing. If there is no internal occupant smoking or combustion devices, if any, are safely vented to the outdoors, then your main source of indoor CO2 is people.

Air contaminants and indoor air quality is a much broader spectrum than CO2, but it can play an important role in helping to achieve good indoor air quality, especially in regard to COVID-19. Measuring CO2 levels in indoor commercial environments may provide an indication of the degree of risk of aerosol transmission of COVID-19 in that space. This is something we investigate further later in this report.

Also the CO2 level is used as a proxy for indoor air quality because it indicates how much air exchange you have between indoors and outdoors. Of course, particulate matter 2.5 microns or smaller (PM2.5) is an important air pollutant mainly from outdoors that may get worse with more ventilation, so you cannot look at a low CO2 level and assume your IAQ is good. Likewise, you may have really low PM2.5 because of good filtration but high CO2 from poor outdoor air ventilation.

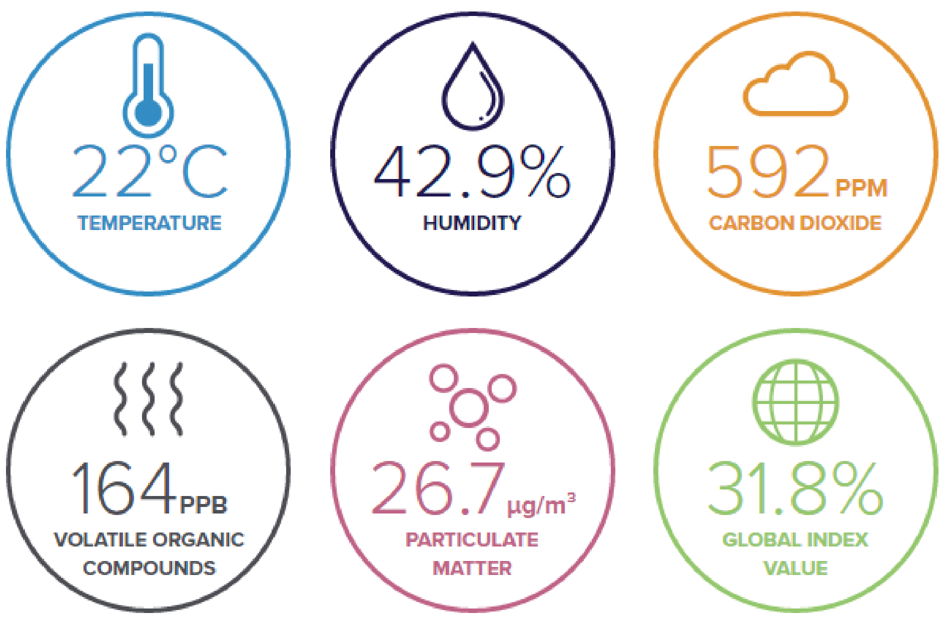


Figure 17 – Representative IAQ Metrics

As a result, to try a capture IAQ in a single metric the Indoor Air Quality Index (IAQI) was developed. It is simply an accessible, descriptive scale to show the level of contaminants or pollution in the air at that time. It is adapted from the U.S. Environmental Protection Agency (EPA) general Air Quality Index (AQI) which measures outdoor air quality in geographic regions by analysing levels of at least five major air pollutants (O3, PMs, CO, SO, NO) over time and assigning their concentration a number from 0 – 500, with the higher the AQI value in your area, the greater the level of air pollution.

Air Quality Index Levels of Health Concern	Numerical Value	Meaning
Good	0 to 50	Air quality is considered satisfactory, and air pollution poses little or no risk
Moderate	51 to 100	Air quality is acceptable; however, for some pollutants there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution.
Unhealthy for Sensitive Groups	101 to 150	Members of sensitive groups may experience health effects. The general public is not likely to be affected.
Unhealthy	151 to 200	Everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects.
Very Unhealthy	201 to 300	Health warnings of emergency conditions. The entire population is more likely to be affected.
Hazardous	301 to 500	Health alert: everyone may experience more serious health effects

Figure 18 – IAQ Index Summary

For indoor air quality index, the descriptive scale can be reused but there are some differences. Concentrations of indoor air contaminants can increase more rapidly in indoor environments and therefore real-time or close-time air quality measurements are required (e.g. every 5 minutes) to monitor changes. Additionally the analysed contaminants can be updated to better reflect the indoor environment (CO2, VOCs, RH for example) and the rating provided as the worst score of the measured contaminants rather than the average to ensure the highest quality of indoor air is targeted regardless of the air pollutant. Breeze Technologies discuss this concept of IAQI more on their website for those interested.

This indoor air quality metric is important as not only do we as humans now spend over 90% of our time indoors, but the often referenced Rule of "1000" estimates that a pollutant introduced indoors is 1000 times more likely to be inhaled compared to outdoors, so highlighting internal emissions sources and mitigating them is vital. CIBSE TM64 2020 Operational performance: *Indoor air quality – emissions sources and mitigation measures* is a fantastic resource for this and information on outdoor and indoor key contaminants of concern for commercial buildings. The guide details the key pollutants, their emission sources, and mitigation measures for typical building types, with an office open plan space example provided below. There are also credits and explanations available as part of the LEED building environmental rating system.

Operational performance:
Indoor air quality – Emissions sources and mitigation measures

CIBSE

TM64: 2020

2 Indoor air quality in offices

2.1 Outdoor sources of air pollution

Emissions sources:

road traffic | transport hubs | industry | thermal plants | construction sites | natural sources

Key pollutants:

nitrogen dioxide (NO_2) | particulates (PM) | allergens | radon (Rn)

Possible mitigation measures:

In some modern office buildings, mechanical ventilation and air conditioning systems have filters to trap particles and gaseous pollutants, and can effectively remove large particles such as pollen, which can cause seasonal allergies. Change or clean the filters regularly as per manufacturers' specifications.

Hot spots that are not related to road transport include transport hubs such as railway stations, airports and harbours. In addition to heavy road traffic near these facilities, diesel locomotives, airplanes and ships may emit considerable amounts of air pollutants in a short time, and emissions may be confined to the area. If not publicly available, ask your council to provide outdoor air quality data and advice for your local area. Use data to develop ventilation strategies accordingly (such as: placing inlets away from pollutant sources, including filtration in areas with highly polluted outdoor air, preparing manuals for efficient ventilation controls and window-opening advice based on historic peak pollutant times).

Construction sites are a source of dirt and debris. Liaise with the construction site manager. Clean filters more frequently during dust-generating activities. Reduce infiltration by sealing cracks.

Placement of grass, climbing ivy and other plants in urban canyons can slightly reduce concentrations of NO_2 and PM at street level. Trees can be effective, but only if care is taken to avoid trapping pollutants beneath their crowns.

Public Health England produces detailed advice on testing and remedial work required to reduce radon levels in buildings; this is available at https://www.ukradon.org.

2.2 Indoor sources of air pollution

2.2.1 Open plan offices

Emissions sources:

carpets | furniture | HVAC | people

Key pollutants:

volatile organic compounds (VOCs) | formaldehyde (VVOC) | particulates (PM) | allergens | bioeffluents

Possible mitigation measures:

If carpets are present, regular vacuuming and deep cleaning is recommended with low-VOC products.

Replace carpets with solid wood flooring or similar, as carpets are reservoirs of dust, pollutants and allergens and they emit VOCs. Adequate ventilation is essential; select durable low-VOC furniture materials and finishes that are simple to clean and maintain.

Temperature-induced increases in emissions can result from the use of radiant flooring (and solar gains). Special attention is required when selecting materials and finishes, while general management of temperature and humidity remains an assumed element of materials emissions control.

During renovation work that produces dust (such as floor sanding), seal inlets and outlets. Do not operate the heating and cooling system until after cleaning up the dust.

At completion of renovation work (when using products that release pollutants into the air such as paints and lacquers, paint strippers and varnishes) operate the building HVAC system at a higher than normal ventilation rate for a period of time to help flush the building of contaminants. Better still, operate source control by using low-VOC materials wherever possible.

Occupant density in London offices has increased significantly. In HVAC-serviced office buildings, ensure provision of appropriate outdoor air quantities for each zone.

Creating a comfortable thermal environment is important, as occupant perception of indoor air quality (IAQ) is closely related to thermal comfort. In addition to controlling temperature, consider monitoring (and if possible controlling) CO_2 concentrations in open plan offices.

Figure 19 – CIBSE TM61-64 Operational Performance Extract

Ventilation

I am not going to start this section with the definition of ventilation and an explanation of all the types (although a few first iterations of this report did have this). However for anyone looking for such information I recommend the CIBSE Guide B2 Ventilation and ductwork or the Knowledge Series (KS) 17 - Indoor air quality and ventilation, although you will struggle to find a consistent definition throughout literature for ventilation (which I discuss a bit more below). I will however borrow the latter's explanation for Indoor Air Quality (IAQ) and the stated requirements for good IAQ: -

> – the provision of sufficient 'fresh' air supply rates to dilute and remove pollutants
> – effective ventilation, i.e. providing ventilation where it is needed and in a form that will most efficiently remove pollutants
> – low external pollution concentrations
> – low pollutant emission rates from internal sources, including materials.

Therefore, in short good IAQ requires air pollution source control (detailed in the previous section) and effective ventilation, including filtration. The major role of ventilation is to secure optimum air quality for occupant health and comfort, but how much ventilation is needed and how do we provide this ventilation?

Figure 20 - Ventilation Graphic

The fact is that the rate of 'adequate' ventilation is still very much a mystery and can depend on a number of factors from the buildings function and construction materials to an occupant's expectations, diet and activity level.

Different research bodies and guidance documents provide various recommended ventilation rates for the same building type. Table 1 below provides a comparison of this in the typical l/s/person value for a mechanically ventilated open plan commercial office based on an occupancy density of 1 person per 10m2 :-

Table 1 - Minimum Ventilation Rates for Offices Across Standards

Minimum vent rates for offices with occupancy density of 1 person per 10m^2	
Part F of Building Regulations (UK/Ireland)	10 l/s per person
CIBSE Guide A, Table 1.5	10 l/s per person
BS EN 16798-1 2019, (assuming *Category II* and *low polluted building)* Compliant with WELL Feature A03 & A06	14 l/s per person
ASHRAE Standard 62.1-2013 Assuming a ventilation effectiveness factor of 1 – see below. Compliant with LEED IEQ prerequisite (& +30% for credit)	5.5 l/s per person
British Council for Offices (BCO) Guide to Specification 2014 Compliant with BREEAM NC 2014 Hea 02, Ventilation credit.	12– 16 l/s per person + 10% allowance for speculative buildings

Several research studies of Lemberg and later Yaglou published across several ASHRAE papers showed that occupant perception of body odor produced by humans could be used as a criterion for ventilation. Perceived odor intensity was used as a criterion for ventilation rate requirements of about 7.5 to 10 L/s (15 to 20 cfm) per person, and CO2 was not considered to be a pollutant but rather an indicator of body odour. Studies in the latter part of the twentieth century by Fanger, Cain, and Iwashita confirmed the results of Yaglou and Lemberg which is the basis for many of our ventilation standards and recommended minimum ventilation rates today.

The ASHRAE 62.1 rates appear to have some scientific basis and Appendix I in the standard tries to provide a description and rationale for ventilation rates specified, but in most cases they were developed by the members of the committee that authored the standard, as explained in the Standard 62.1 User's Manual.

Table I-1 Rate Rationale (see Table 6-1)

Occupancy Category	Description/Rationale	People Outdoor Air Rate, cfm/person	People Outdoor Air Rate, L/s/person	Area Outdoor Air Rate, cfm/ft²	Area Outdoor Air Rate, L/s·m²	Air Class
Correctional Facilities						
Booking/waiting	Occupant activity varies between sedentary and moderate walking. Occupants are generally more vocal. Occupants may not be as well-groomed as typical occupants. Occupant stress levels are generally high. All of which result in higher metabolic rates. There are no significant space-related contaminants.	7.5	3.8	0.06	0.3	2
Cell	Occupant activity is primarily sedentary (seated or sleeping). There are typically higher levels of space-related contaminants due to presence of a water closet, sink, and stored clothing. The presence of a water closet is the primary reason why this space has an Air Class of 2.	5	2.5	0.12	0.6	2
Day room	Occupant activity is primarily sedentary (seated, watching television). There are no significant space-related contaminants.	5	2.5	0.06	0.3	1
Guard stations	Occupant activity is primarily sedentary (seated). There are no significant space-related contaminants.	5	2.5	0.06	0.3	1
Educational Facilities						
Art classroom	Occupant activity is moderate. There is considerable aerobic activity in addition to the occupants being very vocal. Also, the occupants are primarily children with higher metabolic rates. There are significant space-related contaminants, including open paints, glues, and cleaning agents. The presence of these open contaminants result in this space being classified as Air Class 2.	10	5	0.18	0.9	2
Classrooms (ages 5 through 8)	Occupant activity is primarily sedentary (seated or light walking). However, occupants are generally more vocal. Also, the occupants are primarily children with higher metabolic rates and often more bioeffluents. There are some significant space-related contaminants, typically stored arts-and-crafts supplies and cleaning agents.	10	5	0.12	0.6	1

Figure 21 – ASHRAE 62.1 Appendix I Extract on Ventilation Rate Rationale

CIBSE Guides A & B2 on the other hand, still reference BS 5925: 1991 'Code of practice for ventilation principles and designing for natural ventilation' for some ventilation rates, in which Table 4 of this British Standard implies 'some' smoking may still be occurring in offices which tells you just how out of date that guide is!

Interesting to see that smoking in a building recommended a higher outdoor air supply rate person. Should there be such an increase recommended to allow for possible virus pollution in a building? That is something we look at a little later on.

(b) Recommended outdoor air supply rates for sedentary occupants (From reference [16])	
Condition	**Recommended outdoor air supply rate**
	L/s per person
With no smoking	8
With some smoking	16
With heavy smoking	24
With very heavy smoking	32

[1] See statutory requirements and local bye-laws.
[2] Rate of extraction may be overriding factor.
[3] Where queuing occurs in the space, the seating capacity may not be the appropriate occupancy.
NOTE 1. For hospital wards and operating theatres see Department of Health and Social Security Building Notes.
NOTE 2. The outdoor air supply rates given take account of the likely density of occupation and the type and amount of smoking.

Figure 22 – BS 5925: 1991 Code of Practice for Ventilation Principles and Designing for Natural Ventilation Extract

Ventilation should be balanced against other factors, particularly thermal comfort.
It should be noted that these specified ventilation rates are based on comfort - air quality principles and do not necessarily reflect the purity of air with respect to contaminants. Persons adaptability and comfort range, and the related ventilation rates are considered in EN15251 & BS EN 16798 where occupants who have adapted to the air quality for at least 15 minutes - it is estimated that one third of the ventilation rate is sufficient.

This lower adapted ventilation rate is likely most applicable to spaces that are relatively free from sources of pollution, and for ventilation air that is itself is 'clean' but that is an assumption we often make. In addition, for any particular concerning contaminants of a known source (e.g. printing room emissions) Local Exhaust Ventilation (LEV) should be provided. Refer to TR40 – *A guide to good practice for local exhaust ventilation* by the Institute of Local Exhaust Ventilation Engineers (ILEVE) with the Building Engineering Services Association (BESA) for further guidance.

I think it is clear that the specification of adequate ventilation is open to interpretation. Thankfully, *BS EN 16798 Energy performance of buildings. Ventilation for buildings* provides us with 3 methodologies to calculate an 'adequate' ventilation rate required to maintain good IAQ based on the level of expectation of occupants;

1. Method 1 based on perceived IAQ
2. Method 2 based on limit values for substance concentration
3. Method 3 based on predefined ventilation air flow rates

These methodologies have been around for a long time, and define or categorise adequate Indoor Environmental Quality (IEQ), which we can simplify to IAQ as we are focusing on ventilation, based on the level of expectation of building occupants (almost identical to the indoor air quality (IDA) classifications from CIBSE Guide A based on BS EN 13779 – the previous version of BS EN 16798).

Category	Level of expectation	Explanation
IEQ_{I}	High	Should be selected for occupants with special needs (children, elderly, persons with disabilities).
IEQ_{II}	Medium	The normal level used for design and operation.
IEQ_{III}	Moderate	Will still provide an acceptable environment. Some risk of reduced performance of the occupants.
IEQ_{IV}	Low	Should only be used for a short time of the year or in spaces with very short time of occupancy.

Figure 23 – IEQ – IAQ Classifications from BS EN 13779

Method 1 is based on perceived IAQ calculates the ventilation rate based on a function of both people-related and building-related indoor pollutants as the sum two components (shown mathematically below):-

1. ventilation to dilute/remove pollution from the occupants (q_p)
2. ventilation to remove/dilute pollution from the building and systems (q_B)

$$q_{tot} = n \cdot q_p + A_R \cdot q_B$$

where

q_{tot}	= total ventilation rate for the breathing zone, l/s
n	= design value for the number of the persons in the room,
q_p	= ventilation rate for occupancy per person, l/(s person)
A_R	= floor area, m^2
q_B	= ventilation rate for emissions from building, l/(s·m^2)

Therefore for a given IAQ expectation, the total 'adequate' ventilation rate will then depend on building occupancy (n) and building floor area at selected building pollution level type (A_R).

The recommended ventilation rate to dilute/remove pollution from the non- adapted occupants (q_p), and to remove/dilute pollution from the building and systems (q_B) for each IAQ category are provided below:-

Category	Airflow per non-adapted person l/(s per person)	Very low polluting building, LPB-1 l/(s m^2)	Low polluting building, LPB-2 l/(s m^2)	Non low-polluting building, LPB-3 l/(s m^2)
I	10	0,5	1,0	2,0
II	7	0,35	0,7	1,4
III	4	0,2	0,4	0,8
IV	2,5	0,15	0,3	0,6

Figure 24 – BS EN 16798 Method 1 Recommended Ventilation Rates for Occupancy & Building Pollution Dilution

These per person and per building floor area ventilation rates are combined to sum a total design ventilation rate.

However, no evidence or explanation was found why the ‘persons’ ventilation specified to remove bio-effluents cannot dilute building emissions at the same time and act as the 'buildings’ ventilation. Ventilation has been shown to be able to dilute and remove both contamination from both sources once it is distributed and delivered correctly.

Nevertheless, using this method and taking a 10m2, single non-adapted person occupancy, low emitting material office space as an example, the adequate ventilation rate for each IAQ category is provided below;

Category	Low-polluting building	Airflow per non-adapted person	Total design ventilation air flow rate for the room expressed in different ways		
	$l/(s \cdot m^2)$	l/(s per person)	l/s	l/(s per person)	$l/(s \cdot m^2)$
I	1,0	10	20	20	2
II	0,7	7	14	14	1,4
III	0,4	4	8	8	0,8
IV	0,3	2,5	5,5	5,5	0,55

Figure 25 – BS EN 16798 Method 1 Recommended Combined Ventilation Rates

However, what is a non-adapted person, and how does a designer know if a building is low, very low or non-low polluting building?

In terms of non-adapted persons, an adapted person is defined as a person that has occupied a space for more than 15 minutes and then adapted to the odour level of bio effluent from the occupants therefore, a non-adapted person is an occupant outside this i.e. short term in the space or has not adapted - however persons tend to adapt very quickly to the odour (bio effluents) in a space, whereas there is less adaption to emissions from building materials and tobacco smoke for example.

Adapted ventilation rates are proposed as an approach to design specific room types for adapted persons, e.g. auditoriums, cinemas, classrooms where an occupant in the environment for greater than 15 minutes and has adjusted to it. To use design for adapted persons in these types of rooms will require an airing or strong ventilation between sessions (<3 ACH). As shown below adapted ventilation rates can be 1/3 non-adapted rates which can have a significant effect on CO2 levels and possible IAQ. People only adapt to the bio effluents like CO2 and odour so consideration of building related contaminants such as VOCs is still required. In most cases the non-adapted person airflow rates are used.

Category	Expected Percentage of Dissatisfied	Airflow per non-adapted person l/s/ person	Airflow per adapted person l/s/ person
I	15	10	3,5
II	20	7	2,5
III	30	4	1,5
IV	40	2,5	1,0
EN 16798–1 requires a minimum of 4 l/s per person of total ventilation. The value is based on an European study Ventilation and Health and was recommended where the major contributor to the emission would be people.			

Figure 26 – BS EN 16798 Method 1 Basic Ventilation Rates for Diluting Bio-effluent Emissions from People

A typical building is assumed to be low-polluting in that the majority of building materials are low emitting and activity does not result in pollution of the building (e.g. smoking). The category very low-polluting requires that the majority of building materials used for finishing the interior surfaces meet the national or international criteria of very low-polluting materials (e.g. achieving of LEED Material & resources credits). The category non-low polluting building is the opposite and would require the building to have used or include known polluting materials or polluting activity (e.g. industrial activity or smoking).

The more scientific example definition for material pollution emission levels to European standard EN 16516 is given in the table below.

SOURCE	Low emitting products for low polluted buildings	Very low emitting products for very low polluted buildings
Total VOCs TVOC (as in EN 16516)	$< 1\,000$ µg/m^3	< 300 µg/m^3
Formaldehyde	< 100 µg/m^3	< 30 µg/m^3
Any C1A or C1B classified carcinogenic VOC	< 5 µg/m^3	< 5 µg/m^3

Figure 27 - EN 16516 Definition for Material Pollution Emission Levels

This method is specified in both ASHRAE 62.1 and EN IS 15251 so is commonly used in American and select European regions for ventilation rates calculation.

Method 2 is based on limit values for substance concentration in a space and takes into account the generation rate, outdoor concentration, and ventilation system effectiveness (shown mathematically below):-

$$Q_h = \frac{G_h}{C_{h,i} - C_{h,o}} \cdot \frac{1}{\varepsilon_v}$$

where

Q_h is the ventilation rate required for dilution, in m^3 per second;

G_h is the generation rate of the substance, in micrograms per second;

$C_{h,i}$ is the guideline value of the substance, in micrograms per m^3;

$C_{h,o}$ is the concentration of the substance of the supply air, in micrograms per m^3;

ε_v is the ventilation effectiveness.

CIBSE KS17 gives a great derivation of this formula if of interest and also provides ventilation effectiveness (E_v) values for given ventilation distribution systems. The equation is independent of occupancy which is incorporated in the generation rate (i.e. the product of the CO2 generation rate per person by the occupancy).

The design ventilation rates are calculated based on a mass balance formula for the substance concentration to a guideline value for a known indoor generation rate and outdoor air concentration. It applies to steady-state conditions which may not always be true in a busy commercial environment but useful at design stage calculations and possibly post-occupancy checks at known conditions.

Typically used as tracer of human occupancy as known steady-state generation rates and external concentrations exist, CO2 concentration levels are given as the default limit values for each IAQ category for this method as shown in the table below.

Default design CO_2 concentrations above outdoor concentration assuming standard CO_2 emission of 20 L/(h per person)

Category	Corresponding CO_2 concentration above outdoors in PPM for non-adapted persons
I	550 (10)
II	800 (7)
III	1 350 (4)
IV	1 350 (4)

Figure 28 – BS EN 16798 Method 2 Default Design CO2 Concentrations

Values are stated to be the recommended or acceptable change in CO2 concentration above outdoors (i.e. inside CO2 value minus outdoor CO2 value) for each IAQ category (with the approximate ventilation rate in litres per second per person in brackets also). These approximate ventilation rate values are lower than the method 1 and method 3 specified values as it only accounts for 'person' ventilation based on CO2 and not 'building' ventilation. If building pollution is a concern a separate calculation using the most critical building contaminant values and the same formula is recommended with the ventilation value added to the 'person' ventilation value for the total design ventilation. However, again it is noted that no explanation is provided.

This method ventilation rate specification has been available for some time, both CIBSE Guide A & B2 include the methodology however, a quick poll within my own office of its usage or even familiarity would suggest that it is unheard of – with a strong preference towards the prescriptive method by mechanical engineers polled.

Method 3 based on predefined ventilation air flow rates is the simplest of all these methods and uses pre-defined, prescriptive ventilation airflow rates estimated to meet needs for perceived air quality and health of occupants.

The pre-defined ventilation air flow rates can be expressed by a combination of one or more of the following components:

- total design ventilation for people and building components (qtot);
- design ventilation per unit floor area (qm2);
- design ventilation per person (qp);
- design air change rates (ACH);

These pre-defined values can vary depending on source, such as in Table 1 above, however BS EN 16798-1 2019 does provide design ventilation air flow rates as a required rate per person (l/(s per person)), or as a required rate per m2 floor area (l/(s·m2) for each IAQ category as shown below.

Category	Total design ventilation air flow rate for the room	
	l/(s per person)	$l/(s·m^2)$
I	20	2
II	14	1,4
III	8	0,8
IV	5,5	0,55

Figure 29 - BS EN 16798 Recommended Total Design Ventilation Airflow Rate – Typical Building

If design rates are given for both per person and per m2 the higher ventilation air flow rate should be used for design. Interestingly ventilation rates per person are preferred for occupied zones and ventilation rates per floor are preferred for unoccupied zones. The BS EN 16798-1 2019 recommended ventilation rates (l/(s·m2) for each IAQ category (labelled SUP for supply air in table below) for zones <u>not</u> designed for human occupancy are provided below.

Category	Unit	Rate of outdoor or transferred air per unit floor area	
		Typical range	Default value
SUP 1	$l.s^{-1}.m^{-2}$	a	a
SUP 2	$l.s^{-1}.m^{-2}$	> 0,7	0,83
SUP 3	$l.s^{-1}.m^{-2}$	0,35 – 0,7	0,55
SUP 4	$l.s^{-1}.m^{-2}$	< 0,35	0,28
[a] For SUP 1 this method is not sufficient			

Figure 30 - BS EN 16798 Recommended Ventilation Airflow Rate – Zones Not Designed for Human Occupancy

These values, while important to note, generally align with the typically low polluting building ventilation rate values from Figure 23 in Method 1 above, and therefore can be forgotten in favour of those more detailed ventilation rates. Also, from this it can be concluded that the building floor area ventilation rates are suitable only to ventilate a building with no occupancy and therefore can function as a minimum setback or unoccupied room air flow rate.

In my opinion, one clear advantage of the predefined ventilation method is the use design air change rates (ACH) for ventilation rate specification. Simply the measure of the air volume added to or removed from a space in one hour, divided by the volume of the space (or space breathing zone volume depending on source or designer specifying).

This simple, accessible metric is proven to provide indoor air dilution and pollution concentration reduction up to 99%, particularly at high ACH (i.e. > 6) as shown in the graph below.

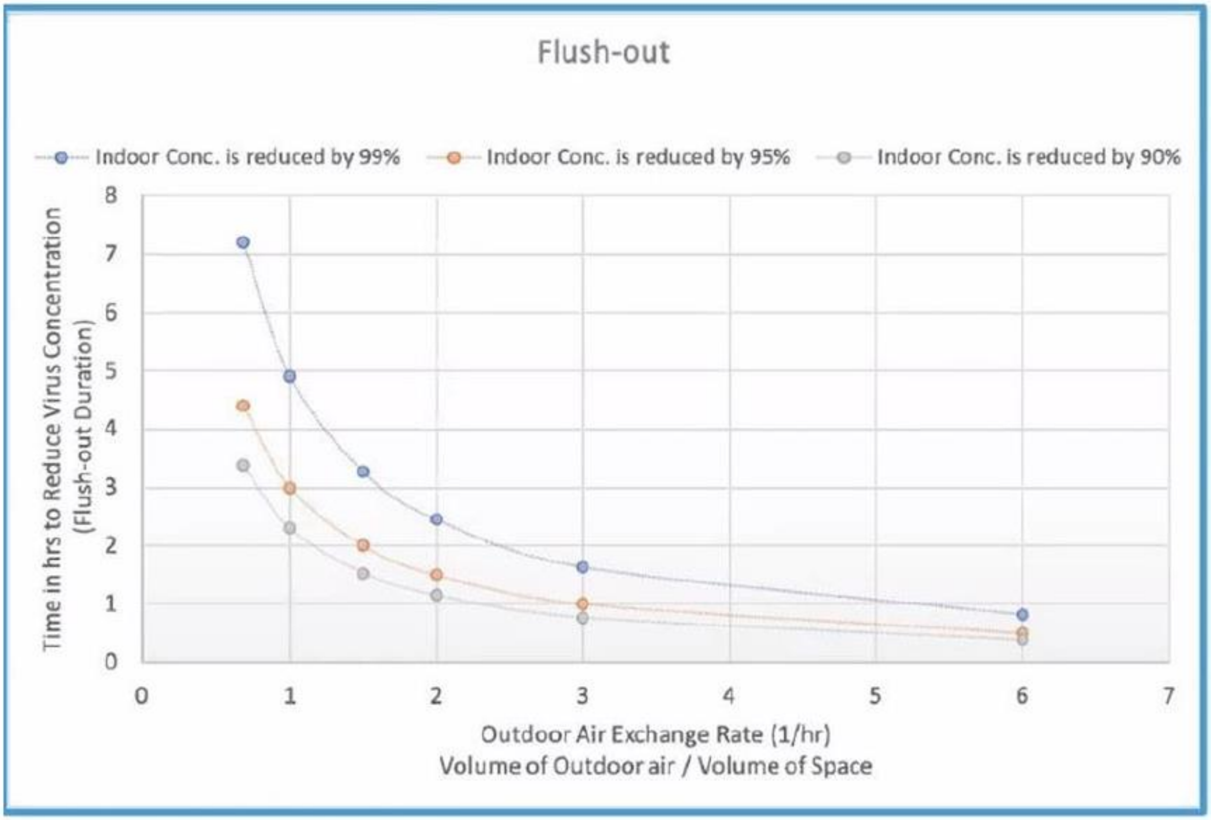


Figure 31 - Ventilation Flush Out Graph - ACH vs Time (hrs)

Overall this accessible and prescriptive method using predefined ventilation values is the simplest and one of the most widespread 'adequate' ventilation rate specification methodologies, being the preferred method of all the mechanical design engineers I quickly polled in a major engineering consultancy across several international offices.

However, while its merits are clear, this methodology is open to interpretation at design stage, it does not directly take into account the proposed building ventilation strategy and system effectiveness and it can be difficult to monitor during the pivotal operational stage of a building. Therefore, I suggest it is time for a more widespread updated ventilation methodology for buildings in the new normal which is detailed further in the research section of this report.

One additional comment on ventilation - does ventilation need to be from outside air? Some references (REHAVA, CIBSE) define ventilation as the exchange of indoor air with 'fresh air' but what constitutes as fresh?

BS EN 16798-1 2019 – Ventilation for buildings defines goes further and defines ventilation as the process of providing outdoor air to a building, whereas ASHRAE Standard 62.1 defines ventilation as 'the process of supplying air or removing air from a space for the purpose of controlling air contaminant levels…', not mentioning outdoor air at all.

This opens the door for air recirculation and filtration as a source of ventilation, or additional ventilation particularly in the case of high ACH requirements.

ASHRAE Standard 62.1 guidance appears to already be taking air recirculation and filtration into account in some of its calculation methodology as shown below.

Table E-1 Required Zone Outdoor Airflow or Space Breathing Zone Contaminant Concentration with Recirculation and Filtration for Single-Zone Systems

Required Recirculation Rate			Required Zone Outdoor Airflow (V_{oz} in Section 6)	Space Breathing Zone Contaminant Concentration
Filter Location	Flow	Outdoor Airflow		
None	VAV	100%	$V_{oz} = \frac{N}{E_z F_r (C_{bz} - C_o)}$	$C_{bz} = C_o + \frac{N}{E_z F_r V_{oz}}$
A	Constant	Constant	$V_{oz} = \frac{N - E_z R V_r E_f C_{bz}}{E_z (C_{bz} - C_o)}$	$C_{bz} = \frac{N + E_z V_{oz} C_o}{E_z (V_{oz} + R V_r E_f)}$
A	VAV	Constant	$V_{oz} = \frac{N - E_z F_r R V_r E_f C_{bz}}{E_z (C_{bz} - C_o)}$	$C_{bz} = \frac{N + E_z V_{oz} C_o}{E_z (V_{oz} + F_r R V_r E_f)}$
B	Constant	Constant	$V_{oz} = \frac{N - E_z R V_r E_f C_{bz}}{E_z [C_{bz} - (1 - E_f)(C_o)]}$	$C_{bz} = \frac{N + E_z V_{oz} (1 - E_f) C_o}{E_z (V_{oz} + R V_r E_f)}$
B	VAV	100%	$V_{oz} = \frac{N}{E_z F_r [C_{bz} - (1 - E_f)(C_o)]}$	$C_{bz} = \frac{N + E_z F_r V_{oz} (1 - E_f) C_o}{E_z F_r V_{oz}}$
B	VAV	Constant	$V_{oz} = \frac{N - E_z F_r R V_r E_f C_{bz}}{E_z [C_{bz} - (1 - E_f)(C_o)]}$	$C_{bz} = \frac{N + E_z V_{oz} (1 - E_f) C_o}{E_z (V_{oz} + F_r R V_r E_f)}$

Symbol or Subscript	Definition
A, *B*	filter location
V	volumetric flow
C	contaminant concentration
E_z	zone air distribution effectiveness
E_f	filter efficiency
F_r	design flow reduction fraction factor
N	contaminant generation rate
R	recirculation flow factor
Subscript: *o*	outdoor
Subscript: *r*	return
Subscript: *b*	breathing
Subscript: *z*	zone

Figure 32 - ASHRAE Standard 62.1 Appendix Recirculation Ventilation Calculations

The above prescribed calculation methodology also takes into account ventilation system effectiveness along with filtration levels. This can not only help promote the consideration of these important factors in ventilation systems but also provides a possible opportunity to meet the IAQ needs of building occupants while reducing the environmental burden of a mechanical HVAC system.

Ventilation Systems

I will keep this section short as it would be my hope that the majority of the readers of this will be familiar with mechanical ventilation systems and their operation which, in a broad sense, can be broken into 2 main types:

Dedicated Outdoor Air Supply (DOAS)

This system is composed of an AHU with a separate supply and exhaust channel which is never mixed, supplying 100% outdoor air to zonal systems such as chilled beams, radiant panels, and fan-coils. Outside air is generally pre-conditioned through a heat recovery device such as a thermal wheel (see below section on heat recovery for more information) extracting useful energy from the exhausting return air.

Heating and cooling is divided between two parallel systems, the AHU handles both the latent and sensible loads, and typically a zonal system handling mostly sensible loads.

The supply air rate is usually equal to the design value, typically code minimum outdoor air rate or a percentage above that (30% is a common value based on LEED credit requirements) to improve indoor air quality, provide flexibility in the types of spaces served, and sometimes to enhance zonal system heating and cooling capacity. Generally air is supplied at a constant rate on a schedule, or is variable using fan speed control strategies as applicable.

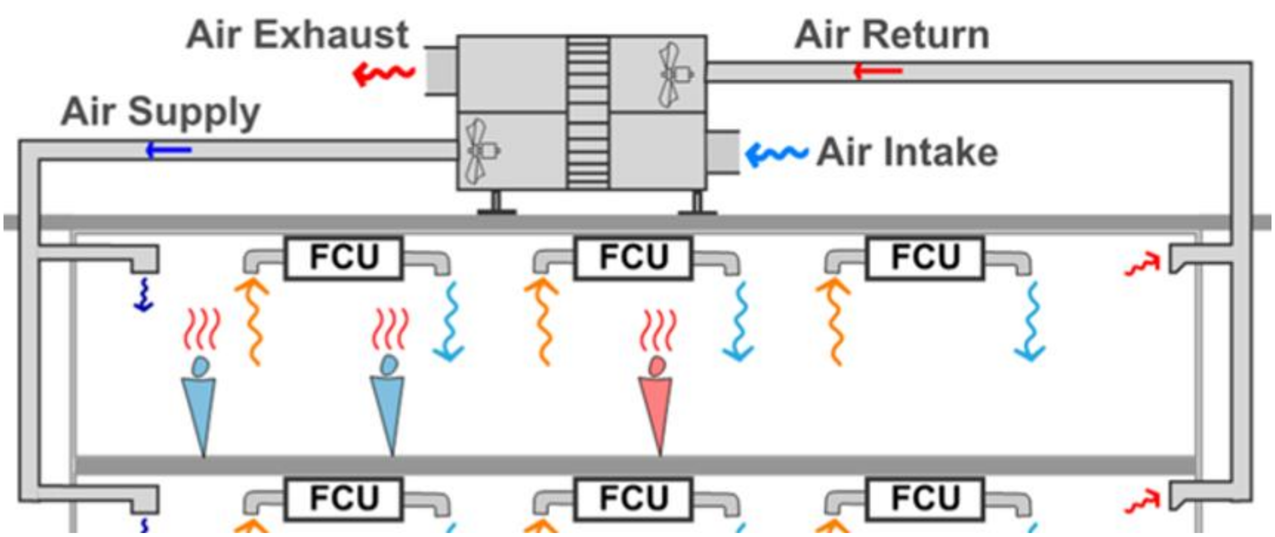


Figure 33 - Dedicated Outdoor Aur Supply (DOAS) Ventilation System Schematic

Recirculation - Variable Air Volume (VAV) systems

This system is composed of an AHU supplying a mixture of outdoor air and recirculated air to terminal units or diffusers (usually via VAV boxes) that control airflow to the space to meet heating and cooling loads.

The design supply air rate is based on peak cooling loads, typically multiple times the code minimum outdoor air rate. Recirculating VAV systems include mixing dampers i.e. the ability to mix return air with outside air to precondition supply air, and outdoor air economizers, i.e. the ability to bring in additional outdoor air, up to 100% of the supply air, when the weather is mild and cool.

Increasing minimum ventilation outdoor air rates will be limited by the capacity of the heating and cooling systems both of which were typically sized for the design minimum (usually 30%) at the design-day maximum external air conditions.

Outdoor airflow can be altered using fan speed control strategies and the outside air economizer / return air damper but with care to not cause associated temperature control problems. Constant air volume recirculation systems are available but are less utilised within the industry due to their relative inefficiency and limited control, hence the VAV type system is detailed here.

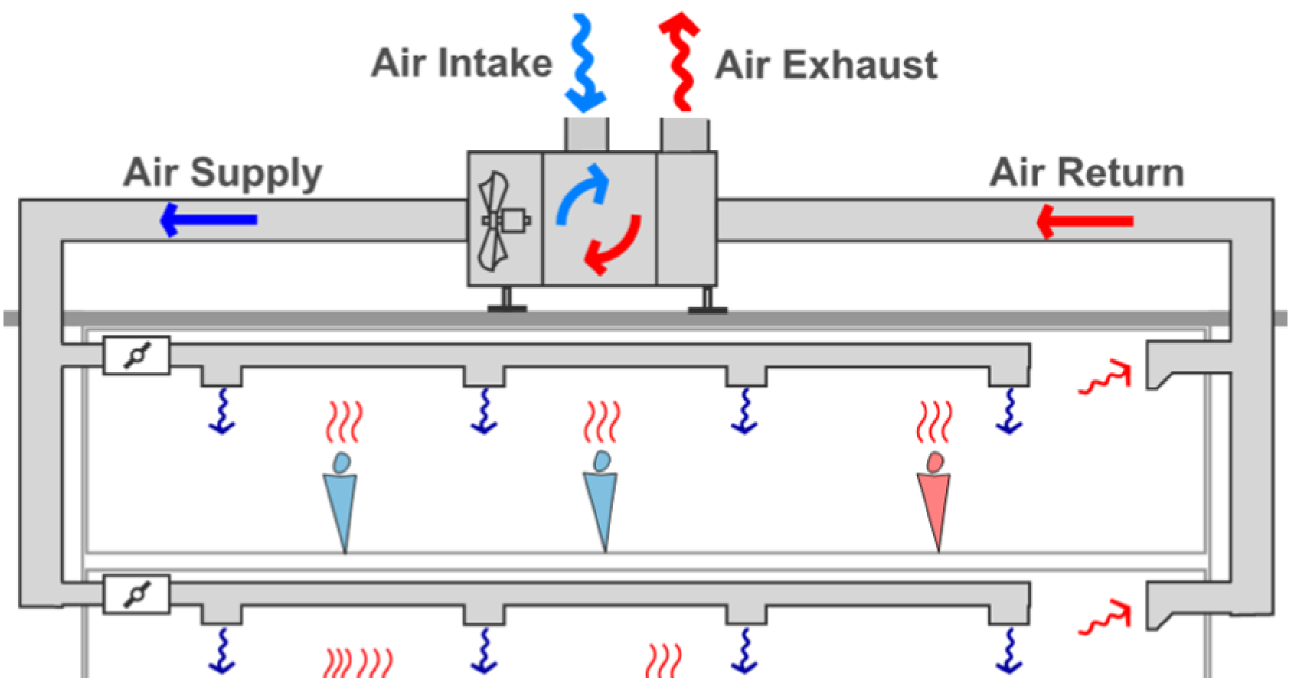


Figure 34 - Recirculation - Variable Air Volume (VAV) systems Schematic

Recirculation VAV systems are typically capital cost effective from a chilled-water and heating-water-pumping perspective Because the unit transfers heat to the space using forced convection and does not require a zonal parallel heating and cooling system.

On the other hand, because the central air handling unit provides all cooling to the spaces, it is required to move a much greater volume of air, but is this an issue in the age of the 'new normal' promoting increased air changes? This larger volume of air does increase energy consumption and duct sizes which does effect sustainability considerations.

DOAS requires minimal air side infrastructure because central air systems are only required for outdoor air ventilation. The result is reduced floor space requirement for central air handling equipment and vertical duct risers. With DOAS the advantages of generally constant air volume, or varied based on demand — namely, reliability and humidity control — simultaneously limit the ventilation supply flowrate once installed therefore detailed consideration of ventilation requirement at design stage is important.

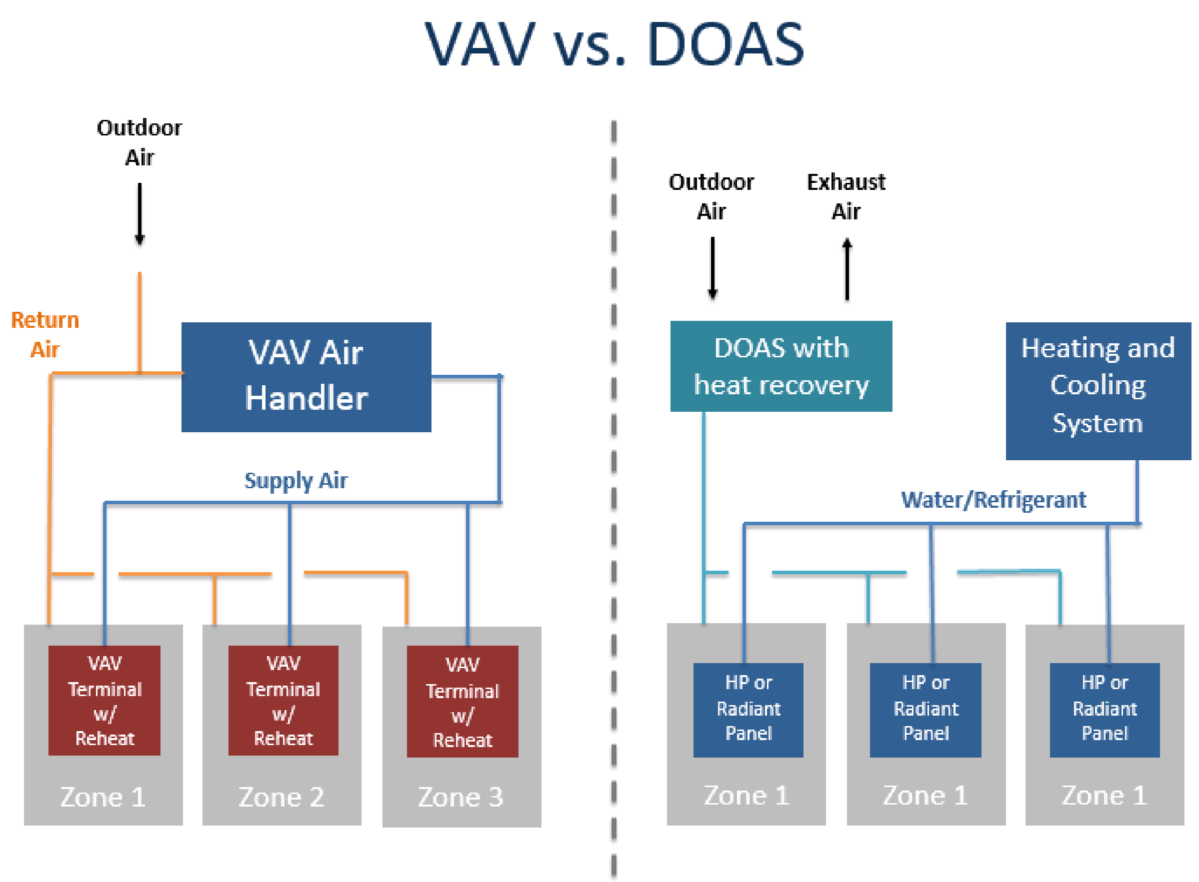


Figure 35 - Ventilation Systems - Recirc. VAV vs DOAS

There are several different types of smaller ventilation systems including Roof-Top Units (RTUs) and Through–Wall Units (TWUs), and several different variations of the DOAS and recirculating VAV systems. I found no one guide that covered them all but as always [CIBSE](#) had several good resources providing information on them all if more information is required.

Ventilation Distribution Systems

Again, keeping it brief and in a broad sense, distribution systems can be broken into three types:

1. Mixing
2. Displacement
3. Personal Ventilation

The final ventilation distribution system of personal ventilation is relatively new (or at least re-newed) and unused in modern building environments, but research and application from medical fields is slowly seeping out into the commercial built environment as discussed later in this section.
There is also what some may consider another ventilation distribution system of a recirculating ventilation systems which typically just move indoor air around (like a standard AC unit) but this does not introduce outside air which then must be sourced from another ventilation strategy so is not often singly employed. In some cases it can include a mixing of indoor air with outdoor air before pumping it into the room (like an un-ducted ceiling FCU system) but this is often categorised under the mixing ventilation system detailed below.

Mixing Ventilation

Mixing ventilation is arguably the most common and well known of the ventilation distribution systems, despite a surge of displacement ventilation systems in the 1970s and 80s. Mixing ventilation generally supply air in a manner such that the entire room volume is fully mixed. The cool supply air exits the outlet at a high velocity, inducing room air to provide mixing and temperature equalization. As a consequence, air diffusion and hence diffuser selection is important to ensure the throw, spread and drop (if you are not familiar with these terms check out this quick video by Osama Khayata) achieve the right distribution characteristics and thermal comfort.
With correct diffusion the entire room is fully mixed, temperature variations throughout the space are small, while the contaminant concentration is uniform throughout the zone. Therefore, air velocity, air temperatures and humidity will be distributed identically and in theory the air quality will be the same everywhere in the room, although from CFD analysis we know there to be some non-uniformity which is not detrimental.

Mixed air ventilation can help dilute the concentration of contaminants in the air but is less effective at removal of contaminants from the breathing zone, which can increase the risk of viral transmission compared to other distribution strategies such as displacement ventilation.

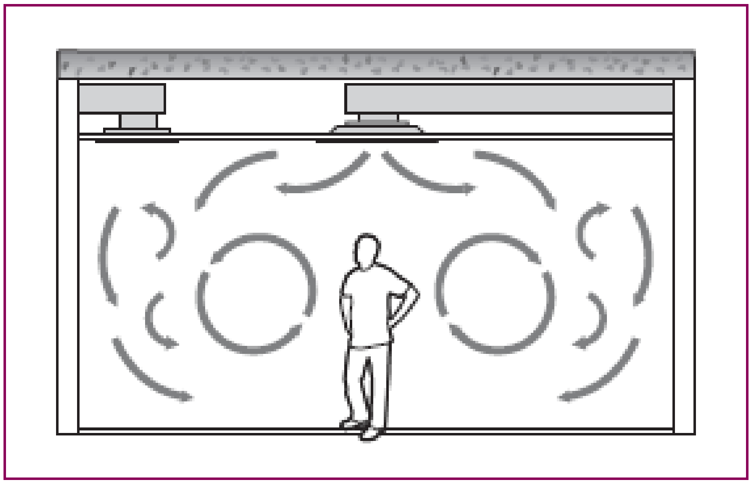


Figure 36 - Mixing Ventilation Graphic

Displacement Ventilation

Displacement ventilation systems introduce air into the space at lower temperatures and velocities, usually also at a low level, which causes minimal induction and mixing. The system uses buoyancy forces in a room, generated by heat sources such as people, lighting, electrical equipment etc., to upwardly remove contaminants and heat from the occupied zone. Therefore zone ceiling height above breathing zone level is required to be effective. Cooled air buoyancy forces ensure that this supply air pools near the floor level, allowing it to be then carried up into the thermal plumes that are formed by heat sources. This type of air distribution is effective at delivering fresh air to occupants and to upwardly remove contaminants and heat from the occupied zone. As a result displacement ventilation typical has a ventilation effectiveness value 20-50% greater than mixing ventilation (depending on supply air temperatures). Displacement ventilation with lower air velocities and higher supply air temperatures is shown to provide the required thermal comfort level at over 20% less thermal energy load compared to mixing ventilation.

Diffuser selection is simpler than in mixing ventilation as displacements inherent characteristics make the concepts of throw, spread and drop redundant however, diffuser sizes, location and adjacent air velocity to create drafts is the primary concern while zone geometry and any airflow obstacles also need to be considered.

Supply air temperature, particularly in the heating mode, must not be too high to avoid 'short circuiting' of air flows to the high level return.

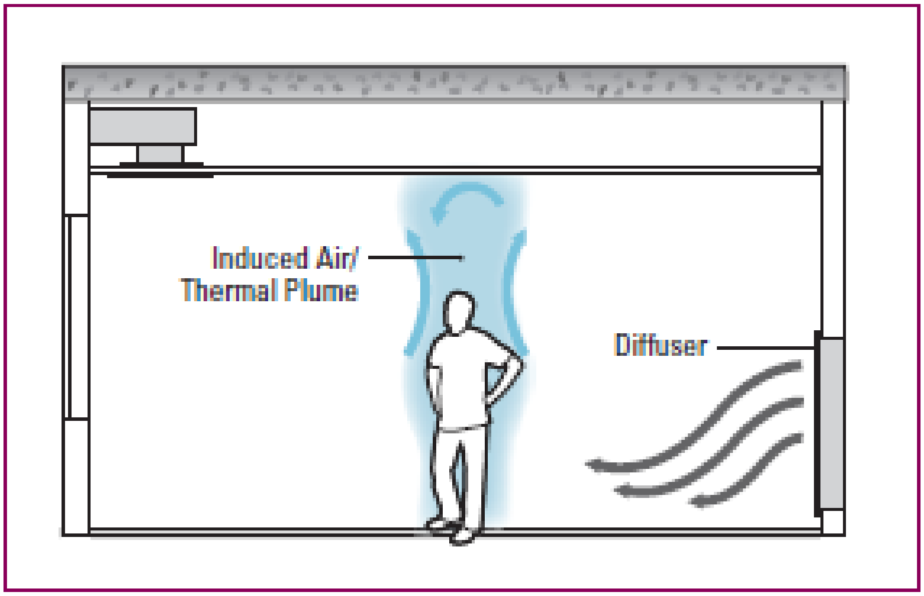


Figure 37 – Displacement Ventilation Graphic

In terms of COVID-19 transmission risk, studies suggest that the displacement ventilation technique produces a better overall performance on reducing the viral airborne infection risk than the conventional mixed ventilation mode.

Displacement ventilation utilises its inherent buoyant characteristic to transport contaminants including virus particles to the ceiling region and out of the breathing zone, and the strategy has been associated with the enhancement of thermal comfort and energy use reduction. These benefits are roughly captured in displacement ventilations increased ventilation effectiveness over mixing ventilation; a concept explained in more detail in the next section of this report. It is worth noting that in real life applications, air mixing is likely to occur even in displacement ventilation strategies with air movement associated with infiltration, desktop fans and occupant movement overcoming buoyancy air velocities. Also, some research has raised concerns about reintroducing falling larger contaminant aerosols through displacement buoyancy forces (Pantelic & Tham 2013[12], Bolashikov et al. 2012[13]) however, this is still debatable and generally overcome by the numerous benefits of displacement ventilation in my opinion.

[12] Pantelic J., Tham K.W. Adequacy of air change rate as the sole indicator of an air distribution system's effectiveness to mitigate airborne infectious disease transmission caused by a cough release in the room with overhead mixing ventilation: a case study. *HVAC R Res.* 2013;19(8):947–961.

[13] Bolashikov Z.D., Melikov A.K. Methods for air cleaning and protection of building occupants from airborne pathogens. Build. Environ. 2009;44(7):1378–1385. [PMC free article]

Personal Ventilation

Personal Ventilation (PV) system facilitates the provision of heating, cooling and ventilation air directly to an occupant, rather than conditioning an entire space. It typically consists of desk or ceiling-mounted modules that provide fresh air to the breathing zone of the workstation occupant. It is an almost unseen concept in the commercial building environment but has gained more interest since the COVID-19 pandemic. The performance of a PV system depends on the physical configuration, the supplied airflow rate and speed, the overall interaction of the airflow with the thermal plume, and the contributions from the room's total volume ventilation – and hence is generally considered in combination with another distribution system, usually mixed ventilation.

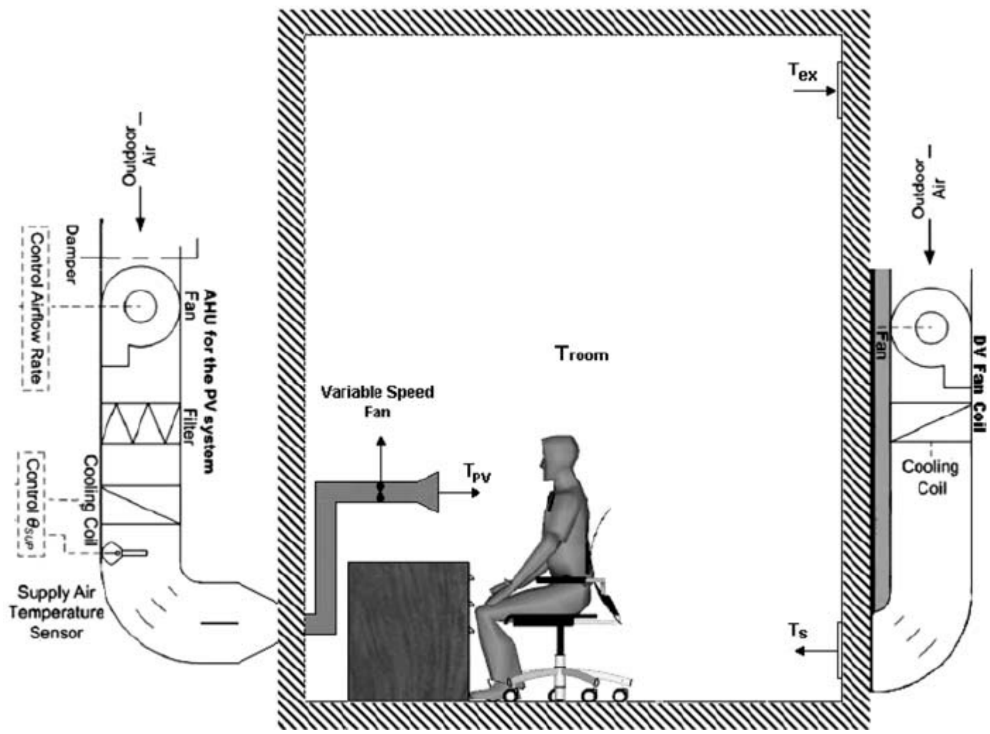


Figure 38 - Diagram of proposed Personal Ventilation (PV) system with Secondary General room air supply14

Personal ventilation has been widely studied in the medical industry and particularly combatting COVID-19 virus transmission in medical settings. Unsurprisingly it has been found to be one of the most effective methods to reducing virus transmission risk with individual clean air supplies to each occupant typically displacing any possible 'stale' or infected air in the typically mixed room.

[14] Makhoul, Alain & Ghali, K. & Ghaddar, Nesreen. (2013). The Energy Saving Potential and the Associated Thermal Comfort of Displacement Ventilation Systems Assisted by Personalised Ventilation. Indoor and Built Environment. 22. 508-519. 10.1177/1420326X12443847.

Supplying cool outside air through a dedicated distribution system to individual personal zones is not seen to be widely commercially viable at this time, but reconsidering our definition of ventilation - the use of filtered recirculated air through a standalone desk mounted device (local air cleaner?) in combination with a zonal outside air system is implementable today, which is worth noting for future ventilation systems design.

For both mixing and displacement ventilation systems CIBSE Guide B2 provides a good summary, advantages, and disadvantages for each system. For personal ventilation I recommend you check out the work of Dr. Chandra Sekhar who has led some excellent research in the area.

Ventilation effectiveness

Ventilation effectiveness is a term describing the performance of an air distribution system in removing pollutants from the occupied zone. For mechanically ventilated spaces, ventilation effectiveness expresses the relationship between the pollution concentrations in the supply air, the extract air, and the indoor air in the breathing zone, which depends on the air distribution, and the type and location of the air pollution sources in the space.

It can be calculated using the formula as per ASHRAE 62.1 Appendix C shown below.

- Zone air distribution effectiveness shall be calculated in accordance with Equation C-1:
- $Ez = (Ce - Cs)/(C - Cs)$ (C-1)
- where
- Ez = zone air distribution effectiveness
- C = average contaminant concentration at the breathing zone
- Ce = average contaminant concentration at the exhaust
- Cs = average contaminant concentration at the supply

These calculation method is a very simplified approach to estimating ventilation effectiveness at a point, and can be helpful for high-level and onsite checks. For more indept understanding of ventilation effectiveness usually air computational fluid dynamics (CFD) analysis is required, in which air diffuser suppliers are often available to assist with this level of detail.

However, generally based on the ventilation distribution system and supply air characteristics the ventilation effectiveness can be assigned a value as per figure 38 below from CIBSE Guide A.

Room ventilation system	Temperature difference between supply and room air ($T_s - T_r$)	Ventilation effectiveness
Mixing ventilation; air supplied and extracted at high level	< 0 2 to 5 > 5	0.9 to 1.0 0.8 0.4 to 0.7
Mixing ventilation; air supplied at high level and extracted at low level	< –5 –5 to 0 > 0	0.9 0.9 to 1.0 1.0
Displacement ventilation; air supplied at low level and extracted at high level	> 2 0 to 2 < 0	0.2 to 0.7 0.7 to 0.9 1.2 to 1.4

Figure 39 – Brief Ventilation Effectiveness Table (CIBSE Guide A)

As shown above, different ventilation distribution configurations and supply air temperatures will provide different ventilation effectiveness. For example, displacement ventilation systems with floor supply of cool air and ceiling return are considered 'superior' distribution (Ev >1.2), while mixing ventilation with ducted high level cool air supply and extract is 'efficient' distribution (Ev =1). Whereas mixing ventilation with high level warm air supply above room temperature provides 'adequate' distribution (Ev =~0.8) assuming correctly spaced supply and extract grills. Incorrectly located supply and extract grills positioned too close to one another will result in air short circuiting with limited mixing occurring and is an 'ineffective' form of distribution of ventilation (Ev <0.8).

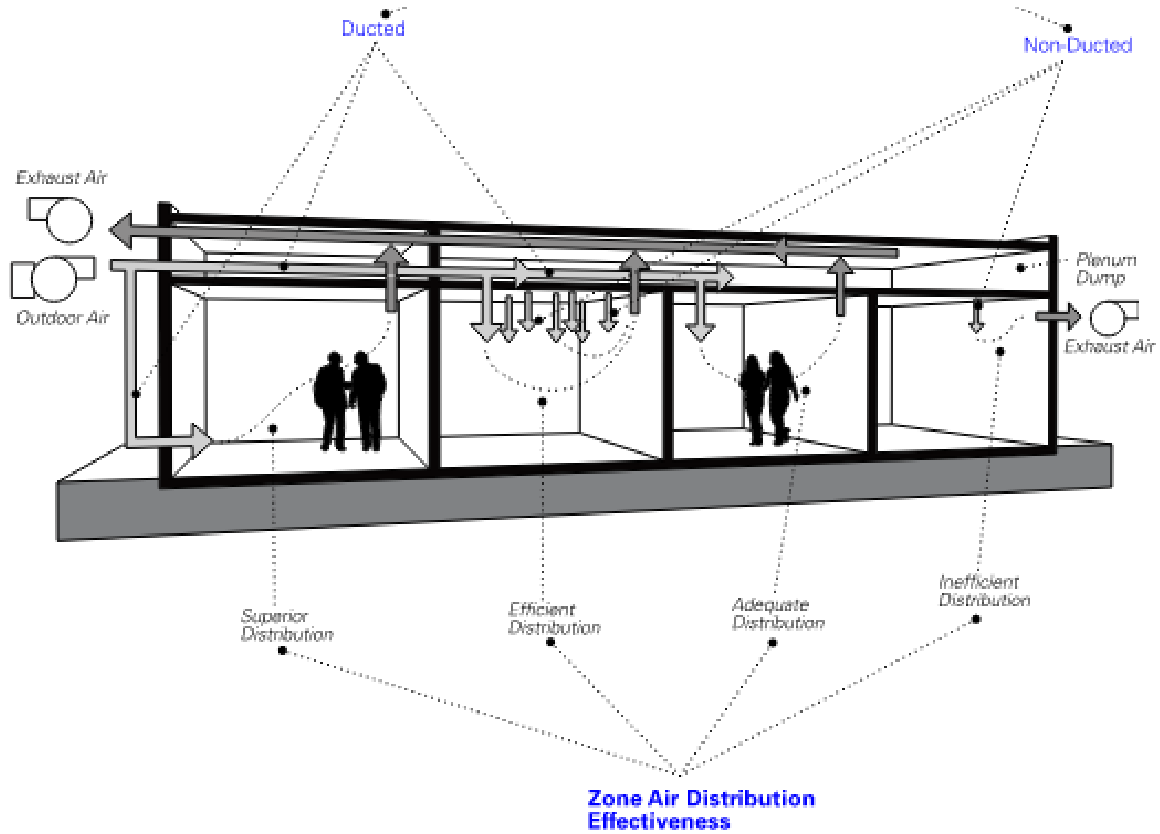


Figure 40 - Ventilation Systems Distribution Effectiveness Graphic (ASHRAE IAQ Guide)

A more in-depth analysis of ventilation effectiveness is conducted in REHVA's Guidebook No. 2 on Ventilation Effectiveness (2004) by Elizabeth Mundt, Hans Martin Mathisen, Peter V. Nielsen and Alfred Moser. It divides ventilation effectiveness into two indices - air change efficiency (ε^a) and CRE or contaminant removal effectiveness (ε^c) as shown in figure 40. The local indices are similar to the system efficiency metrics but characterise the conditions at a particular point and not of the system.

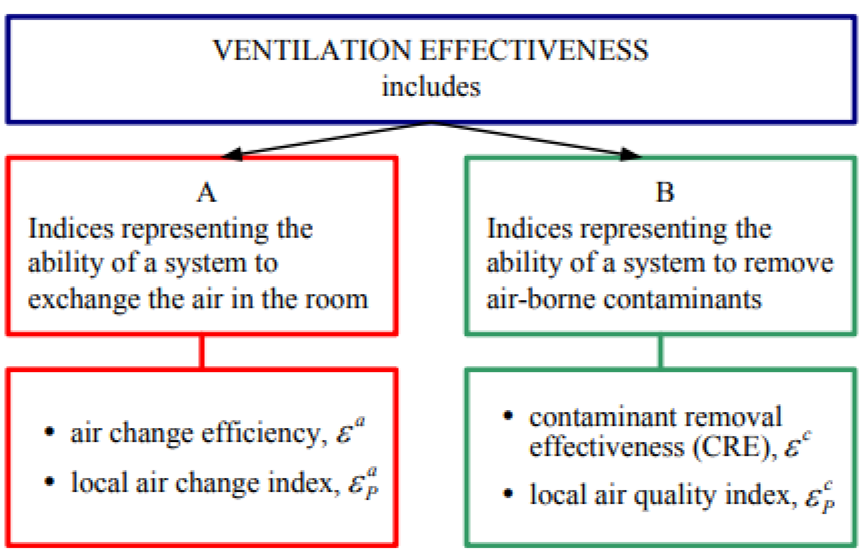


Figure 41 - Ventilation Effectiveness Elements Graphic

The air change efficiency (ε^a) is a ratio between the shortest possible air change time for the air in the room and the actual air change time. The possible shortest air change time occurs for the ideal (and theoretical) piston flow, where air is supplied and exhausted in parallel across a zone with laminar airflow, and therefore is the upper limit for this efficiency at 100%. Then fully mixed flow is half as effective as supply air is perfectly mixed with room air 1:1 and therefore its air change efficiency is 50%, with displacement ventilation greater than this (>50%) by stratification, and not fully mixed or short circuited flow less than this (<50%).

The CRE or contaminant removal effectiveness (ε^c) is a measure of how quickly an air-borne contaminant is removed from the room and is defined as the ratio between the steady state concentration of contaminant in the exhaust air (C_e), and the steady state mean concentration of the room (C). In a fully mixed situation the concentration in the exhaust is the same as in the whole room, which gives CRE equal to 1. In other cases CRE may differ from very small values to very large ones depending on the position of the contaminant source and the air flow in the room. When the contaminant source is uniformly distributed, as would often be the case occupant bio-effluents, the CRE-index and the air change efficiency index are related which is accounted for in full ventilation effectiveness value (Ev).
So the ventilation effectiveness depends on both the type of ventilation system (pistol, personal, displacement, mixed) and the location of system supply and exhaust in relation to the contamination source. This is particularly relevant for personalized ventilation system which can increase CRE and hence Ev by being in close proximity to the main contaminant source – occupants. The result is the highest ventilation effectiveness values for personal ventilation typically Ev >1.4 as shown in figure 41 below from ASHRAE 62.1.

Table 6-4 Zone Air Distribution Effectiveness

Air Distribution Configuration	E_z
Well-Mixed Air Distribution Systems	
Ceiling supply of cool air	1.0
Ceiling supply of warm air and floor return	1.0
Ceiling supply of warm air 15°F (8°C) or more above space temperature and ceiling return	0.8
Ceiling supply of warm air less than 15°F (8°C) above average space temperature where the supply air-jet velocity is less than 150 fpm (0.8 m/s) within 4.5 ft (1.4 m) of the floor and ceiling return	0.8
Ceiling supply of warm air less than 15°F (8°C) above average space temperature where the supply air-jet velocity is equal to or greater than 150 fpm (0.8 m/s) within 4.5 ft (1.4 m) of the floor and ceiling return	1.0
Floor supply of warm air and floor return	1.0
Floor supply of warm air and ceiling return	0.7
Makeup supply outlet located more than half the length of the space from the exhaust, return, or both	0.8
Makeup supply outlet located less than half the length of the space from the exhaust, return, or both	0.5
Stratified Air Distribution Systems (Section 6.2.1.2.1)	
Floor supply of cool air where the vertical throw is greater than or equal to 60 fpm (0.25 m/s) at a height of 4.5 ft (1.4 m) above the floor and ceiling return at a height less than or equal to 18 ft (5.5 m) above the floor	1.05
Floor supply of cool air where the vertical throw is less than or equal to 60 fpm (0.25 m/s) at a height of 4.5 ft (1.4 m) above the floor and ceiling return at a height less than or equal to 18 ft (5.5 m) above the floor	1.2
Floor supply of cool air where the vertical throw is less than or equal to 60 fpm (0.25 m/s) at a height of 4.5 ft (1.4 m) above the floor and ceiling return at a height greater than 18 ft (5.5 m) above the floor	1.5
Personalized Ventilation Systems (Section 6.2.1.2.2)	
Personalized air at a height of 4.5 ft (1.4 m) above the floor combined with ceiling supply of cool air and ceiling return	1.40
Personalized air at a height of 4.5 ft (1.4 m) above the floor combined with ceiling supply of warm air and ceiling return	1.40
Personalized air at a height of 4.5 ft (1.4 m) above the floor combined with a stratified air distribution system with nonaspirating floor supply devices and ceiling return	1.20
Personalized air at a height of 4.5 ft (1.4 m) above the floor combined with a stratified air distribution system with aspirating floor supply devices and ceiling return	1.50

Figure 42 – Detailed Ventilation Effectiveness Table (ASHRAE 62.1)

This table reiterates the importance of supply air temperature, velocity, and inlet and outlet location in the variability of ventilation effectiveness values. These Ev values can play an important role in the design and sustainability of a building as in theory the higher the ventilation effectiveness the lower the total supply air quantity (and associated fan energy, air conditioning load and ductwork size). This can be shown mathematically using the BS EN 16798-1 2019 Method 2 formula on limit values for substance concentration shown overleaf.

$$Q_h = \frac{G_h}{C_{h,i} - C_{h,o}} \cdot \frac{1}{\varepsilon_v}$$

where

Q_h is the ventilation rate required for dilution, in m^3 per second;

G_h is the generation rate of the substance, in micrograms per second;

$C_{h,i}$ is the guideline value of the substance, in micrograms per m^3;

$C_{h,o}$ is the concentration of the substance of the supply air, in micrograms per m^3;

ε_v is the ventilation effectiveness.

Based on this methodology the ventilation rate required for dilution can be increased or decreased inversely by a factor of the ventilation effectiveness. Therefore, a well design personalized ventilation system could supply ~40% less air and achieve the same IAQ level as a mixed ventilation system. BS EN 16798-4:2017 section 8.8 also provides general system recommendations including location of intake and exhaust openings to help maximise ventilation effectiveness.

Another note based on this formula is that for a known ventilation supply rate (assuming negligible infiltration), and contaminant generation rate, outdoor concentration and measured zone concentration an approximation for the ventilation effectiveness in that location can be calculated. While not completely accurate, any major discrepancies with reference distribution system ventilation effectiveness values may indicate an issue with air short circuiting, the contaminant generation in the zone, or air supply rate.
This technique may be used for quick testing and issue identification onsite, an approach tested in this reports case study buildings with some success. The approach is also verified in CIBSE TM61 which according to the guides case study 1 – Office; CO2 concentration levels can be used to infer the ventilation rates where the number of occupants and occupancy pattern of a zone is known.

CO2 / IAQ monitoring & Demand-controlled ventilation (DCV)

For decades, CO2 has been widely accepted as an indicator of ventilation and general IAQ. This is because for a known number of occupants it can be associated with average levels of ventilation rates. There is a relatively strong relationship between CO2 levels and human activity in a typical indoor environment, with the higher the number of people, or occupancy, the greater the CO2 emissions and hence room CO2 concentration. CO2 concentrations recorded will depend on multiple parameters including: the occupant activities; variations in building type, air permeability, weather, and external CO2; and any other CO2 sources within the building if applicable. Ventilation is then introduced to remove, dilute, or maintain this CO2 and other contaminants concentration as required. CO2 is accepted as being a good indicator of bio-effluent pollutants from human activity, but not a good predictor for outdoor sourced pollutants in densely occupied spaces, or indoor pollutants emitted by building materials, finishes or furniture. The renaissance in IAQ has expanded our consideration beyond just CO2 to other contaminants.

For a more robust IAQ perspective measuring CO2, Total Volatile Organic Compounds (TVOC), formaldehyde (HCHO), fine particulate matter (PM2.5) and even NO2 could be used as a more holistic way to approach IAQ. Recently, particulate matter (2.5 & 10 µm), CO2, CO and even TVOCs can be reliably measured by affordable, instant read-out instruments, however other contaminants of potential interest remain relatively difficult to measure at suitable levels of accuracy.

Monitoring systems gathering continuous data on these measurable particles, gasses, and chemicals present in air are the future of healthy and sustainable smart buildings with the goal to identify trends, spot problem areas, and adjust the ventilation system accordingly. This data can be fed back to an Indoor Air Quality Index (IAQI), which we discussed earlier in the Air Pollutants section, to demonstrate the overall condition of the indoor air in one metric.

	AQI	PM 2.5 (ug/m3)	PM 10 (ug/m3)	VOC (ppm)	CO2 (ppm)	Formaldehyde (ppm)
Good	0-50	0 - 12	0 - 54	0 - 15	400 - 650	0 - 0.2
Moderate	51 - 100	12.1 - 35.4	55 - 154	16 - 25	651 - 1500	0.21 - 0.4
Unhealthy for sensitive groups	101 - 150	35.5 - 55.4	155 - 254	26 - 50	1501 - 2000	0.41 - 0.6
Unhealthy	151 - 200	55.5 - 150.4	255 - 354	51 - 75	2001 - 2500	0.61 - 0.8
Very Unhealthy	201 - 300	150.5 - 250.4	355 - 424	76 - 100	2501 - 5000	0.81 - 1
Hazardous	301 - 500	250.5 - 500	425 - 600	101 - 150	5001 - 15000	1.01 - 1.2

Figure 43 – IAQ Index Contaminants Classification Thresholds

In particular, TVOC can provide some of this information for indoor pollutants not related to human activity. It is a representation of materials based chemicals in the air that we can breathe as a simplified metric. PM2.5 or NO2 can be used monitor outdoor air pollution values. The monitoring and consideration in design of outdoor air quality is of increased importance and can help identify the most suitable ventilation strategy. However outdoor air contaminants can be difficult to control other than by filtration and minimising infiltration.
Indoor air contaminants, particularly human related contaminants such as COVID-19 requires greater controls and monitoring. CO2 remains the main metric for human related IAQ monitoring and in many typical human occupied applications CO2 remains a good general proxy for indoor IAQ and ventilation rate.

The relationship between occupancy, ventilation rate and CO2 concentration has been studied and utilised for some time, often taking a known ventilation rate and CO2 concentration to get an estimate of zone occupancy. More usefully, CO2 monitored correctly can be used to control ventilation systems using demand-controlled ventilation (DCV).

CO2-based DCV maintains the CO2 concentration in the zone within an appropriate range by adjusting supply air flowrate. It is CO2 based as in theory any measurable contaminant of know rate and related to the room activity can be used, but CO2 being the most popular. The general principle behind DCV is a control system that reduces ventilation rates during partial occupancy, to reduce energy consumption and extend plant life.

DCV as an effective ventilation control strategy depends immensely on the accurate monitoring of CO2. CO2 and IAQ sensors should be placed in suitable location and then are not fit and forget – they require maintenance and will drift over time and need to be fit for purpose from the outset. This is particularly important in fit-out design, where individual rooms may have high occupancy but the entire floor may have low occupancy. I recommend the CIBSE Journal article '[Making sense of air quality sensors]' by James Hare from May 2021 which gives a great insight into this whole topic. IAQ monitors should be specified such that they meet recognised standards such as [RESET] or [CEN/TC 264] to ensure confidence in the measurements, and IAQ sensor values should also be supplemented with occupant feedback in the zone to ensure data is reflective of a satisfactory environment.

Measurement of CO2 should be carried out in the occupied area of a room with the sensors located away from windows, doors and ventilation grilles. CO2 cannot be used as a proxy for ventilation in spaces where there are other CO2 sources present (e.g. combustion devices) but this is atypical in commercial environment. In the latest UK Building Regulations 2021, new occupied buildings should have a means of monitoring the indoor air quality, and this may be achieved using CO2 monitors or other means of measuring indoor air quality.

IAQ senor location is vital and should follow manufacturer guidelines in respect to minimum distances and air flows. It is also important to place sensors at a specific height depending on the use of the building. A breathing zone for a person working in an office would be much different than a baby crawling in a home, or a nursery as shown below from CIBSE TM64.

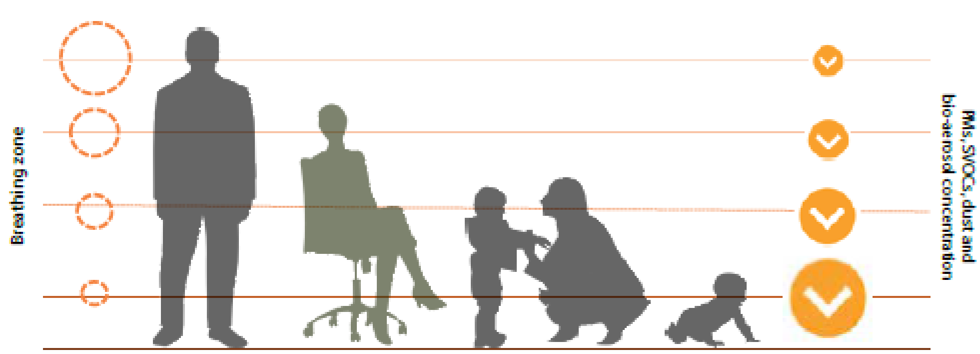


Figure 3.8 Importance of height when measuring air pollutants in different building types

Figure 44 - Importance of Height when Measuring Air Pollutants in Different Building Types

Understanding the ventilation distribution strategy and how it effects the CO2 (and other contaminants) in-room concentration profile is important and can influence the placement of CO2 sensors for DCV.

ASHRAE recently published a position document indoor CO2 measurement for ventilation and IAQ monitoring and control, taking into account the COVID 19 pandemic, and highlighted the importance of sensor accuracy, location, and calibration. It also highlighted that the use of indoor CO2 measurements to assess and control the risk of airborne disease transmission must account for the definition of acceptable risk, the type of space and its occupancy, and differences in CO2 and infectious aerosol emissions.
Additionally, CIBSE TM40 notes that a monitoring capability should be included in the design, enabling opportunities to gather data on operational indoor environmental quality and on user safety, comfort and satisfaction. Refer to the new CIBSE TM68: Monitoring Indoor Environmental Quality for more information IAQ monitoring and more.

For any proposed CO2-IAQ based ventilation specification strategy the above must be taken onboard and considered in the building design and client communication. It is noted that DCV control strategy aligns with an IAQ based ventilation procedure and would help achieve enhanced sustainability of the ventilation system. IAQ - CO2 monitoring is also likely to have value in raising occupant awareness of ventilation requirements and has been used to inform user behaviour to improve ventilation.

Air Filtration & Purification

Ventilation ‘outdoor air’ is not the only method to remove contaminants from the air. Air filtration and air purification/disinfection technologies can also help remove and ever expanding list of contaminants from the air. The contamination removal range and effectiveness of these technologies is improving daily but ventilation remains arguably the best method for removing the widest range of contaminants as represented by the simplified table below.

	Particulate Matter (PM2.5, PM1 etc.)	Gas Molecules (VOCs, O3 etc.)	Biological Agents (CO2, Radon etc.)	Viruses & Bacteria (COVID-19)
Ventilation	✓	✓	✓	✓
Filtration - Mechanical	✓			✓
Filtration - Gas Molecule		✓		✓+
Disinfection/Purification		✓		✓

Figure 45 – Air Contaminants Removal/Dilution Methods Comparison

*Some limited benefit of gas molecule filtration on removing viruses and bacteria has been demonstrated in research. Note the ability for filters and disinfection/purification systems to remove pollutants is dependent on the technology used.

Air filtration, and air purification (also referred to as air disinfection and sometimes air cleaning) are two separate (but interconnected) technologies in themselves but can tackle all kinds of air pollution and can often be applied in tandem. In this case, air filtration is classified as any technology using a fibrous medium to remove air pollution. Air purification or disinfection is any other non-medium based accepted air cleaning technology.

Air pollution, as mentioned previously, comes in two different forms, namely particles and gases. There are two different types of air cleaning filters to deal with them and there is a technical standard for each. The current relevant standards are as follows:

- BS EN ISO 16890:2016 is the global performance test standard for particle filters (PM1, PM2.5). It has been designed to replace BS EN 779:2012 which was withdrawn in June 2018 and the ASHRAE 52.2 US standard. These earlier standards were comparative filter tests and not considered as representative of real-life performance.
- BS EN ISO 10121-2:2013 is the Global performance test standard for molecular gas filters (NO2, but also SO2, O3, H2S, VOCs, Aldehydes).

Mechanical filtration the most common air cleaning technology and is usually used in combination with fresh air ventilation and any further air cleaning technologies. It uses, unsurprisingly, filters or filter media to collect and remove airborne particles from air when it is passes through it.

Filters trap airborne particles by three main mechanisms;

- Inertial impaction - inertia causes the larger particles to separate from the air flow and collide with the fiber as the air passes around it
- Interception – medium sized particles comes into contact with the fiber and adheres to the media
- Diffusion – Small particles travel in irregular paths (known as Brownian motion) and this greater movement increases the probability that the particle will collide with the filter fiber and be caught

As the filter medium collects and stores particles, it is then replaced regularly or cleaned to prevent it from clogging and restricting airflow.

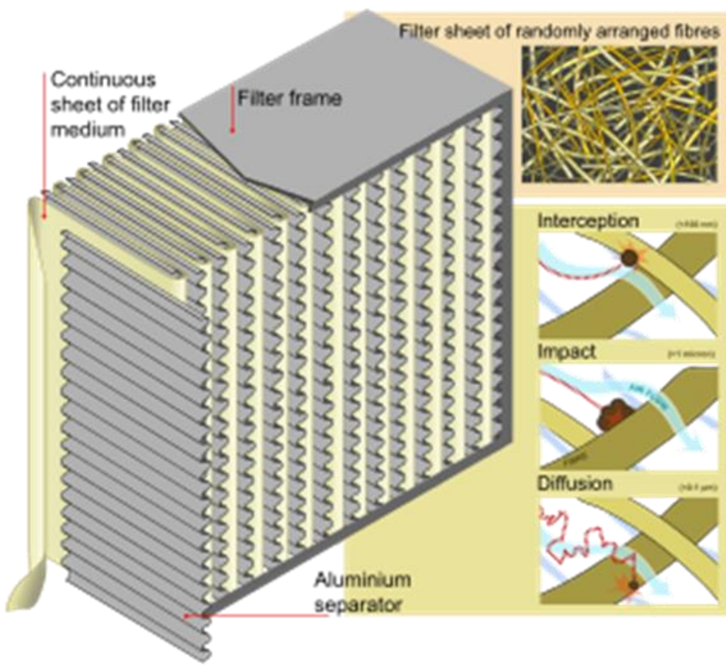


Figure 46 – Mechanical Fibrous Filters Operation Diagram

In terms of air filtration, the filter efficiency is arguably the most important factor of its performance. Air filter efficiency have been tested and categorised across 3 different standards, all of which are used and referred to across different countries and building standards;

- ISO 16890 is the most recent and is supposedly the global reference standard and is in the process of becoming the universal filter classification standard. It uses particle sizes – Coarse (>PM10), PM10, PM2.5 and PM1 - and the associated filter medium efficiency (%) at that size to classify filters.

- EN 779 is the older, superseded version of ISO 16890 but is still heavily referenced throughout the industry today and is identified by its iconic filter groupings of Coarse (G1-4), Medium (M5-6) and Fine (F7-F9) classifications.
- ASHRAE Standard 52.2 uses the Minimum Efficiency Reporting Value (MERV) to classify filters based on their particle removal efficiency across a 1 -16 scale.

The table below showing the relative filter efficiencies across the 3 standards has been in my experience one of the most useful graphics I have presented to date.

ISO 16890	ISO Coarse <50%	ISO Coarse <50%	ISO Coarse >50%	ISO Coarse >50%	ISO ePM10 >50%	ISO ePM2.5 >50%	ISO ePM10 >60%	ISO ePM1 >50%	ISO ePM2.5 >65%	ISO ePM10 >80%	ISO ePM1 >70%	ISO ePM2.5 >80%	ISO ePM10 >90%	ISO ePM1 >80%	ISO ePM2.5 >90%	ISO ePM10 >95%
EN779 2012	G1	G2	G3	G4	M5	M6		F7			F8			F9		
ASHRAE MERV	1	2-3-4	5-6	7-8	9-10	11-12		13			14			15		

Figure 47 – Filters Efficiencies Comparisons Across 3 Main Standards

Note MERV 16 and greater moves into the globally accepted HEPA - high efficiency particulate air - and ULPA - Ultra-Low Particulate Air – filter classifications which have an ISO16890 rating of >99% across all three particle size categories.

Filter efficiencies have been improving over the decades and their usage in mechanical ventilations systems is commonplace, in part due to building environmental rating systems such as LEED, BREEAM and WELL (discussed in more detail later) requiring minimum filtration requirements (MERV13/F7). Particulate filters should be changed based on hygiene, pressure loss and defect factors, and the supplier's maintenance plan. EN 13779 does provide guidance on particulate filter maintenance based on the above factors and summarised below.

Filter stage/ class	Recommended final pressure loss	Hygiene interval	Factors affecting change
	First occurring between		
Only 1 filtration stage		1 year	Spring and autumn – after pollen and spore seasons
1st filter stage		1 year	
2nd Filter stage		2 years	
G1 — G4	150 Pa		Highly polluted or dusty areas
M5 — F7	200 Pa		
F8 — F9	300 Pa		

Figure 48 - EN 13779 Recommended Filter Maintenance Thresholds

Molecular gas filtration or gas phase filtration also uses a filter medium but one targeted at the smaller molecular scale of gases namely through a chemical reaction or adhesion. Filters trap gas molecules by three main methods;

- Adsorption - removal of a contaminant by superficial contact (adhesion) with other materials such as activated alumina, activated charcoal and silica gel
- Absorption - removal of soluble or chemically reactive gases from the air stream by incorporation into the bulk volume of an appropriate liquid (e.g. alkanolamines)
- Catalytic conversion - a contaminant is converted to a chemical form not considered to be hazardous in the presence of a catalyst (e.g. diesel oxidation catalyst process)

As the filter medium collects and stores molecules, it is then replaced regularly prevent it becoming ineffective and restricting airflow. Adsorption gas filtration is the most common and causes gas molecules to accumulate on the surface of a solid filter medium by Van-der-Waals attraction forces. Activated carbon filters, common in ventilation system for odour gas control, utilise adsorption method.

The efficiency of gas molecule filtration systems varies greatly with the technology, air temperature, humidity, and filter lifespan. In terms of operation and maintenance, gas filters do not change pressure loss during normal operation, and therefore their O&M should include requirement for periodic replacement, and whilst their maintenance frequency is not set in EN 13779, some manufacturers recommend changing IAQ gas (molecular) filters after 1 year installed or 5000 hours operation.

Ventilation with ‘clean’ outdoor air remains the most suitable gas molecule pollution removal technology however moderating gaseous contaminants and other ultrafine particles can be achieved using air-cleaning devices in some cases.

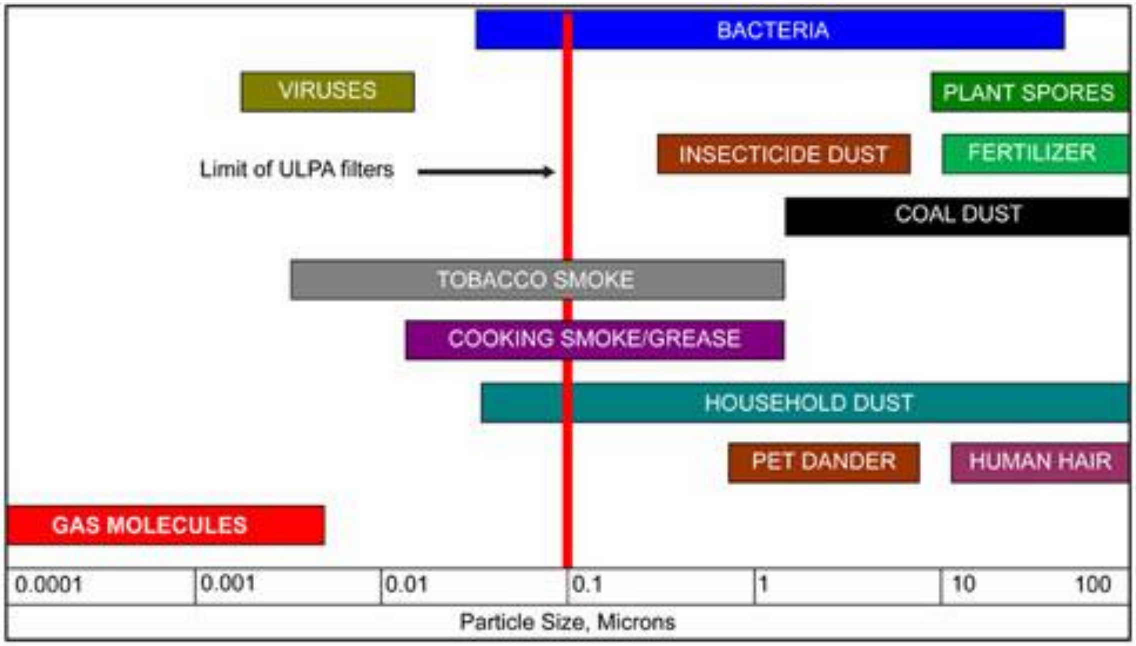


Figure 49 – Typical Contaminants Particle Sizes & Particle Filtration Limit

For more information on air filtration specifications the old but good ©BSRIA Air Filtration Application Guide 8/97 is an excellent resource.

Air disinfection/purification is the newest category in the air cleaning industry and has the widest range of technologies. As a result it also has the greatest number of unknowns and uncertainties. Ultra-Violet (UV) germicidal radiation also known as UVGI or UVC is the most well-known and utilised as discussed below. There are however many air purification technologies on the market including those using photocatalytic oxidation, photoelectrochemical oxidation, electrostatic precipitation, and various ionization technologies including bipolar ionization.

Several guidance notes and documents, including the ASHRAE Position Document on Filtration and Air Cleaning provide an overview and comparison of these air purification technologies. What can be concluded from these studies is that there is not sufficient evidence to support the use of air purification devices in commercial environments for IAQ purposes. There may be some limited use of air cleaners, particularly in-room located technologies, in unventilated areas such as elevators or some meeting rooms but this singly will not provide good IAQ in the long-term.

A study by Melbourne University found portable in-room air cleaners were very effective in removing aerosols, especially for the devices with high flow rate. In a small control room, the aerosols were cleared 4 to 5 times faster with portable air cleaners than the room with HVAC alone. Studies and applications confirming their effectiveness are still at a relatively early stage, and may confirm overwhelming benefits in time but even a recent study of the COVID-19 filtration[15] found the HEPA filter in air cleaners should be effective alone without these additional other options such as UVC. Particularly in well ventilated areas, where if you already have a high ventilation rate (ACH>3) then in room air cleaners will have limited relative effectiveness.

Device	Reduction (%)
Device 1 HEPA filter only, no ionisation	60.2
Device 1 HEPA filter plus ionisation	62.1
Device 1 Ionisation only, HEPA removed	25.2
Device 2 HEPA filter only, no ionisation	52.9
Device 2 HEPA filter plus ionisation	28.1
Device 2 Ionisation only, HEPA removed	1.6

Figure 50 – Research results for Air Cleaning technology Effectiveness for Virus Reduction

Research has found that the benefits to indoor air quality of one type of purifying system can be offset by the generation of other pollutants that are harmful to health[16] and that electronic air cleaners that generate ions or ozone should be avoided as may create supply air that has other contaminants over the WHO pollutant exposure limits.

BS EN 16798-3:2017 is the European technical standard that defines and categorises outside air and building air using WHO pollutant exposure limits combined with a factor to show how clean air is inside and outside of the building. For outside air pollution levels, categories ODA1-3 are defined, and for inside air pollution IDA is used. For supply air filtered by the ventilation air system categories SUP1 to SUP5 are defined. The standard recommends the minimum required particle filter classes and complementary application of gas filter for different classes of ODA and SUP.
An overview of recommended filtration is provided in the table overleaf.

[15] Potential application of Air Cleaning devices and personal decontamination to manage transmission of COVID-19 , SAGE-EMG 4th November 2020

[16] https://research.gatech.edu/study-shows-electronic-air-cleaning-technology-can-generate-unintended-pollutants

Table 2 - BS EN 16798-3 Categories Recommended Filtration Levels

Outdoor Air Quality		**Indoor Air Quality**				
		SUP 1 (Very low concentrations of PMs and/or gases)	**SUP 2** (Low concentrations of PMs and/or gases)	**SUP 3** (Medium concentrations of PMs and/or gases)	**SUP 4** (High concentrations of PMs and/or gases)	**SUP 5** (Very High concentrations of PMs and/or gases)
ODA 1 (only temporarily dusty, e.g. pollen)	(P)	M5 + F7	F7	F7	F5	-
	(G)	Gas filter recommended	-	-	-	-
ODA 2 (high concentrations of particulate matter and/or gaseous pollutants)	(P)	F7 + F7	M5 + F7	F7	F7	M5
	(G)	Gas filter required	Gas filter recommended	-	-	-
ODA 3 (very high concentrations of dust and gases)	(P)	F7 + F9	F7 + F7	M6+F7	F7	F7
	(G)	Gas filter required	Gas filter required	Gas filter recommended	-	-
Filter classes defined according to EN 779 Gas filtration should be considered if design SUP quality is above design ODA quality. Dimensioning should be done in accordance with EN ISO 10121-1 and EN ISO 10121-2. Further consideration on gas filtration is given in CEN/TR 16798-4						

Another useful source of guidance is the EUROVENT 4/23 (2018) document from the European ventilation manufacturers association that gives detailed definitions, applications and building function recommendations for clean air SUP and ODA levels, and filter recommendations in the updated ISO16890 standard.

EUROVENT 4/23			SUPPLY AIR				
OUTDOOR AIR			SUP 1*	SUP 2*	SUP 3**	SUP 4	SUP 5
			HHD	MHD	BHD	LHD	LHD
			PM2.5 <= 2.5	PM2.5 <= 5	PM2.5 <= 7.5	PM2.5 <= 10	PM2.5 <=15
			PM10 <= 5	PM10 <= 10	PM10 <= 15	PM10 <= 20	PM10 <= 30
Particle Sizes	PM2.5	PM10	ePM_1	ePM_1	$ePM_{2.5}$	ePM_{10}	ePM_{10}
ODA 1	<=10	<=20	70%	50%	50%	50%	50%
ODA 2	<=15	<=30	80%	70%	70%	80%	50%
ODA 3	>15	>30	90%	80%	80%	90%	80%
*minimum ePM1 50% final filter **minimum ePM2.5 50% final filter							
Air filters should be selected using ISO16890:2016 individual filter test data. This test standard has a tolerance banding of 5% maximum giving more accurate performance.			BS EN ISO 16890:2016 Minimum air filter requirements for final stage				
			BS EN 16798-3:2017 Air classes SUP Supply Air ODA Outdoor Air				
			Hygiene Demands: High HHD, Medium MHD, Basic BHD, Low LHD				
			Particle concentration annual average in ug/M3 (WHO 2005 comparison)				
			Notation: e=filtration efficiency, <= less than or equal to, > greater than				

Figure 51 - EUROVENT 4/23 Updated Filter Level Recommendations

Note, in no commercial building guidance or standard reviewed was there a single recommendation for air purification or disinfection alone to achieve IAQ requirements. Recent HVAC best practice literature based since the COVID-19 pandemic, which is explored in more detail in the next chapter, raises the ability of Ultra-Violet (UV) radiation and a few other air purification technologies in deactivating virus particles but also notes the significant unknowns and drawbacks of such technologies. Any usage of UV or other air purification technologies should be considered and researched as part of the overall design IAQ plan and filtration strategy.

Cosentini, a long-established building systems consulting engineering firm, produced the table below comparing effectiveness of Filtration (HEPA) to air cleaning technologies of Ionization, UV, and Activated Carbon against certain contaminants. The strong performance of filtration, particularly when including activated carbon for gases, versus air cleaning technologies is clear.

	HEPA Filters	Ionization	UV Light	Activated Carbon
Effectiveness against Viruses	**Very Good**	**Good** (airborne + surfaces)	**Good** (Depending on contact time)	**Poor**
Effectiveness against Bacteria	**Excellent**	**Good** (airborne + surfaces)	**Good** (Depending on contact time)	**Poor**
Removes Gasses (Radon, Formaldehyde, etc.)	Not Effective	Not Effective	Not Effective	Excellent
Eliminates Odors	Not Effective	Good	Not Effective	Excellent
Effectiveness against pet dander	Excellent	Excellent	Not Effective	Not Effective
Effectiveness against pollen	Excellent	Excellent	Not Effective	Not Effective
Effectiveness against mold spores	Excellent	Excellent	Good	Not Effective
Effectiveness against dust mite excreta	Excellent	Excellent	Poor	Poor
Cost per cartridge	Moderate	Moderate	Moderate	Inexpensive
Cartridge life expectancy	1 Year	2 years	1 year	3-12 Months

Ineffective ... Very Effective

Cosentini A TETRA TECH COMPANY

Figure 52 – Qualitative Effectiveness Comparison Summary table (Cosentini)

In the latest UK Building Regulations 2021, ventilation systems that, under normal operation, recirculate air between more than one space must be either capable of supplying 100% outdoor air if required, or incorporate a UV-C germicidal irradiation system that is able to disinfect the air that is being recirculated, or be designed so that they can incorporate HEPA filters, if required, which are able to provide filtration of the recirculated air.

ASHRAE's Position Document on Filtration and Air Cleaning states one key statement in that, at present, there is only significant evidence of health benefits for fibrous mechanical and gaseous filtration systems, with particular reference to COVID-19 transmission not just IAQ.

We know that mechanical filtration technologies do not have 100% efficiency in removing COVID-19 and other contaminant particles (although HEPA and ULPA filters come close) but can achieve significant IAQ improvement and COVID-19 transmission reduction without an unproportional penalty in energy consumption and overall sustainability. Ideally, and in some high IAQ expectation facilities, we would use HEPA+ filters to remove >99% of particle contaminants in the 0.3-10 µm range. However, as specified in CIBSE Guide B the addition of a HEPA filter can add almost 1kW/m3/s of additional ventilation power requirement. For large, central ventilation systems operating for extended periods with generally large quantities of air this is a significant energy and cost penalty. It can also affect ventilation specific fan power (SFP) values which can be limited by country regulations making required values difficult to achieve.

Component	P_{SFP} in (W/(m³ /s))
Additional mechanical filter stage[a]	+ 300
HEPA Filter according to EN 1822-3	+ 1 000
Gas Filter	+ 300
Heat recovery class H2 or H1[b]	+ 300

[a] a second filter (first filter min. F7 for supply or M5 for exhaust) is the additional filter stage.

[b] Class H2 or H1 according to EN 13053:2006+A1:2011.

Figure 53 - EN 16798-3 AH Components Additional SFP Allowances

In contrast a typical mechanical filter stage adds approx. 30% of the energy demand and can achieve substantial particle filtration efficiencies. In an American based study, Azimi and Stephens (2013) found that Fine classed filters MERV13-14 (F7-F8) offered the best value balancing risk of virus infection with operating costs, and will have low bypass filter rates as required by EN1886:2007.

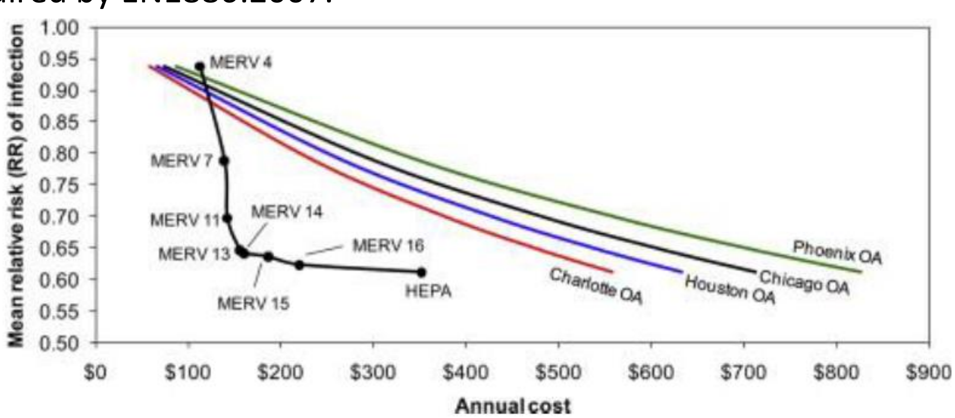


Figure 54 – Relative Virus Transmission Risk Reduction Vs Operational Cost in America [17]

[17] HVAC filtration for controlling infectious airborne disease transmission in indoor environments: Predicting risk reductions and operational costs Parham Azimi and Brent Stephens*

The most advantageous MERV 13 and 14 (F7 and F8) can achieve particle filtration efficiency between 50 -100% depending on particle size.

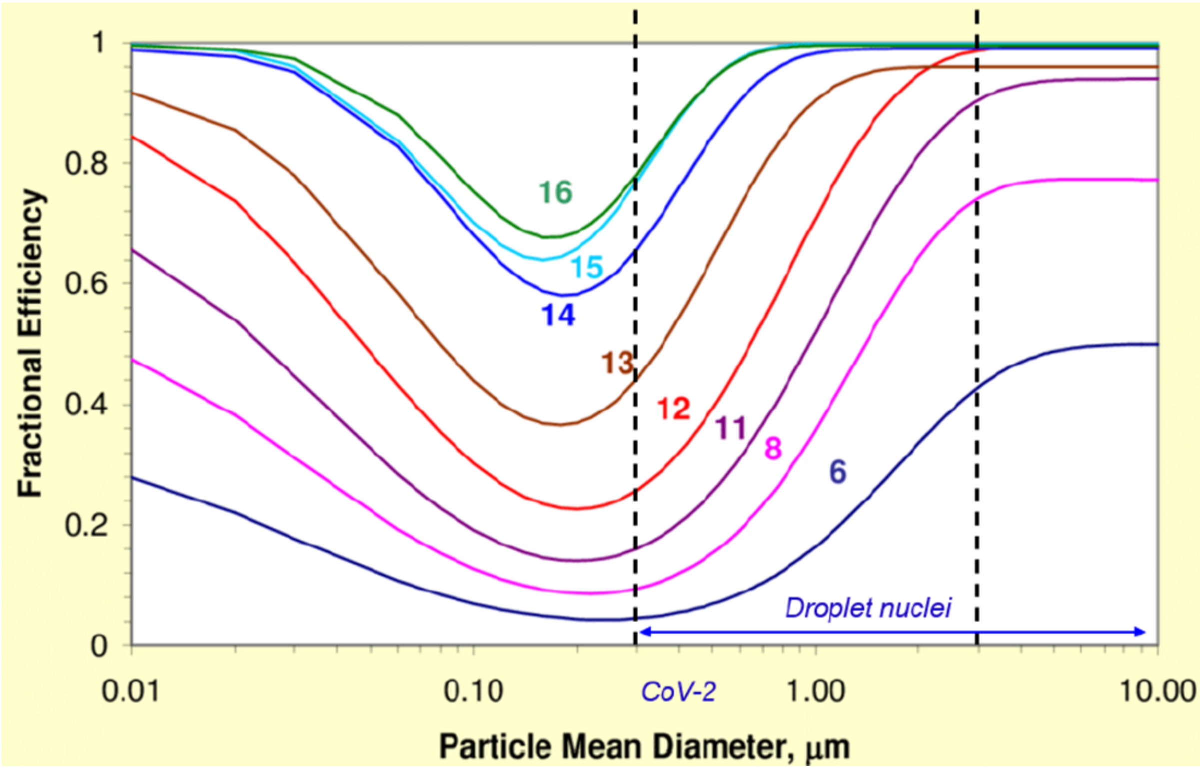


Figure 55 – Filtration Efficiency Ranges for COVID-19 Droplet Nuclei Graphic

However, for COVID particle reduction and general IAQ a single representative filtration efficiency figure would be beneficial and required for a simple IAQ ventilation calculation to account for filtration efficiency.

As stated previously in the Air Pollutants chapter of this report, the air contaminants of concern in this report are typically between the size range of 0.3µm - 10µm. With a specific focus on virus particles, the initial inspiration for this report, research by Azimi and Stephens in 2013 and summarised in the table below found the mean distribution of virus particle sizes across several studies.

Source	Sampling environment	Sampling location(s)	Particle size distribution of influenza virus reported			Assumed distribution of influenza virus in modified ranges for use with ASHRAE Standard 52.2 (F_i)		
						0.3–1 µm	1–3 µm	3–10 µm
[51]	Urgent care clinic	Personal indoor	<1.7 µm 32%	1.7–4.9 µm 16%	>4.9 µm 52%	19%	20%	62%
		Stationary indoor (lower floor)	<1 µm 13%	1–4.1 µm 37%	>4.1 µm 50%	13%	24%	63%
		Stationary indoor (upper floor)	<1 µm 9%	1–4.1 µm 27%	>4.1 µm 64%	9%	17%	74%
[52]	Hospital emergency room	Combination of personal and stationary indoor	<1 µm 4%	1–4 µm 49%	>4 µm 47%	4%	33%	63%
[53]	Cough aerosol collection system	Personal cough airstream	<1 µm 42%	1–4 µm 23%	>4 µm 35%	42%	15%	43%
[54]	Health center, daycare center, and airplanes	Stationary indoor	<1 µm 36%	1–2.5 µm 28%	>2.5 µm 36%	36%	37%	27%
[55]	Patient room with breathing manikin	Combination of personal and stationary indoor	<1 µm 19.5%	1–4 µm 75.5%	>4 µm 5%	20%	50%	30%
Mean viral distribution across all studies						20%	29%	51%
Standard deviation						14%	12%	18%
Relative standard deviation						0.70	0.44	0.36

Figure 56 – Virus Particles Sizes Mean Viral Distribution Research Results

Based on this distribution and the known filter removal efficiencies at the given particles size ranges, the following table provides the representative filtration efficiency based on ASHRAE 52.2 MERV ratings. These single value filtration efficiencies can then be easily used for future ventilation and IAQ calculations if required.

MERV Rating (Based on 52.2-2017)	Filter Droplet Nuclei Efficiency
4	16.80%
5	26.55%
6	32.45%
7	41.13%
8	55.57%
9	62.00%
10	64.65%
11	72.86%
12	83.39%
13	89.93%
14	94.94%
15	96.18%
16	97.40%

Figure 57 - Representative Droplet Nuclei Filtration Efficiency Based on ASHRAE 52.2 MERV Ratings

These values are translated across to EN779 and ISO 16890 standards in the table below.

Table 3 – Global Representative Droplet Nuclei Filtration Efficiency

ASHRAE MERV Filter Rating	EN779 Filter Rating	ISO 16890 Filter Rating	Est. Filter Effiency (%)
1	G1	ISO Coarse < 50%	< 15%
2	G2	ISO Coarse < 50%	< 15%
3			< 15%
4			16.80%
5	G3	ISO Coarse > 50%	26.55%
6			32.45%
7	G4	ISO Coarse > 50%	41.13%
8			55.57%
9	M5	ePM10 > 50%	62.00%
10			64.65%
11	M6/F6	ePM2.5 > 50%	72.86%
12		ePM10 > 60%	83.39%
13	F7	ePM1 > 50%	89.93%
		ePM2.5 > 65%	
		ePM10 > 80%	
14	F8	ePM1 > 70%	94.94%
		ePM2.5 > 80%	
		ePM10 > 90%	
15	F9	ePM1 > 80%	96.18%
		ePM2.5 > 90%	
		ePM10 > 95%	
16		ePM1 > 85%	97.40%
		ePM2.5 > 95%	
		ePM10 > 95%	
HEPA +	HEPA +	HEPA +	> 99%
ULPA +	ULPA +	ULPA +	100%

These average calculated filtration efficiency values for mechanical filters across each rating system can provide consistency in application for any future early stage design IAQ and ventilation calculations. These can be updated or replaced by manufacturer filter information if available but should provide coverage across the same 0.3 – 10 µm range. Note for more specific contaminants of concern of known size, such as smoke for example (0.3 -0.5 µm), specific filter efficiency data should be used for design considerations. Data for air purifiers and UV technology should utilise manufacturer information but careful consideration of the design and its application is essential.

Summary

The onset of the COVID-19 pandemic reawakened the importance of ventilation and IAQ in building design and operation. However, IAQ extends much beyond COVID-19 and virus contaminants, with a range of external (PMs, NO) and internal (TVOCs, CO2) source contaminants of varying form and particle size requiring consideration for occupant comfort and wellness.

Similarly IAQ is more than just ventilation – the introduction of (outside) air to remove or dilute contaminants. The need to manage IAQ through source control is highlighted in the latest CIBSE TM 61 2020 - Operational performance of buildings, including the identification of key external and internal sources for pollution, material selection, and detailing of ventilation strategy such as position of air intakes - crucial to maximising IAQ. Only then is ventilation considered for IAQ, and although an essential element with 'adequate' ventilation a vital requirement for occupant comfort. The fact is that the rate of 'adequate' ventilation varies immensely across research, and can depend on a number of factors from the buildings function and construction materials, to an occupant's expectations, diet and activity level.

Table 4 - Minimum Ventilation Rates for Offices Across Standards

Minimum vent rates for offices with occupancy density of 1 person per $10m^2$	
Part F of Building Regulations (UK/Ireland)	10 l/s per person
CIBSE Guide A, Table 1.5	10 l/s per person
BS EN 16798-1 2019, (assuming *Category II* and *low polluted building)* Compliant with WELL Feature A03 & A06	14 l/s per person
ASHRAE Standard 62.1-2013 Assuming a ventilation effectiveness factor of 1 – see below. Compliant with LEED IEQ prerequisite (& +30% for credit)	5.5 l/s per person
British Council for Offices (BCO) Guide to Specification 2014 Compliant with BREEAM NC 2014 Hea 02, Ventilation credit.	12– 16 l/s per person + 10% allowance for speculative buildings

Adequate minimum ventilation levels differ across regulations as shown in the table above, however BS EN 16798-1 2019 – *Ventilation for buildings* provides us with guidance and 3 methodologies to calculate the recommended ventilation rate required to maintain good IAQ based on a predefined rating scale of occupant expectations:-

1. Method 1 based on perceived IAQ
2. Method 2 based on limit values for substance concentration
3. Method 3 based on predefined ventilation air flow rates

Category	Level of expectation	Explanation
IEQ_I	High	Should be selected for occupants with special needs (children, elderly, persons with disabilities).
IEQ_{II}	Medium	The normal level used for design and operation.
IEQ_{III}	Moderate	Will still provide an acceptable environment. Some risk of reduced performance of the occupants.
IEQ_{IV}	Low	Should only be used for a short time of the year or in spaces with very short time of occupancy.

Figure 58 – IEQ – IAQ Classifications from BS EN 13779

Method 1 – Perceived IAQ combines a ventilation rate for occupancy to remove bio-effluents, and ventilation rate for building floor area to remove building related contaminants for a total ventilation rate. However, in my opinion the inherent ability of outside air ventilation to remove or dilute all internal contaminants regardless of being human or building based should negate the need for two separate ventilation specifications. No evidence or explanation was found why the 'persons' ventilation specified to remove bio-effluents cannot dilute building emissions at the same time and act as the 'buildings' ventilation. Ventilation has been shown to be able to dilute and remove both contamination from both sources once it is distributed and delivered correctly.

$$q_{tot} = n \cdot q_p + A_R \cdot q_B$$

q_{tot} = total ventilation rate for the breathing zone, l/s

n = design value for the number of the persons in the room,

q_p = ventilation rate for occupancy per person, l/(s person)

A_R = floor area, m^2

q_B = ventilation rate for emissions from building, $l/(s \cdot m^2)$

Consideration of non-occupant related pollution such as building material emissions is important and should be included in early stage design. Those buildings which design to minimise building pollution to very low levels should be rewarded with a lower specified ventilation rate compared to typical standards to achieve the same IAQ level.

Additionally, any building with significant building related pollution (such as some industrial buildings) require more detailed design consideration such as local exhaust ventilation. Therefore, Method 1 – Perceived IAQ with its dual ventilation specification is not seen as wholly necessary for the future of ventilation design.

Method 2 - limit values for substance concentration in a space requires a calculation to specify the ventilation rate requiring known contaminant generation rate, outdoor concentration, and ventilation system effectiveness. CO2 is the recommended substance for this method.

$$Q_h = \frac{G_h}{C_{h,i} - C_{h,o}} \cdot \frac{1}{\varepsilon_v}$$

Q_h is the ventilation rate required for dilution, in m^3 per second;

G_h is the generation rate of the substance, in micrograms per second;

$C_{h,i}$ is the guideline value of the substance, in micrograms per m^3;

$C_{h,o}$ is the concentration of the substance of the supply air, in micrograms per m^3;

ε_v is the ventilation effectiveness.

The requirement for calculations and known contaminant generation rates makes this methodology significantly more detailed and complex, particularly at early stage design when ventilation rates are key to space planning and load calculations. Therefore Method 2 - limit values for substance concentration in a space - is not seen as universally applicable for the future of design ventilation specification. However, a possible application for Method 2 is in validating the design ventilation rate and system effectiveness in building operation stage by adapting the formula to calculate the estimated zone CO2 level expected for the specified design ventilation rate and comparing it to site measurements, with significant deviations indicating possible issues.

Method 3 - predefined ventilation air flow rates uses prescriptive ventilation airflow rates, typically in litres per second per person-occupant (l/s/p), litres per second per m2 building floor area (l/s/m2) or air change rate (ACH), estimated to meet needs for perceived air quality and health of occupants.

Category	Total design ventilation air flow rate for the room	
	l/(s per person)	$l/(s \cdot m^2)$
I	20	2
II	14	1,4
III	8	0,8
IV	5,5	0,55

Figure 59 - BS EN 16798 Recommended Total Design Ventilation Airflow Rate – Typical Building

Single prescriptive ventilation rates is the simplest of all three methods, and the most preferred method amongst engineers polled for this research. Therefore, Method 3 - predefined ventilation air flow rates is seen as most applicable for the future of design ventilation specification.

However, these pre-defined values can vary depending on source and therefore, a universal standard for pre-defined values or a corresponding IAQ rating for ventilation rates is needed. This, and the possible use of the BS EN 16798-1 2019 standard is investigated further later in this study.

The mechanical ventilation system utilised affects many future design decisions, and therefore the many advantages and disadvantages associated with both DOAS and recirculation based systems need to be considered early on for future building ventilation design. The ventilation distribution strategy and its inherent effectiveness is a key, and often overlooked, aspect of ventilation. The high-level mixing ventilation strategy remains the modern industry standard, however the effectiveness and energy load benefits of displacement ventilation systems, and more recently personal ventilation systems, although perhaps not commercially acceptable yet, have reintroduced these strategies into the building design and sustainability agendas.

Table 6-4 Zone Air Distribution Effectiveness

Air Distribution Configuration	E_z
Well-Mixed Air Distribution Systems	
Ceiling supply of cool air	1.0
Ceiling supply of warm air and floor return	1.0
Ceiling supply of warm air 15°F (8°C) or more above space temperature and ceiling return	0.8
Ceiling supply of warm air less than 15°F (8°C) above average space temperature where the supply air-jet velocity is less than 150 fpm (0.8 m/s) within 4.5 ft (1.4 m) of the floor and ceiling return	0.8
Ceiling supply of warm air less than 15°F (8°C) above average space temperature where the supply air-jet velocity is equal to or greater than 150 fpm (0.8 m/s) within 4.5 ft (1.4 m) of the floor and ceiling return	1.0
Floor supply of warm air and floor return	1.0
Floor supply of warm air and ceiling return	0.7
Makeup supply outlet located more than half the length of the space from the exhaust, return, or both	0.8
Makeup supply outlet located less than half the length of the space from the exhaust, return, or both	0.5
Stratified Air Distribution Systems (Section 6.2.1.2.1)	
Floor supply of cool air where the vertical throw is greater than or equal to 60 fpm (0.25 m/s) at a height of 4.5 ft (1.4 m) above the floor and ceiling return at a height less than or equal to 18 ft (5.5 m) above the floor	1.05
Floor supply of cool air where the vertical throw is less than or equal to 60 fpm (0.25 m/s) at a height of 4.5 ft (1.4 m) above the floor and ceiling return at a height less than or equal to 18 ft (5.5 m) above the floor	1.2
Floor supply of cool air where the vertical throw is less than or equal to 60 fpm (0.25 m/s) at a height of 4.5 ft (1.4 m) above the floor and ceiling return at a height greater than 18 ft (5.5 m) above the floor	1.5
Personalized Ventilation Systems (Section 6.2.1.2.2)	
Personalized air at a height of 4.5 ft (1.4 m) above the floor combined with ceiling supply of cool air and ceiling return	1.40
Personalized air at a height of 4.5 ft (1.4 m) above the floor combined with ceiling supply of warm air and ceiling return	1.40
Personalized air at a height of 4.5 ft (1.4 m) above the floor combined with a stratified air distribution system with nonaspirating floor supply devices and ceiling return	1.20
Personalized air at a height of 4.5 ft (1.4 m) above the floor combined with a stratified air distribution system with aspirating floor supply devices and ceiling return	1.50

Figure 60 – Detailed Ventilation Effectiveness Table (ASHRAE 62.1)

IAQ monitoring has seen a renaissance in post pandemic building design, and is now a requirement in the most recent UK Part F regulations. IAQ monitoring by measuring CO2 has been widely accepted as an indicator of ventilation and general IAQ, with CO2 typically a good proxy of IAQ in most cases, particularly with communication and colour coding of values and their significance for IAQ. CO2 measurements are also typically the basis for demand controlled ventilation (DCV), and this control strategy aligns with an IAQ based ventilation procedure and would help achieve enhanced sustainability of the ventilation system.

	AQI	PM 2.5 (ug/m3)	PM 10 (ug/m3)	VOC (ppm)	CO2 (ppm)	Formaldehyde (ppm)
Good	0-50	0 - 12	0 - 54	0 - 15	400 - 650	0 - 0.2
Moderate	51 - 100	12.1 - 35.4	55 - 154	16 - 25	651 - 1500	0.21 - 0.4
Unhealthy for sensitive groups	101 - 150	35.5 - 55.4	155 - 254	26 - 50	1501 - 2000	0.41 - 0.6
Unhealthy	151 - 200	55.5 - 150.4	255 - 354	51 - 75	2001 - 2500	0.61 - 0.8
Very Unhealthy	201 - 300	150.5 - 250.4	355 - 424	76 - 100	2501 - 5000	0.81 - 1
Hazardous	301 - 500	250.5 - 500	425 - 600	101 - 150	5001 - 15000	1.01 - 1.2

Figure 61 – IAQ Index Contaminants Classification Thresholds

However, increased awareness of wellness has expanded our consideration beyond just CO2 to other contaminants. For a more robust IAQ perspective measuring CO2, Total volatile organic compounds (TVOC), temperature, relative humidity, fine particulate matter (PM2.5) and even NO2 could be used as a more holistic way to approach IAQ. As a result, and to try a capture IAQ in a single metric the Indoor Air Quality Index (IAQI) was developed. It is simply an accessible, descriptive scale to show the level of contaminants or pollution in the air at that time. All IAQ monitors should be positioned carefully and specified such that they meet recognised standards such as RESET or CEN/TC 264, and be well maintained to ensure confidence in the measurements. It is recommended that IAQ sensor values also be supplemented with occupant feedback in the zone to ensure data is reflective of a satisfactory environment.

Finally, appropriate air cleaning - filtration strategy can help protect building users from major outdoor sources of pollution, and strike the right balance between indoor air quality and energy efficiency in the ventilation system. For mechanical filtration, filter efficiency is arguably the most important factor of its performance.

Air filter efficiency have been tested and categorised across 3 different standards - ASHRAE MERV Filter Rating, EN779 Filter Rating and ISO 16890 Filter Rating, all of which are used and referred to across different countries and building standards, although ISO 16890 is the most recent and globally applicable standard.
Based on the mean distribution of the main contaminants of concern (including viruses) particle sizes across several studies, the average calculated filtration efficiency values for mechanical filters across each rating system is provided below.

Table 5 – Global Representative Droplet Nuclei Filtration Efficiency

ASHRAE MERV Filter Rating	EN779 Filter Rating	ISO 16890 Filter Rating	Est. Filter Effiency (%)
1	G1	ISO Coarse < 50%	< 15%
2	G2	ISO Coarse < 50%	< 15%
3			< 15%
4			16.80%
5	G3	ISO Coarse > 50%	26.55%
6			32.45%
7	G4	ISO Coarse > 50%	41.13%
8			55.57%
9	M5	ePM10 > 50%	62.00%
10			64.65%
11	M6	ePM2.5 > 50%	72.86%
12		ePM10 > 60%	83.39%
13	F7	ePM1 > 50%	89.93%
		ePM2.5 > 65%	
		ePM10 > 80%	
14	F8	ePM1 > 70%	94.94%
		ePM2.5 > 80%	
		ePM10 > 90%	
15	F9	ePM1 > 80%	96.18%
		ePM2.5 > 90%	
		ePM10 > 95%	
16		ePM1 > 85%	97.40%
		ePM2.5 > 95%	
		ePM10 > 95%	
HEPA +	HEPA +	HEPA +	> 99%
ULPA +	ULPA +	ULPA +	100%

These average calculated values can provide consistency in application for any future early stage design IAQ and ventilation calculations, particularly in terms of effective air change (ACHe) and clean air delivery rates (CADR). These can be updated or replaced with specific manufacturer filter information once available if required.

Research indicates that MERV13-14 (F7-F8) offered the best value balancing pollution removal and risk of virus infection with energy penalty and operating costs, and are therefore recommended for future commercial building design.

Air disinfection/purification is the newest category in the air cleaning industry and has the widest range of technologies. As a result it also has the greatest number of unknowns and uncertainties. The ASHRAE Position Document on Filtration and Air Cleaning provide an overview and comparison of these air purification technologies. What can be concluded from these studies is that there is not sufficient evidence at this stage to support the use of air purification devices in commercial environments for IAQ purposes. There may be some limited use of AHU or in-duct UVC in warmer, cooling dominated environments, and air cleaners, particularly in-room located technologies, in unventilated areas such as elevators or some meeting rooms but this singly will not provide good IAQ in the long-term.

The strong performance of filtration, particularly when including activated carbon, versus air cleaning technologies is demonstrated well in the table below.

	HEPA Filters	Ionization	UV Light	Activated Carbon
Effectiveness against Viruses	**Very Good**	**Good** (airborne + surfaces)	**Good** (Depending on contact time)	**Poor**
Effectiveness against Bacteria	**Excellent**	**Good** (airborne + surfaces)	**Good** (Depending on contact time)	**Poor**
Removes Gasses (Radon, Formaldehyde, etc.)	Not Effective	Not Effective	Not Effective	Excellent
Eliminates Odors	Not Effective	Good	Not Effective	Excellent
Effectiveness against pet dander	Excellent	Excellent	Not Effective	Not Effective
Effectiveness against pollen	Excellent	Excellent	Not Effective	Not Effective
Effectiveness against mold spores	Excellent	Excellent	Good	Not Effective
Effectiveness against dust mite excreta	Excellent	Excellent	Poor	Poor
Cost per cartridge	Moderate	Moderate	Moderate	Inexpensive
Cartridge life expectancy	1 Year	2 years	1 year	3-12 Months

Ineffective — Very Effective

Cosentini A TETRA TECH COMPANY

Figure 62 – Qualitative Effectiveness Comparison Summary table (Cosentini)

A final note, with the advancements and benefits of filtration and air cleaning technologies is ventilation required to be from outdoors i.e. 'outdoor air'. ASHRAE Standard 62.1 defines ventilation as 'the process of supplying air or removing air from a space for the purpose of controlling air contaminant levels…', not mentioning outdoor air at all. This opens the door for air recirculation and filtration as a source of ventilation, or additional ventilation particularly in the case of high ACH requirements.

HVAC Best Practice Guidance Literature Review Summary

Overview

A pivotal aspect of this study was the review and discussion of HVAC - ventilation in particular - best practice guidance issued during and post the COVID-19 pandemic.
There has been a multitude of guidance documents and best practice guides produced over the last 2+ years with HVAC institutions around the world issuing advice and guidelines concerning buildings' air-conditioning and ventilation systems to help reduce COVID-19 transmission risk. The advice provides general consensus that certain HVAC measures can be beneficial and are recommended, but specifics do vary across institutions. HVAC systems can assist in reducing transmission risk however HVAC measures should be adopted in conjunction with other administrative and personal measures as part of a broader infection-control strategy in buildings.

All agree that national public health guidance should first be implemented including regulatory and statutory requirements, and recommendations such as vaccination, wearing of masks and other personal protective equipment, social distancing, administrative measures, circulation of occupants, hygiene, and sanitation as applicable. HVAC measures recommended vary across institution but in general cover topics from ventilation rates, air cleaning and heat recovery to IAQ monitoring. A summary of these topics is displayed well in the below graphic from REHVA[18].

[18] https://www.rehva.eu/fileadmin/user_upload/REHVA_COVID-19_guidance_document_V3_03082020.pdf

1. Ventilation rates
2. Ventilation operation times
3. Overrule of demand control settings
4. Window opening
5. Toilet ventilation
6. Windows in toilets
7. Flushing toilets
8. Recirculation
9. Heat recovery equipment
10. Fan coils and split units
11. Heating, cooling and possible humidification setpoints
12. Duct cleaning
13. Outdoor air and extract air filters
14. Maintenance works
15. IAQ monitoring

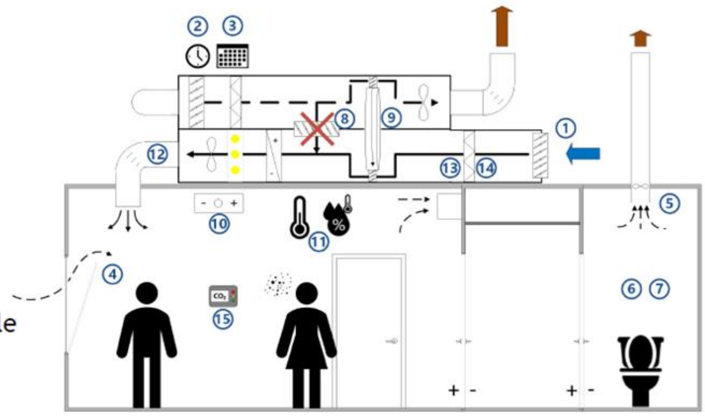


Figure 63 – REHVA COVID-19 HVAC Measures (REHVA)

Appropriate HVAC measures should be assessed on case-by-case basis and consider the effectiveness of each measure, its cost and ease of implementation, and its impact on energy performance and occupant comfort for a particular building. Other factors should also be considered such as building location, local climate, and occupancy rates for example.

Taking this into account, the main aim of this section was to provide a comprehensive summary table of guidance from across the industry, and provide comment on the measures ease of implementation, long-term applicability, and effect on transmission risk and building operation.

This proved more difficult than expected due to the vast amounts and constantly changing guidance. Nevertheless, the resulting table below, to the best of my knowledge, summarises the main recommendations from 5 globally recognised HVAC industry expert bodies – ASHRAE (USA), AIRAH (Aus.), CIBSE (UK), REHVA (EU), and ISHRAE (India) – covering a range of geographies and climates.

Institute	ASHRAE	AIRAH	CIBSE	REHVA	ISHRAE
Ventilation System	Ventilation with 'effective airflow patterns' recommended	Switch AHUs with central recirculation to 100% outdoor air	Avoid air recirculation if possible	Avoid air recirculation if possible	Ducted mechanical ventilation recommended
Ventilation Distribution System (effectiveness)	promote mixing of space air without causing strong air currents	No reference	No reference	No reference	No reference
Ventilation Operation	Between occupied periods, operate systems for a time required to achieve 3 ACH of equivalent clean air supply	Ventilation 2 hours before and after occupancy Keep toilet ventilation 24/7 in operation	Extended AHU operation times at nominal speed 1 hour before and after occupancy are recommended	Ventilation 1-2 hours before and after building usage to achieve 3 ACH	Ventilation system should be kept on throughout the off cycle
Ventilation Rate – 'Fresh Air' Quantity	Increase OA to maximum that system can condition Min OA during off-hours No reference to specific air change rate for occupancy	Increase outdoor ventilation of spaces Ensure CO2-controlled ventilation runs at maximum capacity during occupancy	Change system to 100% fresh air when occupied, recirculating with filtration/UV ok when unoccupied to clean air at lower energy cost. No reference to specific air change rate	Change system to 100% fresh air, supply as much fresh air as reasonably possible, use window airing to boost ventilation. Demand control ventilation to be set to achieve 550 ppm CO2 setpoint.	Ventilate indoor areas with fresh air as much as possible. Introduce fresh air duct with fan or use operable windows. Min. 2.36 l/s/p recommended
Temperature	Maintain dry bulb temperatures within the comfort ranges, ref. ASHRAE Standard 55 -2017	N/A	No recommendations	No practical effect	24-30°C
Humidity	40-60% recommended for general occupant comfort, no specific recommendation for COVID-19	40-60% recommended	>40% recommended	No practical effect on virus - 25-40% min recommended to prevent nasal sensitivity to infection	40-70% recommended
Filtration	Maximum filter grade AHU can accommodate; MERV-13 or greater recommended	There is no clear indication that special filters should be installed in offices and similar environments.	Increased filtration is recommended and is especially valuable in poorly ventilated area with high occupancy where increasing ventilation rates is difficult.	Increased filtration of the main ventilation system is recommended.	MERV 13 or higher filter recommended at AHU.

Institute	ASHRAE	AIRAH	CIBSE	REHVA	ISHRAE
UV Treatment	UVGI is effective at inactivating the virus, best application may vary by project concerns	N/A	Upper room UV can reduce the risk in poorly ventilated spaces. In-duct systems may be effective only when duct velocity and radiation intensity are Manage Portable units may be effective, careful attention needed to size correctly.	UV air cleaning equipment is effective at killing bacteria and viruses, but normally only a heath care grade equipment would be suitable	UVGI recommended for larger ducted AHUs
Other Air Cleaning Technology	Only use air cleaners for which evidence of effectiveness and safety is clear	No reference	Air disinfection or cleaning using UV or HEPA filters has 'potential'. No reference to other technologies.	Electrostatic filtration devices of similar efficiency to HEPA filters acceptable	Referenced but no specific guidance provided
Mechanical Ventilation Heat Recovery	Bypass energy recovery ventilation systems that leak potentially contaminated exhaust air back into the outdoor air supply – emergency response	No reference	Avoid recirculation in device if possible TW rotor off if thermal comfort achievable without it.	Dedicated heat recovery guide Not necessary to switch TW rotor off. Ensure TW properly constructed. Test leakage. Purge sector recommended	No reference
Local/In-room Air Cleaners	Local room air cleaners are recommended for "poorly ventilated" areas	No reference	Local room air cleaners are recommended for "poorly ventilated" area. Central location is room recommended	To be effective, air cleaners need to have HEPA filter efficiency. Correct sizing and location advised	No reference
IAQ Monitoring	No reference	Install CO2 monitor with traffic light indication	Measurements of elevated CO2 levels in indoor air are an effective method of identifying poor ventilation. CO2 monitors should be non-dispersive infrared (NDIR)	Installation of CO2 monitors in occupied zones as indicators of outdoor air ventilation	No reference

Table 6 Summary main recommendations from HVAC industry expert bodies

Many of these recommendations are issued in sole consideration of virus risk transmission, and so not in greater consideration of the overall effect on building operation and sustainability (now incorporating IAQ and resilience). Therefore, I discuss these recommendations from a broader long-term sustainability perspective, focusing on measures that can be incorporated into future building design in the new normal.

Ventilation System & Distribution Effectiveness

In Ventilation systems, nearly all guidance makes reference to the inherent benefit of a dedicated outdoor air system (DOAS) with 100% fresh outside air supply over a recirculating system – the minimised risk (only zero in case of separated air streams in heat recovery e.g. run-around coils) of entrainment of contaminants including virus particles into the supply air. ASHARE is the primary institution submitting that recirculation type system, which are immensely popular in the Americas region, with suitable filtration and/or air cleaning is an appropriate ventilation system once minimum recommended outdoor air rates are maintained. The added benefit of higher air change rates for greater contamination dilution achievable by a central recirculation ventilation system is an often overlooked advantage. However, moving more air through central ducted system can come with a greater plant space requirement and energy penalty that does need to be considered. Despite the majority of guidance literatures preference for DOAS, well designed recirculation type systems also have a place in the future of sustainable ventilation design.

Air distribution and ventilation effectiveness is relatively overlooked across the guidance, except for some references to effective airflow patterns and reducing stagnant air areas. From my research I can understand why, the concept can be complex, and difficult to implement and then verify in the field. However, I do believe there is an opportunity to promote and utilise ventilation effectiveness to a greater extent in building design and operation. The effectiveness of the ventilation system should be considered at the design stage, when specifying ventilation rates, and during building operation to confirm adequate ventilation is being achieved. This would help to achieve high IAQ and improve sustainability.

Good air distribution is critical to any design, and it is likely that well mixed, ceiling based ventilation will achieve this, but research indicates that displacement type ventilation systems with lower air velocities will reduce the risk of virus transmission and likely lower building energy demand.

Ventilation Rate & Operation

'Adequate' ventilation is recommended across the guidance documents but with no consensus on the definition of 'adequate ventilation' or how it is demonstrated in building operation. The variance in recommended ventilation rates across different guidance is detailed in the previous 'Ventilation' section of this report, and characterizing adequate ventilation is one of the aims of this research.

Additionally, the distinction between "ventilation air" and "outdoor air" is not always absolute. ASHRAE standards define ventilation as "the process of supplying air to or removing air from a space for the purpose of controlling air contaminant levels, humidity, or temperature within the space." There is no mention of outdoor air or percentage of outdoor air. Any air that has a lower concentration, even if non-zero, of the contaminant that is being diluted can provide "ventilation". On this basis recirculated, filtered or cleaned air would be able to provide ventilation. However, we know that most air cleaning and filtration cannot remove bio-effluents like CO2 and therefore 'outside air' ventilation is still required for occupants, but ventilation can be boosted by recirculated air if required, typically at a lower energy and sustainability penalty than outside air.

Even in the majority of healthcare environments, there is no limitation on air recirculation only the requirement for an 'adequate' supply of outside air and suitable filtration of recirculation air combined to achieve design airflow.

Therefore, the discounting of air recirculation and only recommending 100% outdoor air for typical commercial buildings such as offices suggests that these spaces should be more stringent with respect to air recirculation than healthcare facilities.

The initial recommendation to run HVAC systems 24/7 has thankfully been scaled back to a set pre and post occupancy run time - usually 2 hours, or recommendation to achieve a minimum number (typically 2-3 ACH) of air changes between occupancies. I personally am more in favour of the latter as we know 3 ACH can achieve >95% contaminant removal, can be incorporated into ventilation 'optimum start' or night cooling procedures, and in some cases (for certain contaminants for example) can be achieved by full filtered/cleaned air recirculation if required. However, note the latest UK Part F regulations does not allow for this with 'purge air' to be exhausted to outside a requirement. It is also noteworthy that BS EN 16798-1 2019 recommends a minimum amount of air to be delivered prior to occupation to achieve at least 1 volume within 2 hours of the zone to be ventilated (i.e 0.5 ACH for 2 hours).

Alternatively the ventilation can be lowered for un-occupied periods (if such ventilation turndown rate is available), and the total air flow rate for diluting emissions from building should be minimum 0,15 l/s.m2 of floor area in all rooms, but there is no supporting evidence for the basis for this provided.

Additionally, as suggested in BS EN 16798-1 2019 Method 2, using CO2 concentration is acceptable as basis for adequate ventilation design and IAQ . As a result I cannot agree with the guidance measure to turn off or lower DCV to <400ppm (or 550 PPM in later guidance) enabling full constant ventilation. Assuming the ventilation rate to the corresponding CO2 level is adequate to the required IAQ level, I see no need to alter the DCV settings, even considering any time delay in increasing ventilation rates based on slow reacting CO2 measurements as COVID related infection risk varies minimal in such short time frames.

If ventilation strategy is well designed to provide adequate ventilation to meet occupant and building level requirements there should be no need to disable control strategies such as DCV in the future. It should be ensured however, that a minimum amount of ventilation (per m2 floor area) should be provided to dilute room or building related contaminants and achieve suitable ACH regardless of measured CO2 level.

Temperature & Humidity

Temperature and humidity although key components of IEQ and IAQ, particularly in terms of relative humidity which in high levels can promote microbial growth such as mould and bacteria, but both are lightly reference throughout the guidance. This is due to the fact that temperature and humidity have relatively little effect on COVID-19 in the comfort range of occupancy. Nevertheless across the guidance there is consensus to maintain temperature in usual climate comfort range, and relative humidity between 40-70% to minimise the risk of microbial growth, as well as maintaining the health and comfort of human occupants.

Air Filtration & Air Cleaning

Air Filtration

There are different recommendations by industry bodies on the level of required recommendation – ranges from HEPA grade filters down to no specific filtration required. HEPA filters can be viewed as medical grade filtration, rated to remove 99.97% of particles at 0.3microns in size, useful where it is known that a large bioburden will be in the space such as healthcare environments.

For all other spaces, such as those in commercial settings, a MERV 13/14 filter is a practical filter grade for strong IAQ, economic and energy performance. This grade of filter will remove roughly 90% of particles at 0.3 microns in size, very close to the performance of a HEPA filter, but as discussed in the August 2020 CIBSE Journal article by T Dwyer ‘Understanding HEPA filters’ the air-pressure drop across a HEPA filter is likely to be two or three times that of a typical filter. A 50Pa of added pressure drop through a filter passing 1m3/s will consume an additional 1.2kWh of fan power every 24 hours which can be significant on larger scale systems. Selecting a filter with the deepest pleat your system can accommodate reduces the added pressure drop across the filter and improves filtration, but can increase AHU size and space requirements.

Air Cleaning – UV and Other Technologies

Air Cleaning includes Ultraviolet (UV) disinfection and other air cleaning technologies such as photocatalytic oxidation, photoelectrochemical oxidation, electrostatic precipitation, and various ionization technologies including bipolar ionization

UV technology has been used for years to kill or inactivate microorganisms, and is variously abbreviated as UV-C (with the suffix indicating the wavelength band, 200 to 280 nm), UVGI (ultraviolet germicidal irradiation), and GUV (Germicidal Ultraviolet). Many of these systems, save UVC, are relatively new and in most cases these products have concerns about by-product emissions such as Ozone, and have not been tested by independent parties or lack test standards against which to measure their performance. As a result you will find little reference to these throughout my or many institutions recommendations, and any available guidance recommends caution and comprehensive verification if selecting one of these newer, unproven technologies.

In contrast UVC air cleaning or disinfection is referred to in several guidance documents, as ASHRAE’s Position Document on Infectious Aerosols recommends consideration of all three UVC applications – in AHU, in-duct, and in room - for “high-density spaces such as waiting rooms, prisons, and shelters,” for non-healthcare buildings, presumably because these spaces are more likely to be inhabited by infected people due to limited control over who occupies the space and other control measures. The Illuminating Engineering Society (IES) in their Germicidal Ultraviolet (GUV) FAQ report states that the most effective UVC application for disease control is irradiation at the room level, or upper-room UVC. However, the need for specific disease control in commercial environments, particularly with other controls in place, should be limited.

Additional concerns about the health effects of UV radiation in proximity to human occupants, and the possible production of Ozone means any recommendation to include in-room UV technology needs to be carefully considered.

While duct and air handler UVC applications can mitigate recirculated COVID-19 risk, in order for a UV sterilisation system to function correctly the dwell time, the intensity (approximately 0.4W per L/s of air minimum) and the correct wavelength are required to deactivate viral content. Additionally, if adequate filtration is applied it should already be removing a large quantity of viral material and other contaminants prior to the UVC. In the authors opinion, the only consideration for UV technology in the AHU system or ducts is to irradiate wet downstream cooling coil and drain pan surfaces in warm and humid environments where coils are wet for long periods. This will help deactivate any viral particles still present in the air, and simultaneously reduce or eliminate fungal amplification on the coil and drain pan, reducing fouling and air resistance improving energy efficiency. Care must be taken to ensure UV does not degrade materials such as filter media (especially synthetic media), pipe insulation, and wiring jackets.

ASHRAE's Position Document on Filtration and Air Cleaning states: "One key statement is that, at present, there is only significant evidence of health benefits for porous media particle filtration systems. For a few other technologies, there is evidence to suggest health benefits, but this evidence is not sufficient to formulate firm conclusions. A key position is that filtration and air-cleaning technologies are not recommended for use if they produce significant amounts of contaminants [such as ozone] that are known or expected to be harmful for health".

Local / In-room Air Cleaners

While not fully consistent, most guidance suggest that local air cleaning and filtration may be beneficial for reducing air pollution and virus transmission risk in some spaces, particularly if it is not possible to increase ventilation (in this case referring to outside-air ventilation). All such devices will increase the "effective" ventilation rate; however their impact will depend on the volume of the room, the flow rate through the device (CADR), and the location of the device in the room, all of which need to be considered before specifying local air cleaners. They can either stand-alone consumer devices which can be readily deployed in any space, or installed in a similar manner to a local air conditioning unit. Noise and any other emissions from the device should also be considered.

Again, use of these devices will not change CO2 concentrations in a room and therefore 'outdoor' air ventilation to dilute bio-effluents to the desired IAQ level would still be needed. Local air cleaning devices typically use HEPA filters and/or UVC irradiation to remove or inactivate contaminants and viruses. There are also many other air cleaning technologies on the market but again, and even more so for in-room locations, the current lack of independent testing and standards limits their reliable, safe use in commercial environments, and hence are not recommended at this time.

ASHRAE's Position Document on Filtration and Air Cleaning summarises this well with: "Presently, minimal data are available on the health consequences of using [local] packaged air cleaners employing multiple technologies." However, several studies show they may be beneficial to reducing pollution concentration if placed near the source. Most residential portable air cleaners come with HEPA filters, but many also offer UV-C and activated charcoal as well. Relative to COVID-19, the HEPA filter should be effective alone without these other options, and electronic air cleaners that generate ions or ozone should be avoided.

IAQ Monitoring

Most of the reference to IAQ monitoring throughout the guidance is to CO2 monitoring as a metric for confirming 'adequate' ventilation in a space. For decades, CO2 has been widely accepted as an indicator of ventilation and it should continue to do so as CO2 measurements may also be used to help verifying ventilation effectiveness and supply rates during building operation. However, in a future of building design considering IAQ, it is recommended that a more wholistic measurement of IAQ including building based contaminants such as VOCs, and possible external contaminants such as PMs or NO should also be monitored. Detailed guidance on the monitoring of IAQ is available from multiple IAQ monitoring equipment suppliers such as Kaiterra, or the WELL Building standard for future building designs.

Mechanical Ventilation Heat Recovery (MVHR)

Heat recovery devices used in ventilation systems generally provide recovered heat from exhaust to supply air in winter, and can also recover cooling in peak summer conditions. There are multiple types of MVHR including flat plate heat exchangers, run-around coils and thermal wheels, a detailed description of each is available numerous CIBSE and ASHRAE guides.

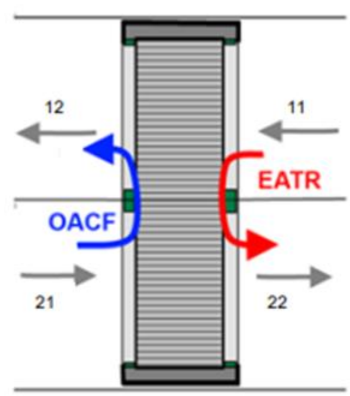
Heat recovery systems air leakage and possible COVID-19 transmission risk was a highly studied concept initially during the pandemic, with dedicated heat recovery and specific thermal wheel guidance documents produced.

In general, the HVAC best practice guidance produced focused on thermal wheels which have the greatest potential for air cross leakage and hence COVID-19 transmission risk. Thermal wheels are also generally accepted as the most efficient heat recovery device except for some instances in arid climates where plate heat exchanger technology is preferred. Although has been some recent improvements in run-around coil technology with its minimal air leakage possibility, and lower system weights is seeing an increased interest in the technology (e.g. Flaktwoods ECONET).

Initially, and still in some instances, guidance recommended that heat recovery systems be bypassed or shut off to avoid risk of cross contamination. This is important as the heat recovery function is usually integral to the ventilation system design in terms of simultaneously delivering adequate air flow and meeting heating or cooling demand so should not be off when required. As our knowledge of COVID-19 progressed, the guidance generally progressed from bypassing the heat recovery systems to recommending measures to reduce risk of cross contamination such as installation of purge sectors, adequate seals, and correct fan placement and operation for positive pressure differentials on supply air.

Some of these recommended measures and heat recovery terminology play an important part in this research and therefore are summarised here: -

The main indicator of internal leakage of potentially contaminated air leaving the room to supply air through the exchanger is expressed by Exhaust Air Transfer Ratio (EATR).



Outdoor Air Correction Factor (OACF) represents the leakage of the outdoor air to the exhaust air, which mainly affects the energy consumption.

Eurovent 17/11-2015 provides an explanation OACF and EATR, and while the diagram makes ratios function clear, the calculation behind OACF and EATR in particular are inaccessible to most engineers and facility managers alike.

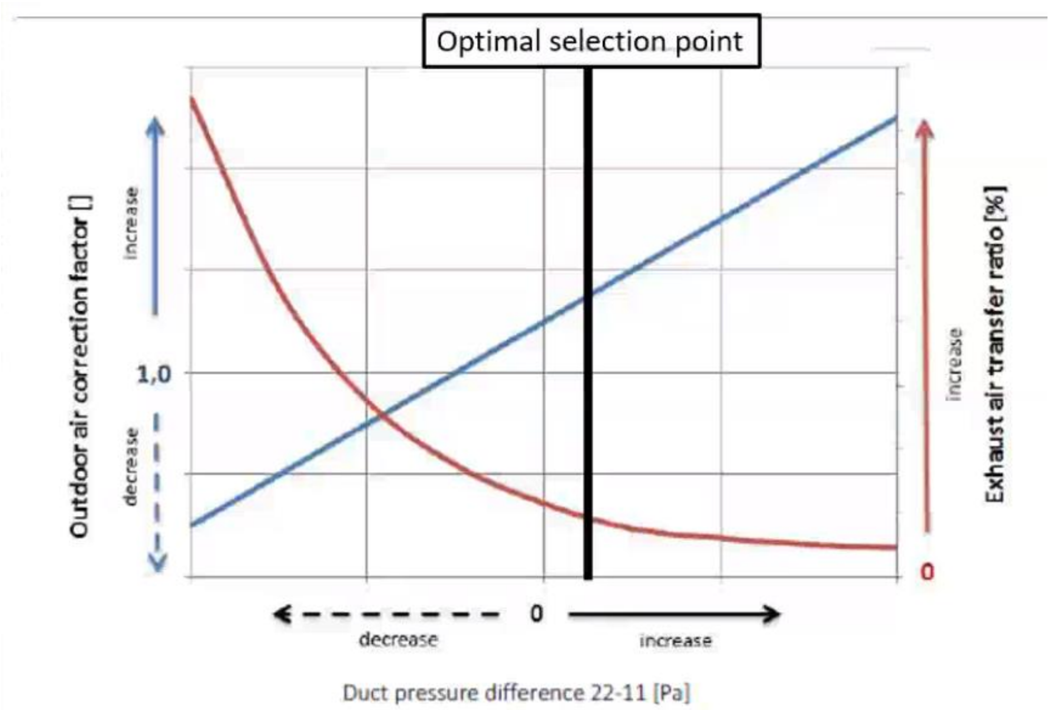


Figure 64 – EATR vs OACF Graph with Optimal Selection Point (Eurovent)

To calculate OACF & EATR requires additional accurate measurements of air flowrates at each quadrant of the heat exchanger – difficult to accurately measure airflow as requires long straight runs of duct/AHU but can be measured indirectly using fan VSD estimations. A simplified estimation of EATR is provided in pre-print prEN308 but can only be done when heat recovery is in bypass i.e. the rotor is stopped.

Simplified method to estimate EATR

1. Measure temperatures (t_{11}, t_{21}, t_{22})
2. Test at deactivated heat recovery (stc

$$EATR = \frac{t_{22} - t_{21}}{t_{11} - t_{21}}$$

As illustrated in Figure 64 below, EATR is a function of the pressure difference between supply air side downstream exchanger (p22) and the extract air side upstream the exchanger (p11), and its value depends on the type of sealing and conditions. Also the rotor speed and inclusion of a purge sector would have an impact on EATR. Other points of leakage such as AHU casing, air inlets and outlets, and ducts should also be considered and minimised in the design and installation stage.

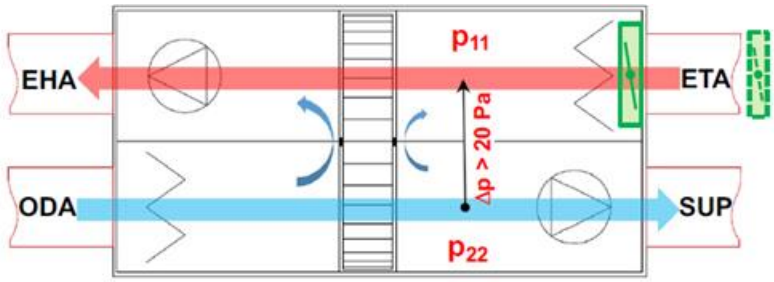


Figure 65 - Typical Thermal Wheel AHU Pressure Differential

For a correctly designed, set-up and maintained rotary heat exchanger, the leakage of potentially contaminated extract air to supply air is typically very low and in practically negligible. Nevertheless, in case of improper layout of AHU fans or lack of correct pressure balance setting, the leakage may be significantly higher. The main recommendation is to keep positive differential pressure on the supply air side, and in this way, ensure the possible leakage from supply to exhaust air (i.e. EATR = 0%). The ideal AHU fan position to achieve this is with fans placed after the thermal wheel in their respective airstreams. AHUs should include pressure taps to measure p11 and p22 or ideally include differential pressure sensors for continuous monitoring. Following this, strong and well maintained sealing is the most effective recommendation to limit any leakage across airstreams (EATR and OACF). Perimeter and middle bean sealing in thermal wheel chambers is essential to minimising sealing leakage, which constitute the large majority of EATR. OACF is typically lower on larger units which is worth taking into consideration also.

Remaining a recommendation in some guidance - purge sectors are an additional specially designed part that mounts on to the rotary wheel housing at the airflow-dividing panel, and covers an area of the rotary wheel between the extract and supply air flows that purges the contaminated air from the wheel structure.
The purge sector is only effective, however, if the correct pressure potential is present and the correct fan configuration is used. Most rotors operate without purge sectors since typically a small mixing of exhaust air into the supply air is permissible, particularly as air is typically also filtered. In terms of COVID-19 there is some limited evidence of viral material being detected in air handling units, although its infectious viability is not confirmed. Additionally the ability of a purge sector to remove this viral material is not confirmed. However, it is known that the purge sector can add a point of weakness between thermal wheel middle beam sealing, and a functioning purge zone increases OACF approximately by the amount of purge flow, increasing energy consumption to still achieve the required supply flow rate.

Building Certification and IAQ

A large part of this research was to review the recommended measures to tackle COVID-19 and improve general IAQ. This extends to the requirements and credits incorporated into several of the international building certification standards.

The international building certification standards reviewed include:-

- WELL Building Standard
- LEED
- BREEAM
- NABERS Indoor Environment (IE)*
- IMMUNE Building Standard*

*NABERS IE and IMMUNE were later additions as the research progressed and I became aware of them, and are therefore are less detailed.

For the main globally renowned building certification standards of WELL, LEED and BREEAM a summary table of IAQ related features is presented providing the requirements, commentary, and a relative difficulty of implementation scale for each. Additional information on each building standard can be found on their respective website. There are a lot of synergies between the building certification standards which are typically summarised in 'crosswalk documents' that detail the alignment between different certification standards and are found on their respective websites.

WELL Building Standard (V2)

The WELL Building Standard is an evidence-based system for measuring, certifying, and monitoring the performance of building features that impact health and well-being created by the International WELL Building Institute (IWBI). Currently available in 2 versions, and an additional Health-Safety rating, it is arguable the most relevant standard in terms of IAQ and ventilation with an entire category devoted to 'Air'.
Certification costs for WELL building standard start at $15,500, and go to over $100,000 depending on building floor area. However, information on the rating system measures and their implementation is widely accessible online.
The below summary focuses on the later V2 version which is more relatable to modern ventilation elements – encompassing 14 features covering ventilation effectiveness to air cleaning. WELL version 1 is a broader version of WELL V2 with a more cumbersome 'Air' category incorporating 29 features.

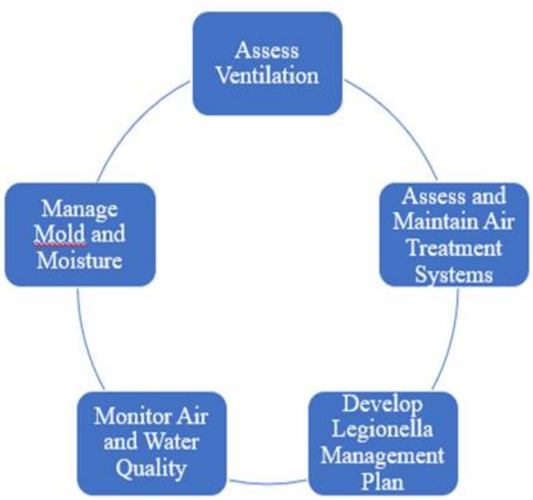
WELL Building Standard (V2)			
Precondition = mandatory Optimization = optional	**Requirements**	**Commentary**	**Difficulty** * Low ***High
Feature A01 Air Quality			
Part 1 PM Thresholds	*Requires air quality tests/monitoring to show PMs meet acceptable thresholds.*	Needs consideration of typical outdoor air quality and air cleaning/filtration strategy. More difficult in urban locations	*
Part 2 VOC Thresholds	*Requires air quality tests/monitoring to show VOCs meet acceptable thresholds.*	Needs consideration of building materials and furnishing, and air cleaning/filtration strategy.	*
Part 3 Inorganic Gases Thresholds	*Requires air quality tests/monitoring to show inorganic gases meet thresholds.*	Needs consideration of typical outdoor air quality and air cleaning/filtration strategy. More difficult in urban locations	*
Part 4 Radon Thresholds	*Requires air quality tests/monitoring to show Radon gas meet thresholds.*	Can and is often achieved by meeting A03 Part 1 ventilation design requirement meaning testing is not required.	*
Part 5 Measure Air Parameters	*Measure at least once per year PMs, TVOCs, CO and O3*	Requires a once yearly independent IAQ test or IAQ monitoring system. Should be used to confirm and recommission ventilation system design	*
Feature A02 Smoke-Free Environment			
Part 1 Prohibit Indoor Smoking	*Requires no smoking indoors*	Standard practice – generally required by regs	*
Part 2 Prohibit Outdoor Smoking	*Requires No smoking signage at applicable locations*	Standard practice to have signage and designated smoking area away from building	*
Feature A03 Ventilation Design			
Part 1 Ensure Adequate Ventilation	*Install & Commission ventilation system to meet chosen Regulation/Standard*	Standard practice – select the appropriate ventilation strategy and regulation/standard for project	*
Feature A04 Construction pollution management			
Part 1 Mitigate Construction Pollution	*Requires protection OR vacuuming of ductwork.* *Requires replacement of >MERV8 filter prior to occupancy.* *Implement dust & moisture management procedures*	All typically standard practice in construction industry, although often not well-enforced.	*
Feature A05 Enhanced Air Quality			
Part 1 Enhanced PM Thresholds	*Requires air quality tests/monitoring to show PMs meet acceptable thresholds.*	Needs consideration of typical outdoor air quality and air cleaning/filtration strategy. More difficult in urban locations	**
Part 2 Enhanced VOC Thresholds	*Requires air quality tests/monitoring to show VOCs meet acceptable thresholds.*	Needs consideration of building materials and furnishing, and air cleaning/filtration strategy.	**
Part 3 Enhanced Inorganic Gases Thresholds	*Requires air quality tests/monitoring to show inorganic gases meet thresholds.*	Needs consideration of typical outdoor air quality and air cleaning/filtration strategy. More difficult in urban locations	**
Feature A06 Enhanced Ventilation Design			
Part 1 Increase Outdoor Air Supply	*Requires 30% (60% for 2 points) increase in minimum rates or prediction of effective ventilation as per Regs / ASHRAE / CIBSE AM10.*	Generally achievable. For offices, achieving 16l/s per person as per BCO specs likely suffice. More challenging for naturally ventilated buildings. Option to use DCV CO2 ppm limits (750ppm 2 points, 900ppm 1 point) also given. A downside can be increased energy input.	*

Part 2 Improve Ventilation Effectiveness	*Use Displacement ventilation (90% of area) or personal ventilation (50% workstations) to improve ventilation effectiveness*	Not standard practice and does have additional design considerations. Personal ventilation is limited in commercial environments.	**
Feature A07 Operable Windows			
Part 1 Provide Operable Windows	*> 75% of occupied areas have operable windows to outdoor air. OR openable window area is >4% the occupied area*	For mechanically ventilated strategies openable windows is generally not applicable.	**
Part 2 Manage Window Use	*Outdoor PMs, temp and RH are monitored. And Indicator lights at windows for occupant opening cues*	Outdoor air measurement at least once per hour is demanding but can be from other monitoring station within 2.5 miles of site if available. Window indicator lights are not common practice and additional expense	***
Feature A08 Air quality monitoring and Awareness			
Part 1 Install Indoor Air Monitors	*Requires monitoring and reporting of 3 or more – PMs, CO2, CO, O3, NO2, TVOC, Formaldehyde*	Not standard practice but increasingly asked for by Clients. Requires sensor and monitoring strategy, annual calibration and reporting all implying additional CapEx and OpEx costs.	**
Part 2 Promote Air Quality Awareness	*Display IAQ data collected simply in occupied spaces*	Not standard practice, implies additional CapEx costs.	**
Feature A09 Pollution Infiltration Management			
Part 1 Design Healthy Entryways	*Requires regularly used entrances have air and foot pollution retention system.*	Requires communication with Architect and client on entryway lengths and revolving doors / vestibules etc. and additional maintenance	**
Part 2 Perform Envelope Commissioning	*Requires a competent façade engineer produce an envelope commissioning plan and report*	Not standard practice, results in CapEx increase.	**
Feature A10 Combustion Minimization			
Part 1 Manage Combustion	*Requires no space conditioning or cooking combustion technology is used, and no vehicle idling signage*	Becoming more standard practice with several alternative electric options	*
Feature A11 Source Separation			
Part 1 Manage Pollution and Exhaust	*Requires direct exhaust for toilets, cleaners/ chemical storages, printer/copiers rooms.*	Relatively standard practice. Requires particular consideration in speculative offices targeting 'WELL-readiness'.	*
Part 2 System Performance	*Require CFD analysis and comfort verification.*	Complex, but becoming more common, particularly when displacement systems are specified.	**
Feature A12 Air Filtration			
Part 1 Implement Particle Filtration	*Use required filter grades (MERV 12 +) depending on outdoor air quality And Maintain according to manufacturer recommendations*	MERV 12+ filters are now standard practice. Will require outdoor air quality (PMs) measurement	*
Feature A13 Enhanced Supply Air			
Part 1 Improve Supply Air	*Supply 100% OA, OR acceptably filter/clean recirculated air*	Requires DOAS AHU or MERV14+ and carbon filters (in AHU or in room) to achieve which is currently not standard practice but worth considering. Additional CapEx and small OpEx.	**
Feature A14 Microbe and Mold Control			
Part 1 Implement Ultraviolet Treatment For HVAC Surfaces	*Requires UV light on cooling coils and drain pans, AND proper maintenance of same*	Not standard practice. May have some benefit in warm, humid climates. Additional CapEx and small OpEx	***

Some additional, overlapping features for consideration include:-

- Community C03 – Emergency Preparedness: which includes the requirement for an emergency management plan outlining the building response to emergency situations such as wildfires (if applicable).
- Materials X06 - VOC Restrictions: which includes restrictions of VOC off-gassing from wet-applied products and internal furniture and products.
- Materials X11 - Cleaning Products and Protocols: which includes preferred cleaning products with less hazardous chemicals and improved cleaning practices.

Image Source: IWBI (International WELL Building Institute)



As a stand-alone building certification, The WELL Health-Safety rating was created by the IWBI in response to the COVID-19 pandemic and is aimed at facility operations and management of new and existing buildings. Rather than focusing on long-term design strategies typically covered in WELL, the WELL Health-Safety rating focuses on strategies that can be implemented immediately within the scope of facility operations and management to reduce the risks of infectious disease spread.

The WELL Health-Safety rating includes more than 20 features across the following core areas, a minimum of 15 of which need to be met:

- Cleaning and Sanitization Procedures
- Emergency Preparedness Programs
- Health Service Resources
- Air and Water Quality Management
- Stakeholder Engagement & Communication

Projects undergo an annual renewal process validating their on-going operations and maintenance to ensure integrity and consistency. More information is available from the IWBI website on WELL Health-Safety rating. As not typically a building design certification standard but more of a facility operations and management procedures guide, the WELL Health-Safety rating is not wholly applicable to building design and is not explored further in this study.

LEED (V4)

Leadership in Energy and Environmental Design or LEED provides a globally recognised building certification standard and framework for healthy, efficient, carbon and cost-saving green buildings of for all building types. Developed by the non-profit U.S. Green Building Council (USGBC) in 1998, its latest version V4 released in 2015 and a pilot updated version V4.1 available since 2019. Certification costs for LEED start at approx. $4,000, and is uncapped with rates varying depending on building floor area. However, information on the rating system measures and their implementation is widely accessible online. It is a design tool rather than a performance-measurement tool and focuses on operational and embodied carbon. However, there are credits that impact occupant health and IAQ as summarised below.

LEED (V4)			
	Requirements	**Commentary**	**Difficulty** *Low ***High
EQ Prerequisite Minimum Indoor Air Quality Performance			
Ventilation	*Requires compliance with minimum rates in ASHRAE 62.1 or EN15251 & EN 13779.*	Minimum rates vary depending on application but generally this would be achieved through good practice standards.	*
Monitoring	*Requires airflow monitoring devices, CO_2 sensors for naturally ventilated spaces*	Typically beyond standard practice but becoming more common. Adds extra CapEx	**
EQ Prerequisite Environmental Tobacco Smoke (ETS) Control			
Prohibition	*Prohibit smoking inside building and within 7.5 meters of air inflows, include signage*	Standard practice with regulations and any designated smoking area required can just be adequately signed	*
EQ Credit Enhanced Indoor Air Quality Strategies			
Option 1 Enhanced IAQ Strategies	*Requires entryway systems, cross-contamination prevention and filtration and/or natural ventilation design calculations.*	Relatively easy to achieve, with generally minor CapEx impact. For naturally ventilated spaces, compliance with CIBSE AM10 is required.	*
Option 2 Additional enhanced IAQ Strategies	*Requires exterior contamination prevention study, +30% ventilation rate, source control and monitoring (e.g. CO_2) and natural ventilation room-by-room calculations.*	Exterior contamination prevention analyses (CFD, dispersion modelling, wind tunnel, etc.) are beyond standard practice. CO2 monitoring also not commonly specified.	**
EQ Credit Construction Indoor Air Quality Management Plan			
	Requires IAQ Management plan including protection of ductwork, filter replacement etc.	Normally specified, although often not well-enforced.	**
EQ Credit Indoor Air Quality Assessment			
Option 1 Flush out	*Requires building flush-out under specific environmental conditions.*	Although flush-out is common practice, required air volumes are challenging and may have cost and/or programme implications.	**
Option 2 Air Test	*Pre-occupancy IAQ testing to meet standards*	Not common practice but overlaps with WELL requirements if applicable	**
EQ Credit Low-Emitting Materials (V4.1)			
Low-Emitting Materials	*Use building interior materials that meet low emitting criteria*	Requires research, specification and calculation of 'low-emitting' materials. Limited data available.	***

Some additional, overlapping credits for consideration include the Materials and Resources credit Building Product Disclosure and Optimization - Material Ingredients; which encourage the use of products and materials that have environmentally, economically, and socially preferable life-cycle impacts.

LEED also introduced multiple new Safety First Pilot Credits in response to COVID-19 covering space cleaning protocols, designing for and managing IAQ with COVID-19, and HVAC systems maintenance and recommissioning.

BREEAM

BREEAM (Building Research Establishment Environmental Assessment Method) is a sustainability assessment method launched in 1990 by the Building Research Establishment (BRE). It sets standards for the environmental performance of buildings through the design, specification, construction, and operation phases, and can be applied to new developments or refurbishment schemes. Certification costs for BREEAM building standard start at £1,000, and go to over £4,000 depending on building floor area. However, information on the rating system measures and their implementation is widely accessible online.

For BREEAM the assessment must be undertaken by independent licensed assessors using scientifically-based sustainability metrics and indices which focuses on sustainable value across range of categories including Energy, Pollution, and Health and Wellbeing, the relevant requirements related to IAQ from BREEAM New Construction 2018 summarised below.

BREEAM			
	Requirements	**Commentary**	**Difficulty** *Low ***High
Hea 02 Indoor Air Quality - Minimising sources of air pollution			
Indoor air quality (IAQ) plan - one credit			
Requirement 1	*Requires an IAQ plan covering acceptable pollution levels, IAQ monitoring & testing, contamination sources removal etc.*	Concept usually discussed but not always well recorded and enforced.	*
Ventilation			
Requirement 2a	*Requires fresh air rates in accordance with relevant good practice standards.*	Referenced standards are commonly employed	*
Requirement 2b	*Requires minimum intake / exhaust separation and intake or windows distance from sources of pollution.*	Subject to space and site constraints – more challenging for refurbishment or buildings located in dense urban areas	**
Requirement 2c	*Filtration as per BS EN 13779:2007 Annex A3.*	Updated to new EN 16798-3. Standard F7 filters may not be sufficient in ‘polluted’ locations.	**

Requirement 2d	*Requires CO_2 sensors to adjust ventilation strategy in areas with variable occupancy.*	Typically beyond standard practice but becoming more common. Adds extra CapEx	**
Requirement 2e	*Requires natural ventilation strategy to CIBSE AM10 or ClassVent.*	Requires high level of coordination with architectural design since early stage (room depths, window areas, etc.).	***

Some additional, overlapping credits for consideration include up to two credits for Emissions from construction products, and one credit from Post-construction indoor air quality measurement.

NABERS (IE)

NABERS (National Australian Built Environment Rating System) is a national rating system that measures the environmental performance of Australian, and more recently international, buildings. The rating system is independent, based on real data and provides a comparison to similar buildings, and all NABERS ratings are only valid for twelve months. This annual model ensures that a rating represents a building's current operational performance and not just the building design.

NABERS originally focused on energy criteria with the NABERS Energy rating that measures the efficiency of a building and rates its performance by comparing the energy consumption against a set of benchmarks that have been developed using actual data. It has since expanded into water, waste, and indoor environment rating systems.

NABERS ENERGY NABERS WATER NABERS WASTE NABERS INDOOR ENVIRONMENT

Figure 66 – NABERS Rating Systems Icons

The more recent NABERS Indoor Environment (IE) rating measures the indoor air quality, lighting quality, temperature, and thermal comfort as well as acoustic quality of a building. Its main features are summarised below;

- There are three different rating types which are base building, whole building, and tenancy ratings. Different rating types require different key indicators to be assessed.
- Results are communicated in a 1 to 6 star-scale benchmarking the buildings or tenancy's performance against the market. IE results are valid for one year.
- The rating system generally requires occupant satisfaction survey (qualitative) and on-site data (quantitative).

- The key indicator most relevant to this report is indoor air quality. The indoor air quality parameter is assessed in terms of ventilation effectiveness and indoor pollutants.
- Ventilation effectiveness measurement is based on CO_2 level, specifically on meeting the required difference between indoor and outdoor CO_2 levels.
- Four components of indoor pollutants are measured including particulates (PM_{10}), formaldehyde, total volatile organic compounds (TVOCs) and carbon monoxide (CO).

NABERS IE data can be used to assist in meeting WELL certification or recertification, and any other applicable rating system (e.g. LEED). There is significant overlap between NABERS IE the WELL building standard as summarised in this crosswalk document produced by IWBI.

In summary, the NABERS IE standard is relatively new and does focus on building operation rather than design. It does have many similarities with the more established WELL building standard, and this overlap means there is a high likelihood of achieving certification in one making the other easy to also achieve if desired. Therefore, WELL remains the preferential IAQ standard in commercial environment but I expect NABERS family of certifications to become more prevalent in the building industry in the future.

Immune Building Standard

The IMMUNE building standard is the latest of the building certification rating systems and is stated as the world's first standard to address the immunity of our built environment. Designed in response to the COVID-19 pandemic, and inspired by advanced technologies and procedures successfully used in medical now adapted for use in commercial real estate, it is a self-proclaimed leading innovative solution for minimizing the impact of pandemics like COVID-19, and other bacteriological and toxicological health threats in the built environment.

The IMMUNE building standard's independent third-party certification assessment is based on a scoring index across a set of 135 recommended measures, technical solutions, and facility management practices to certify the level of resilience of a building to present and future health challenges.

The measures cover categories including Legislation, Governance and Compliance, Area specific (office, reception, restroom), and Building Exterior measures. Examples of measures include designation of quarantine rooms, different access paths for ingress and egress, entrance thermal scanning, touchless elevators, and appropriate staff PPE and sanitation.

Based on the weighted points awarded, a building can achieve IMMUNE Strong (3 stars), IMMUNE Powerful (4 Stars) and IMMUNE Resilient (5 Stars).

Figure 67 – Immune Building Standard Rating Icons

The IMMUNE building standard is a direct reaction to the COVID-19 pandemic and as a result includes measures such as thermal scanning and office masks/PPE that are widely debated as necessary in the commercial environment. Being based on medical institutions with a focus on medical health rather than wellbeing and IEQ – IAQ, I personally see minimal application for this standard in the commercial environment in the future. To make your own conclusions more information is available at the IMMUNE Standard website.

For an even more in-depth analysis of building standards and rating systems related to IAQ, the recently published AHSRAE Report of Multidisciplinary Task Group (MTG) Health and Wellness in the Built Environment (HWBE) provides a detailed summary overview of IAQ and greater IEQ subjects covered in relevant ASHRAE and global building rating standards.

Summary

There has been a multitude of guidance documents and best practice guides produced over the last 2+ years from building services institutions to help HVAC systems reduce COVID-19 transmission risk. The advice provides general consensus that certain HVAC measures can be beneficial and are recommended, but specifics do vary across institution. Many of these recommendations are issued in sole consideration of virus risk transmission, and so not in greater consideration of the overall effect on building operation and sustainability (now incorporating IAQ and resilience), therefore some of these measures may not align with the future of ventilation design proposed here. Across the guidance issued the main measures can be categorised and summarised as in Table 6 previous, and are discussed from a sustainability perspective below:-

- **Ventilation System & Distribution Effectiveness** - Despite the majority of guidance literatures preference for DOAS, recirculation type systems with suitable filtration (and in some cases UVC) is an appropriate ventilation system once minimum outdoor air rates are maintained. Effective air distribution is critical to building design, and it is likely that well mixed, ceiling based ventilation will achieve this, but research indicates that displacement type ventilation systems will realise 20-50% greater ventilation effectiveness, and lower energy demand.
- **Ventilation Rate & Operation** - 'Adequate' ventilation is recommended across the guidance documents but with no consensus on the definition of 'adequate ventilation' or how it is demonstrated in building operation - something this research aims to rectify. However based on this research, and in contrast to most guidance documents, well designed and commissioned ventilation systems, including DCV systems, should operate as normal to achieve the desired IAQ, while ensuring minimum ventilation levels are maintained to achieve desired air changes for contaminant removal. For 'purge ventilation' between occupancies it is recommended to achieve a minimum of 3 ACH which can achieve >95% contaminant removal, and this can also be incorporated into ventilation 'optimum start' procedures if applicable.
- **Temperature & Humidity** - have relatively little effect on COVID-19 in the comfort range of occupancy, but recommended to maintain temperature in usual climate comfort range, and relative humidity between 40-70% to minimise the risk of microbial growth, as well as promoting the health and comfort of occupants.

- **Air Filtration & Air Cleaning** – There are different recommendations by industry bodies on the level of filtration required, however, research indicates that MERV13-14 (F7-F9) offered the best value balancing pollution removal and risk of virus infection with energy penalty and operating costs, and are therefore recommended for future commercial building design.
  For air cleaning technologies, UV is the dominant technology in guidance documents but based on my research the only consideration for UV technology in the AHU system or ducts is to irradiate wet downstream cooling coil and drain pan surfaces in warm and humid environments where coils are wet for long periods. Few guidance documents reference other technologies specifically, and any available guidance recommends caution and comprehensive verification if selecting one of these newer, unproven technologies.
  Most guidance suggest that local air cleaning (UV based) and filtration (HEPA) may be beneficial for reducing air pollution and virus transmission risk in some spaces with low ventilation rates, but do not replace outdoor air ventilation.
  Local in-room air cleaners may also help achieve higher effective ACH where required.
- **IAQ Monitoring** - CO2 monitoring has been widely accepted as an indicator of ventilation, and it should continue to do so as CO2 measurements may also be used to help verifying ventilation effectiveness and supply rates during building operation. However, for future commercial building design in the new normal it is recommended that building based contaminants such as TVOCs, and possible external contaminants such as PMs or NO, should also be monitored for a more wholistic measurement of IAQ.
- **Mechanical Ventilation Heat Recovery (MVHR)** – MVHR is essential to sustainably achieving the indoor environmental quality required by occupants and should not be turned off or bypassed unless the climate allows for it. Airstream cross contamination and virus transmission risk may be minimised using suitable AHU fan locations and pressure regimes, and adequate sealing. For most commercial applications (IAQ II – IV) it is not recommended to install a purge sector as this increases OACF with minimal reduction is cross contamination, and can introduce a sealing point of weakness.

Not all guidance measures or even this research recommendations are required or even suitable for all projects. Appropriate HVAC measures for buildings should be assessed on case-by-case basis and consider the effectiveness of each measure, costs and ease of implementation, impact on energy performance, and thermal comfort for the building. This is demonstrated in the case study building analysis of this research.

Several building certification and rating systems also address ventilation design and operation with recommended measures, and therefore 5 select building ratings systems of WELL, LEED, BREEAM, and in less detail NABERS IE, and Immune building standards were reviewed.
Summary information on each respective building standard is provided in Building Certification and IAQ section of this report above, but in general these prevalent international building standards do earnestly address IAQ consideration in design. However, the principal building standards of WELL, LEED, and BREEAM have expensive certification costs inaccessible to many projects, and are therefore often disregarded. On the other hand, information on these standards specific measures and their implementation is often freely accessible online (which greatly helped this research). As a result, with improved knowledge of these useful measures from these prominent building standards, they can be considered and included in building design and operation without the need for expensive certification of projects.

Based on the completed summary review, and this authors opinion on 'useful measures', it is recommended that WELL Building standard ventilation or 'Air' measures be included and considered as part of the building design process. It is not expected every feature will be required or applicable to all projects, and particular features for example recommending increase in ventilation rates (A06), openable windows (A07) and UVGI air cleaning (A14) should be analysed specifically taking into account the overall building sustainability, ventilation strategy and IAQ plan, but all are recommended to be considered.
LEED is a forerunner in terms of materials and low emissions specifications with the EQ Credit on Low-Emitting Materials (V4.1), and the Materials and Resources credit Building Product Disclosure and Optimization - Material Ingredients credits particularly useful in minimising building source pollution, and improving IAQ and sustainability.

From BREEAM, the Hea 02 Indoor Air Quality (IAQ) plan credit requires an IAQ plan covering acceptable pollution levels (IAQ category), ventilation strategies, IAQ monitoring & testing, contamination sources removal etc. which is recommended to be implemented for all projects at early stage design and communicated with the clients

It is proposed, based on this research, that these useful measures all be incorporated into the future of commercial building ventilation design approach. The IMMUNE building standard, heavily based on medical environment measures is not seen as applicable in the future sustainable design of ventilation systems. In contrast, the design for performance and operational data verification requirement for certification of NABERS IE may increase its market share and consideration in building design in the future but is not currently at the global market acceptance stage.

Research Analysis

At this point I have written a substantial amount on the objective of this study, ventilation systems and their design, air pollutants, and HVAC measures to improve IAQ and minimise virus transmission risk. The majority of this has been based on the excellent research of various HVAC industry experts, leading bodies and air quality standards which have built the themes of this report, beyond which I ever could have achieved on my own. But returning to the aim of this research under the CIBSE Ken Dale travel bursary – an award for recipients to spend three to four weeks outside their own country researching their topic – which is to analyse the impact of this guidance on selected case study buildings sustainability performance.

A quick overview of the case study buildings and why they were chosen is provided below with more detailed information on their HVAC systems and associated analysis provided later in this report: -

1. Arup Office, 1 Albert Quay, Cork, Ireland – Located in a Cool Humid (5A) climate zone the Arup office in Cork provided a local commercial office case study building which was more easily accessible during pandemic restrictions, an adaptation needed for this year's CIBSE Ken Dale award.
2. NUS SDE4, Singapore - Located in a Very Hot Humid (1A) climate zone the National University of Singapore's (NUS) School of Design and Engineering 4 (SDE4) building is a leading sustainably designed educational facility with leading researchers in ventilation design and COVID-19 transmission risk reduction.
3. 161 Collins Street, Melbourne, Australia – Located in a Mixed Humid (4A) climate zone the recently refurbished historic commercial office building has a VAV recirculating AHU ventilation system.
4. 20 Martin Place, Sydney, Australia - Located in a Warm Humid (3A) climate zone the redeveloped commercial office with ground floor retail has dedicated outdoor air AHU with perimeter chilled beams ventilation system. Sydney is also susceptible to wildfire smoke during recent dry summer seasons.
5. 70 Eagle Street, Brisbane, Australia - Located in a Hot Humid (2A) climate zone the 2008 built commercial office with ground floor retail building has a VAV recirculating AHU ventilation system.

The three Australian case study buildings are owned by Pembroke Real Estate who were kind enough to allow me to use and access these buildings as case studies for this research. The proposed cold climate case study building in Moscow, Russia was excluded. Further information on the climate zones based on ASHRAE weather data is available here - https://www.ashrae.org/technical-resources/bookstore/weather-data-center.

Based on our review of building ventilation attributes, and HVAC best practice guidance there are 2 main subjects for analysis in the research case study buildings: -

1. Ventilation Adequacy – analysis of the building ventilation design 'adequacy' in achieving desired IAQ, using the research-based proposed methodology.
2. HVAC Measures – analysis of the need and suitability of distilled HVAC measures from best practice guidance, and their impact on air contaminants and virus transmission risk, while also considering their economic costs, ease of implementation, and impact on building sustainability.

For each case study building a summary of the HVAC system will be provided followed by analysis of the ventilation adequacy and HVAC measures suitability and impact. An overview of the methodology for the analysis of both is provided below.

1. Ventilation Adequacy

'Adequate' ventilation is widely discussed and recommended across HVAC guidance documents but with no consensus on the definition of adequate rate, or how it is demonstrated in building operation. Minimum ventilation rates vary across standards, geographies and building types, and I believe this is acceptable as different building projects require different design considerations.
However, a homogeneous ventilation or air quality class rating system would be beneficial for both design team and client communication, and for enabling ventilation adequacy conformance checks using design and operational data.

Fortunately, the recent BS EN 16798-1 provides an updated categorisation of adequate levels of Indoor Environmental Quality (IEQ), which we can simplify to IAQ as we are focusing on ventilation, based on the level of expectation of building occupants as summarised below: -

Table 7 – IEQ-IAQ Categories Level of Expectation & Explanation

Category	Level of expectation	Explanation
IEQ_I	High	Should be selected for occupants with special needs (children, elderly, persons with disabilities).
IEQ_{II}	Medium	The normal level used for design and operation.
IEQ_{III}	Moderate	Will still provide an acceptable environment. Some risk of reduced performance of the occupants.
IEQ_{IV}	Low	Should only be used for a short time of the year or in spaces with very short time of occupancy.

This is translated into corresponding recommended predefined ventilation flow rates for each IAQ category in l/s/p occupancy or l/s/m2 building floor area for a typical commercial office building. These predefined values appear to be based on perceived air quality and expected percentage of people dissatisfied at given air flowrate, and ventilation rates required for diluting typical building type emissions.

Default predefined design ventilation air flow rates for an office person)

Category	Total design ventilation air flow rate for the room	
	l/(s per person)	$l/(s{\cdot}m^2)$
I	20	2
II	14	1,4
III	8	0,8
IV	5,5	0,55

The use of the predefined ventilation rate procedure is preferred and common amongst designers but does not directly consider IAQ in a meaningful way in my opinion. This 'brute force' approach relies solely on bringing in high volumes of outside air to continuously replace indoor air and remove the contaminants generated by people, building materials, and furniture, with outside air assumed clean (free or lower in contaminants of concern) and specified values often blindly accepted as adequate to remove the contaminants to an adequate degree.

The alternative IAQ procedure as directed in ASHRAE 62.1 is a "performance-based procedure" that allows "any method to be used to achieve the contaminant concentration limits, including source control, air cleaning, or dilution of indoor contaminants with outside air" and is a valid basis for design - once it can be reliably demonstrated that the resulting air quality meets the required criteria.

Because it is performance-based approach it allows for the inclusion of ventilation systems performance metrics and the use of air cleaning to reduce contaminants in the indoor air. This can result in reduced ventilation and outdoor air rates compared to predefined values, reducing overall energy usage of the project and helping to keep outdoor pollutants outside the building. However, this IAQ procedure requires calculations and demonstrable results just to simply specify ventilation rates which can be a hurdle, particularly at early stage design.

Based on this research, I am proposing a mixed methodology where the preferred and simpler predefined ventilation rates in l/s/p occupancy or l/s/m2 building floor area are established on IAQ performance based calculations, and used with an additional consideration of the performance based inherent ventilation system characteristics in the form of the ventilation effectiveness (Ev) value.

For a typical building and design process (i.e. those not taking into account building source pollution limitation), or those premium commercial buildings aiming for LEED or WELL building certification using the current standards, I propose to use below as recommended outdoor ventilation rates taking the greater of l/s/p or l/s/m2 value for your project.

Table 8 - Typical Low Polluting Environment (BS EN16798) Recommended Ventilation Rates

Category	Rec. Ventilation Rate	
	l/s/p	l/s/m2
I	$\frac{20}{Ev}$	$\frac{2}{Ev}$
II	$\frac{14}{Ev}$	$\frac{1.4}{Ev}$
III	$\frac{8}{Ev}$	$\frac{0.8}{Ev}$
IV	$\frac{5.5}{Ev}$	$\frac{0.55}{Ev}$

These recommended prescriptive ventilation rates are adapted from BS EN 16798-1 and established on IAQ performance based calculations, but any referenced specified ventilation rate can be used. It also includes the ventilation distribution characteristic of ventilation effectiveness (Ev). Therefore, for example a typical mixing ventilation system with Ev =1 the recommended ventilation rate for a category II premium commercial office is 14 l/s/p or 1.4 l/s/m2 floor area whichever is greater based on occupancy density.

Similarly, for a displacement type ventilation system with Ev = 1.2 the recommended ventilation rate for a category II premium commercial office would be 11.67 l/s/p or 1.167 l/s/m2 floor area to achieve the same IAQ classification, a significant ventilation energy and plant space saving opportunity.

As a partly IAQ procedure based methodology, and taking into account contaminant source control consideration enabled by this, the recommended ventilation should be updated accordingly. Therefore, for low polluting buildings which have minimised sources of internal pollution and followed guidance in specifying low emission internal building materials, such as WELL Materials X06 feature, or LEED EQ credit on Low-Emitting Materials for example, I propose the below recommended ventilation rates for each design category.

Table 9 - 'Very Low' Polluting Environment (BS EN16798) Recommended Ventilation Rates

Category	Rec. Ventilation Rate	
	l/s/p	l/s/m2
I	$\frac{15}{Ev}$	$\frac{1.5}{Ev}$
II	$\frac{10.5}{Ev}$	$\frac{1.05}{Ev}$
III	$\frac{6}{Ev}$	$\frac{0.6}{Ev}$
IV	$\frac{4.125}{Ev}$	$\frac{0.4125}{Ev}$

I propose these lower ventilation rates, adapted from BS EN 16798-1 and tested with IAQ procedure calculations to demonstrate results, for low internal polluting buildings to enable them to take advantage of the 'cleaner' indoor air as less contamination dilution and removal is required within the building to achieve the same IAQ levels. I provide more information on the requirements for classification as a low polluting building in the Background – Ventilation section of this report above or refer to the definition of very low polluting buildings in BS EN 16798-1.

The above proposed recommended ventilation rates, even without the ventilation effectiveness value, may differ from those recommended or minimum ventilation rates specified across the HVAC bodies and regulations. Under this proposed ventilation methodology, using these other building services bodies or regulation ventilation rates is acceptable, and the values applied may be compared or benchmarked against the above proposed ventilation classifications to aide communication of the air quality implications of the ventilation rate specified to the client.

For example, a typical building specifying 12 l/s/p would classify as a good Category III Moderate IAQ environment design, whereas a low polluting building specifying 12 l/s/p would classify as a Category II Medium IAQ environment design – highlighting the benefit of strong pollution source control.

This design stage IAQ benchmarking can be further enhanced using an adapted Method 2 (BS EN 16798-1) limit values for substance concentration formula to calculate the estimated zone IAQ level using CO2 as the chosen known contaminant in this case. The adapted Method 2 formula below estimates the ventilation zone CO2 level at design conditions: -

$$Chi = \frac{Gh}{(Qh \cdot Ev)} + Cho$$

Chi Estimated CO2 level at given vetilation rate (mg/m3)
Qh Design Ventilation rate in m3/s/p
Gh CO2 generation rate in mg/s/person
Cho Outdoor CO2 levels (mg/m3)
Ev Ventilation Effectiveness

Note CO2 levels can be converted to more relatable parts per million (ppm) values by the formula: concentration (ppm) = 24.45 x concentration (mg/m3) ÷ molecular weight (44.01 g/mol for CO2).
Using this formula the CO2 level expected for the specified design ventilation rate is estimated, and may be compared against the below table of classified absolute indoor CO2 levels to categorise the design IAQ level. For this research the outdoor CO2 levels for each case study are assumed constant at 400ppm for comparative purposes but measured outdoor levels are recommended.

Table 10 - BS EN 16798 Recommended Absolute CO2 Level Category(ppm)

Category	Absolute CO2 Level
	ppm CO2
I	< 800
II	< 1000
III	< 1500
IV	< 2000

These IAQ procedure calculated CO2 levels align with the previous categories recommended ventilation rates, and are given in absolute values (not increase over ambient as is common in some guidance) as required in the adapted formula, and for consistency as we make no such allowances for any other contaminant of concern. Additionally, those buildings located in regions with low atmospheric carbon should be rewarded, and those with higher levels be incentivised to reduce these (beyond the current climate change minimisation rationale).

One of the main benefits of this calculation is that the estimated design CO2 levels provide verifiable values (+/- 50ppm) that can then be used to validate achievement of the zone design target IAQ Category using the ventilation rates specified, and its effectiveness during operation, with significant deviations in site measured CO2 rates compared to design values highlighting any potential issues in ventilation delivery. This approach is utilised in the case studies in this research.

This method uses CO2 as proxy representation for IAQ as the CO2 generation rate for typical commercial environment is well known and referenced, but note any measured contaminant with known generation rate can be used (e.g. VOCs for low occupancy but high emissions building) as the basis for the calculation.

There are many studies in which CO2 is used as an indicator of ventilation and IAQ. As CO2 is emitted by human metabolic processes and activity, levels correlate well with occupancy as a marker for human-generated pollutants, assuming no combustion appliances or any other sources of CO2 in the area. Use of CO2 as an indicator for IAQ categorisation and ventilation effectiveness is more difficult in spaces with lower numbers of occupants due to the increased influence of individual variations in CO2 generation rate; any measurements in spaces with lower occupancy must take this into account in their consideration of the accuracy and meaning of the results. CO2 is also present in the outside air but is usually well measured and its outdoor concentration is taken into account in the calculation.

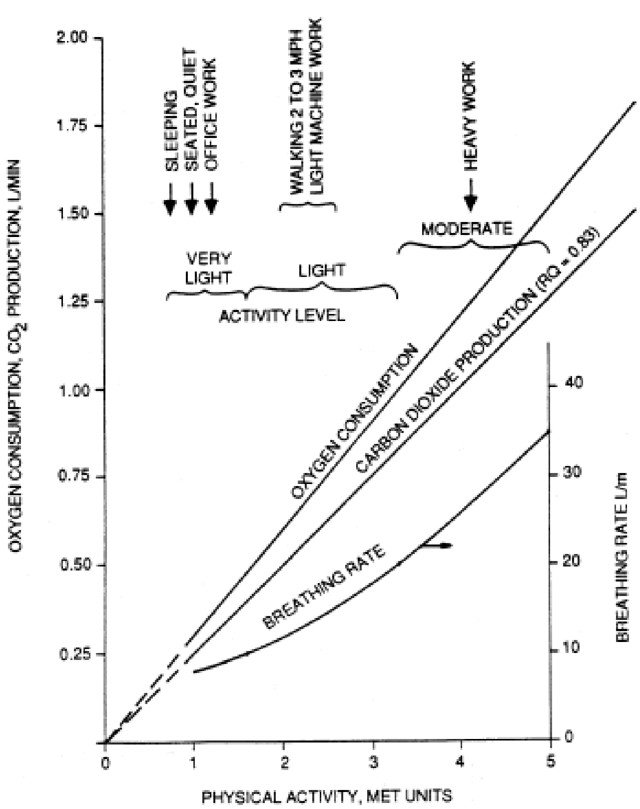
The CO2 emissions rate for a typical seated office occupant is 0.004 – 0.005 l/s as calculated by the formula below and as outlined in CIBSE Guide B Table 2.2.

Table 2.2:
Emission rates of carbon dioxide for occupants and various processes[3]
(Note: 1 met is the heat generation rate ($W \cdot m^{-2}$) of an adult male sitting quietly.)

Process	Emission rate	Comments
Occupant Seated at rest (1 to 1.5 met)	0.004 to 0.005 l/s	$P = 4 \times 10^{-5} \times M A$ P = CO_2 emission rate (l/s) M = metabolic rate ($W \cdot m^{-2}$) A = body surface area (m^2) (M = ~ 70 $W \cdot m^{-2}$; A = ~ 1.8 m^2)

Figure 68 – CO2 Emissions Rate CIBSE Guide B Table 2.2

Taking the average occupant body surface area to be consistent at 1.8m2 the occupant CO2 emissions rate can vary based on the metabolic rate which can range between 1.0 Met for typical quiet seated activity up to 4.0 – 5.0 Mets for heavy work and exercise activity. Typically, and recommended here, for a commercial office environment a CO2 emissions rate of 0.005 l/s per occupant is used allowing for an average metabolic rate of 1.25 (70W/m2) over an occupancy period. Conventional metabolic rates for different activities are provided in the figure below.



Activity	Met
Seated, quiet	1.0
Reading and writing, seated	1.0
Typing	1.1
Filing, seated	1.2
Filing, standing	1.4
Walking at 0.9 m/s (2 mph)	2.0
House cleaning	2.0-3.4
Exercise	3.0-4.0

Figure 69 – Average Metabolic Rates for Activity

This correlation of increasing pollutant emissions rates with increased activity is also seen in research related to COVID-19. While data on COVID-19 viral emission rates is very limited, some research estimates used in modelling have suggested it may vary by several orders of magnitude depending on the individual and their activities as summarised in the table below from Buonanno, Stabile and Morawska, 2020[19].

Activity	Quanta emission rate, quanta/h
Resting, oral breathing	3.1
Heavy activity, oral breathing	21
Light activity, speaking	42
Light activity, singing (or loudly speaking)	270

Figure 70 – Estimated COVID-19 Emission Quanta Rate with Activity

The viral emissions rate in quanta per hour may not be as directly correlated to activity like CO2 emissions, this is likely due to the affect vocalization (speaking and singing for example) has on emissions but indications that emissions are likely to be influenced by the breathing rate of individuals which could vary by a factor of 6 between passive, sedentary breathing to high exertion aerobic exercise is supported by research (Adams 1993)[20] in the field. A study of ventilation improvements during a TB outbreak in university buildings (Du et al., 2020)[21] showed when CO2 was reduced to <1000 ppm was independently associated with a 97% decrease in the incidence of TB among contacts.

As a result, for this research we can assume that the consideration for increased CO2 emission rate from occupants based on activity level also in general takes into account the possible increased viral emissions rate of COVID-19 or other viruses due to activity levels.

[19] Buonanno, G, L. Morawska, and L. Stabile (2020b) Quantitative Assessment of the Risk of Airborne Transmission of SARS-CoV-2 Infection: Prospective and Retrospective Applications. Environmental International 145. https://www.sciencedirect.com/science/article/pii/S0160412020320675?via%3Dihub.

[20] Adams, W. C. (1993) 'Measurement of Breathing Rate and Volume in Routinely Performed Daily Activities', Epidemiology. California Environmental Protection Agency. doi: 10.1097/00001648-199503000-00162

[21] Du CR, Wang SC, Yu MC, Chiu TF, Wang JY, Chuang PC, Jou R, Chan PC, Fang CT. Effect of ventilation improvement during a tuberculosis outbreak in underventilated university buildings. Indoor Air. 2020 May;30(3):422-432. doi: 10.1111/ina.12639. Epub 2020 Jan 16. PMID: 31883403; PMCID: PMC7217216.

Therefore CO2 can continue to be used as a proxy for IAQ in the new normal using this methodology, and achieving the desired high IAQ level should reduce the risk of virus transmission, including COVID-19, in a space. Please note however this is not a methodology expressly to calculate or reduce the risk of infection of COVID-19 or other viruses in a commercial environment.

We have established that using CO2 as a proxy for IAQ is acceptable, however measurement of CO2 cannot account for other HVAC based mitigation strategies such as filtration, local air cleaners and UVC disinfection strategies which remove or deactivate virus and other particle contaminants from the air but have no effect on CO2. As a result, these strategies will not be directly measurable or verifiable using adapted method 2 approach using CO2 detailed above.

Yet, as we are already aware, air filtration and cleaning can play a vital role in ventilation strategy. Therefore, fittingly, the ASHRAE 62.1 IAQ procedure has adopted the effective air change rate (ACHe) metric to account for these mitigation strategies in IAQ based ventilation design. This ACHe and its calculation use recirculated air volumes and air cleaning efficiencies to approximate relative ventilation supply, and is detailed in the attached Equivalent Outdoor Air Calculator spreadsheet, and applied in the below research case studies for further information.

ACH is important metric in contamination removal and dilution, and increased effective air changes results in greater pollution removal and dilution potential using the performance based IAQ procedure if required. Based on the BS EN 16798-1 2019 recommended outdoor ventilation rates, independent of ventilation effectiveness for this case, and assuming a 10m2 per person occupancy density and a 1.8m vertical breathing zone as recommend in BS EN 16798-1 the outdoor air change rate per hour or ACH for each categories recommend ventilation can be estimated as in table 11 below.

Table 11 - BS EN 16798 Recommended Outdoor Ventilation Rates – Typical Building and Very Low Polluting Building

Category	Rec. Outdoor Ventilation Rate		
	l/s/p	l/s/m2	**ACH**
I	20	2	**4**
II	14	1.4	**2.8**
III	8	0.8	**1.6**
IV	5.5	0.55	**1.1**

Category	Rec. Outdoor Ventilation Rate		
	l/s/p	l/s/m2	**ACH**
I	15	1.5	**3**
II	10.5	1.05	**2.1**
III	6	0.6	**1.2**
IV	4.125	0.4125	**0.8**

These ACH rate for both standard and low polluting buildings are relatively high and would be acceptable for typical operation. However, for resilience and capability to operate during a public health or contamination event, increased air exchange rates for greater contaminant removal, particularly in a purging scenario, is recommended by the American CDC and several guidance documents.

For target ACH rates care must be taken to ensure clean air delivery rates are provided to achieve the desired design air exchange. Guidance has indicated that for a well-mixed room >6 ACH can remove 99% of contaminants in space, 3 ACH can remove 95% of contaminants, 2 ACH can remove 86% of contaminants, and 1 ACH can remove 63% of contaminants in a space respectively, assuming zero concentration of the contaminant in ventilation air and the contamination source is controlled. This is the basis of my recommended design target air exchange rates for each IAQ category below.

Table 12 – Recommended Effective Air Change Rate based on American CDC and BS EN 16798 Standard

Category	Rec. ACH
	ACHe
I	≥6
II	≥3
III	≥2
IV	≥1

For typical low polluted buildings aiming for category II – IV IAQ design relatively low additional air changes of 0.2 – 0.4 ACH (~8% - 25% additional ventilation) is recommended. However, for very low polluted buildings aiming for category II – IV IAQ design significantly more ventilation air exchange (~50%) is required to achieve recommended resilient air change rates for contaminant removal, despite the buildings generally being less polluted in normal operation.

In both cases, buildings aiming for category I IAQ design require almost a doubling of existing ventilation air exchange rate. Note however these estimated contamination removal efficiencies per ACH rate would likely be even greater for displacement and personal type ventilation systems which would help achieve design targets.

This additional air exchange does not necessarily need to be provided by central mechanical ventilation providing outside air. It can be supplied by natural ventilation through façade openings in the building, or zonal dedicated through-wall heat recovery ventilation systems, both common across the buildings industry.

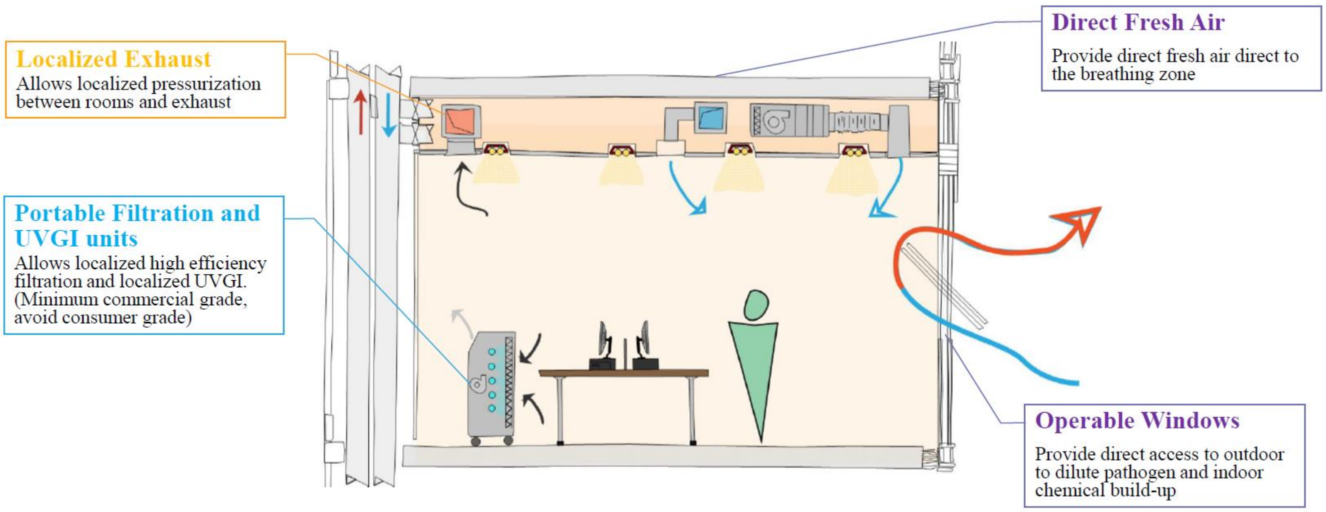


Figure 71 – Air Exchange Pollution Dilution Options Diagram

Alternatively, effective ventilation air exchange can be provided through recirculating clean and filtered air, and measured using the ASHRAE 62.1 IAQ procedure Equivalent Outdoor Air Calculator. For example, buildings aiming for category I IAQ design for vulnerable occupants requiring almost a doubling of existing ventilation air exchange rate should already be considering air cleaning technologies in my opinion, and these can help in achieving the additional effective air changes required. Recirculation VAV ventilation systems with high grade filtration and/or air disinfection can help achieve higher effective ACHe rates at large scale in required circumstances.

Research by the Pacific Northwest National Laboratory (PNNL)[22] provides an interesting assessment on the impact of ventilation rates, recirculation and filtration on the potential for Covid-19 cross-infection through transmission of aerosols (which can reasonably be extrapolated to other similar airborne contaminants). It confirms that the potential for infection in a single ventilated space reduces significantly as (uncontaminated) air-change rates rise, which supports this effective air change approach.

[22] https://www.pnnl.gov/publications/investigation-potential-aerosol-transmission-and-infectivity-sars-cov-2-through

Based on this research, it is proposed that the general commercial office ventilation adequacy can be classified at design stage using the proposed updated BS EN 16798 IAQ categories. It may also be validated in operation stage using the adapted Method 2 (BS EN 16798-1) limit values for substance concentration formula to calculate the estimated zone IAQ level using CO2 as the chosen known contaminant and comparing it to operational CO2 measurements. Enhanced commercial ventilation and IAQ adequacy for the new normal to achieve greater building resilience should take into account zone effective air changes, and target adequate contamination dilution rates in the form of ACHe in line with the desired design IAQ category as outlined above.

For both these ventilation adequacy analysis approaches the calculation, measurement and collection of respective CO2 and air flowrate data is required.

For the research case studies, all of which are buildings in operation, analysing building ventilation adequacy based on IAQ using the adapted Method 2 – CO2 contaminant, and effective air change (ACHe) approach requires on site measurement if CO2 levels and collection of airflow data where available. This was typically achieved using Building Management System (BMS) data, and IAQ measurements using the AIRTHINGS View Plus; a class-leading air-monitoring device with sensors to detect levels of radon; small particulate matter as PM2.5; carbon dioxide (CO2); temperature; humidity; air pressure, and volatile organic compounds (VOCs). The wireless monitor feeds data back to an online platform over wi-fi and also includes a small screen and colour-coded LED indicator display to provide instant in-room air quality feedback. The IAQ monitor and sensors adhere to the aforementioned regulations and guidance on IAQ monitoring and therefore was used in each of the case study buildings.

Figure 72 - AIRTHINGS View Plus Air Quality Monitor

2. HVAC Measures

A pivotal aspect of this study was the review and discussion of HVAC, and ventilation in particular, best practice guidance issued during and post the COVID-19 pandemic. Using the case study buildings as a blueprint this section provides an analysis of the both the need and suitability of distilled HVAC measures from best practice guidance. There is a focus on their impact on indoor air quality and virus transmission risk, while also considering their economic costs, ease of implementation, and impact on building sustainability. Cost is an indicative rough-order-of-magnitude cost and refers to supply and installation costs only.

These distilled HVAC measures are listed below with their main analysis points while full summary details of each is provided previously in this report.

- **Ventilation System & Distribution Effectiveness** –
  - DOAS vs Recirculation ventilation systems
  - Mixing vs Displacement vs Personal ventilation distribution
- **Ventilation Rate & Operation** –
  - ‘Adequate’ ventilation achievement
  - Demand Controlled Ventilation (DCV) operation
  - Purge Ventilation
- **Temperature & Humidity** –
  - Acceptable temperature and humidity ranges
- **Air Filtration & Air Cleaning** –
  - Air filtrations levels
  - Air cleaning technologies
  - Local in-room air cleaners
- **IAQ Monitoring** –
  - CO2 monitoring & dashboarding
  - IAQ measurement & occupant awareness
- **Mechanical Ventilation Heat Recovery (MVHR)** –
  - AHU sealing and pressure regimes (fan locations)
  - Thermal Wheel (TW) purge sectors

These distilled HVAC measures are analysed across each case study building and presented in tabular form.

Case Study 1 - Commercial Office, Cork, Ireland

The 1 Albert Quay building is located in Cork, Ireland in cool humid climate zone 5A on the river front of the River Lee in the historic Port of Cork region of Cork City, its newly developing central business district.
Constructed in 2016, the seven-story, 15,800m2 office development with central atrium, over a double basement car park replaces an existing warehouse on the site and can accommodate up to 1,800 personnel.

The main focus of this case study - the Arup Cork Office is located on the 1st floor of the 1 Albert Quay Building providing 1900 m2 NLA floor area of commercial office space with an occupancy of approximately 180 people.
Designed to LEED Gold standards, the Arup Cork office was also the first in Ireland to achieve the WELL Gold standard for fit-out.

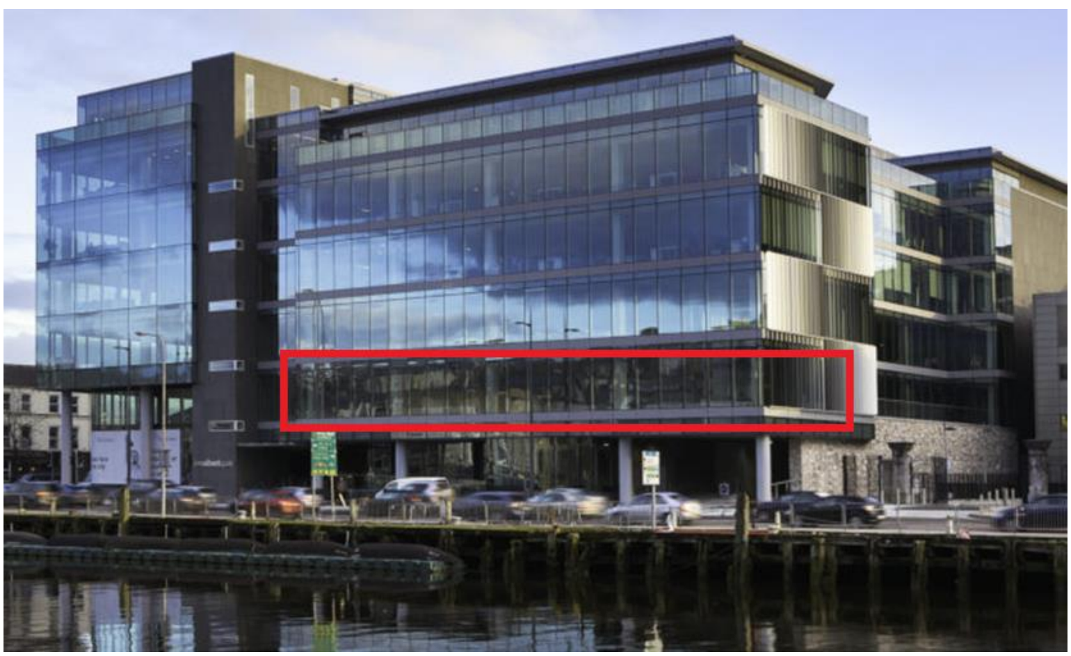


Figure 73 - Arup Office, Cork, Ireland

HVAC System Summary

A summary of the HVAC system as of June 2020 with a focus on the building ventilation system is provided in table 13 below. The building was constructed in 2016 with all the existing HVAC equipment still in use today.

Table 13 - Arup Office Cork HVAC Summary Table

Item	Description	Notes
Plant	Centralised Air Handling Units	5 no. AHUs located on roof serving office floors L1 to L7 (including landlord & toilet areas)
Design IAQ Target	Category II	Premium Office
Type	Dedicated Outdoor Air Supply (DOAS)	Supply VRF FCUs in ceiling void
Distribution	High Level Supply & Return Mixing	Effectiveness (Ev) of ~1
Filtration	F7 supply air G4 return air	Bag filter type Panel filter type
Outside Air Provision	Design: Min. 15 L/s/person Actual: 21 L/s/person	Design occupancy density: 7.5 m^2/person Actual occupancy density: ~10m²/person
Outside Air as % of Supply Air Approx. Total Air Change Rate	100% ~3.5 ACH	AHU 3 Serves Arup Office on the North Lower Floor supply. N/A
Outside Air Modulation	Yes	Outside air has no speed control modulation
Economy Cycle / Heat Recovery	Yes	Thermal Wheel (TW) Heat Recovery
Internal Temperature	22.5 °C (Summer) ± 1.5°C 21.5°C (Winter) ± 1.5°C	N/A
Humidity	Not controlled	No humidity sensors
Normal Hours of Base-Building Air-Conditioning Plant Operation	7am to 7:30 pm Weekdays 9am – 2pm Saturday	N/A
Centralised Plant Cooling and Heating Capacity	Gas fired indirect heater in the Landlord AHU to temper air before entering office No central cooling	520 kW of decentralised VRF AC units throughout office for heating and cooling

5 no. centralised AHUs located on roof supply 100% outside air and extract return as a balances system to seven office floors via risers distributed throughout the floor. Refer to air schematic in figure 73 for additional information.

AHU 03 serves the 1st floor including the Arup Office and incorporates a heat recovery thermal wheel and an indirect gas fired heater to temper supply air. AHU fan arrangement is the recommended fan pull-through arrangement with brush sealed thermal wheel heat recovery.

Additional heating and cooling is provided by tenant VRF system. There are tenant supplementary air systems such as tenant 100% outside air and tenant general exhaust systems available for connections on the office floors.

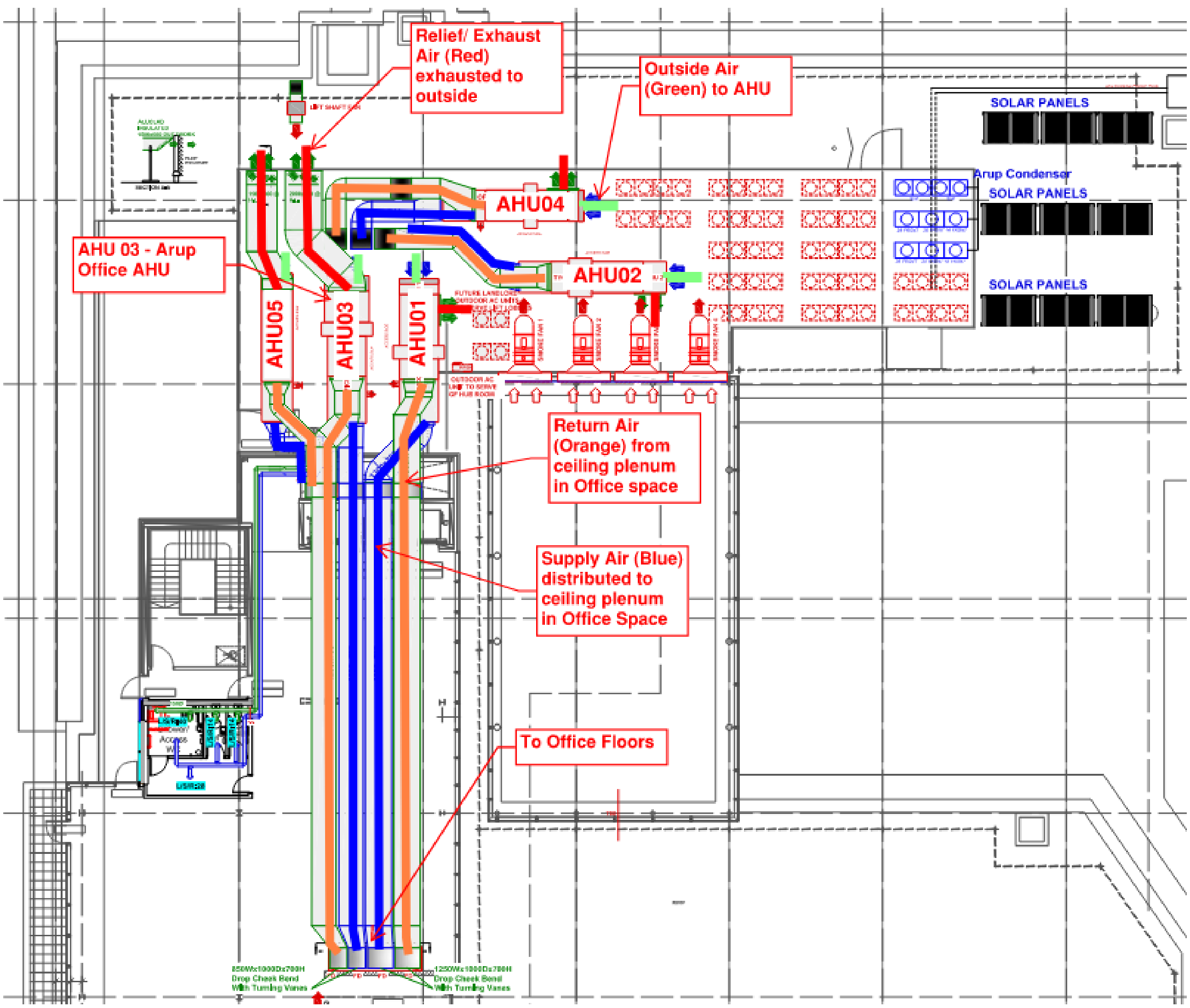


Figure 74 - Arup Office Cork Air Layout

Supply air from the DOAS is ducted to the office space ceiling plenum towards the back of specified zone Air Conditioning Units (ACU) or Fan Coil Units (FCUs) which supply tempered (18 -21 °C) air to room via ducted high level ceiling swirl and disc diffusers. Return air is extracted from high level via ducted swirl grilles in co-ordinated locations. Eggcrate plenum return grilles in the ceiling enable recirculation of some return air to the supply air through the plenum FCUs. Meetings rooms are supplied with ducted outside air supply. Transfer air from the open plan office space is used for single occupancy 'focus rooms' and services rooms (kitchenettes, drying room etc.) with a high air change rate of 6 to 10 ACH respectively.

Supply air is constant volume during occupied hours (although with recent upgrades is currently modulated using the BMS system based on a High, Medium, and Low fan speed settings to supply air for full occupancy, partial occupancy and low/zero occupancy as required – more on this in HVAC Measures section). No continuous CO2 or IAQ monitoring was included in the design however air quality tests were completed as part of the WELL Gold standard assessment, and two independent CO2 monitors are located in the office. Air is filtered in the AHU with F7/MERV13 supply air and return air filter (before thermal wheel in case of leakage).
There are currently no air cleaning devices utilised within the AHU or office zones.

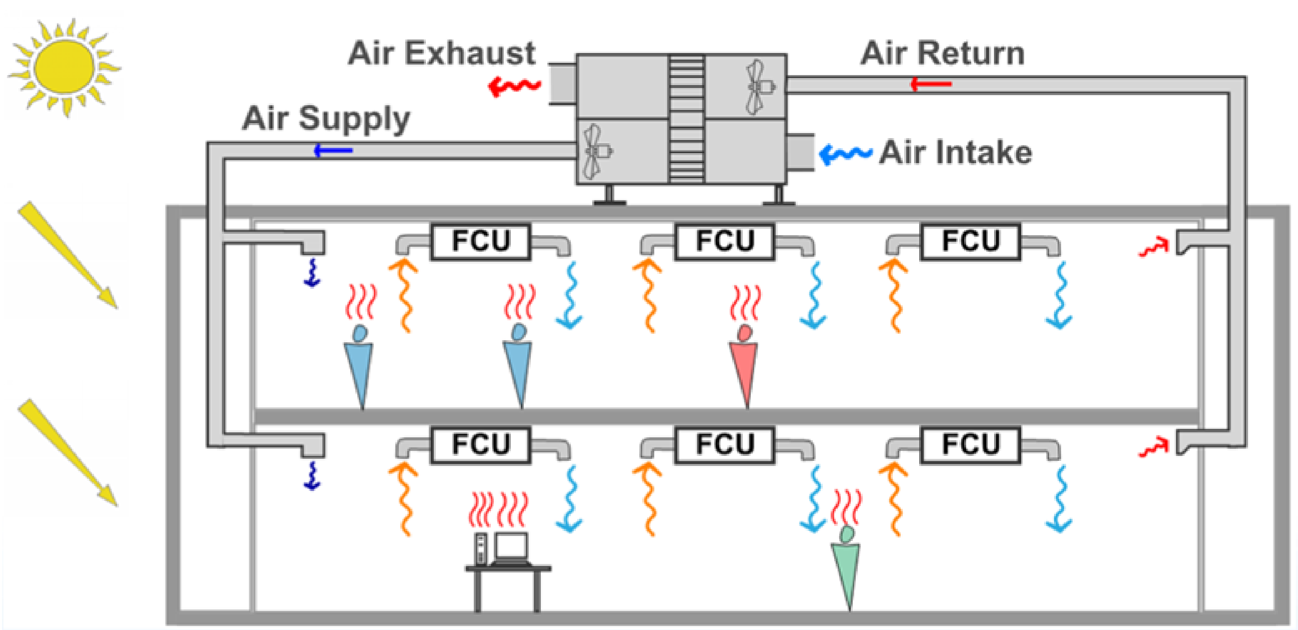


Figure 75 - Arup Office Cork HVAC Schematic

Ventilation Analysis

The 1 Albert Quay building and the Arup office within would be a premium office space aiming to achieve IAQ II category or better in design. The office space achieved WELL Gold Office Fit-out certification while the overall building achieved LEED gold certification, however confirmation that very low polluting materials were used and related credits achieved was not available therefore a typical low polluting environment (BS EN16798) is assumed, with the associated recommended ventilation rates provided below for reference.

Table 14 - Typical Low Polluting Environment (BS EN16798) Recommended Ventilation Rates

Category	Rec. Ventilation Rate	
	l/s/p	l/s/m2
I	$\frac{20}{Ev}$	$\frac{2}{Ev}$
II	$\frac{14}{Ev}$	$\frac{1.4}{Ev}$
III	$\frac{8}{Ev}$	$\frac{0.8}{Ev}$
IV	$\frac{5.5}{Ev}$	$\frac{0.55}{Ev}$

The core and shell building made an initial ventilation allowance of 15 l/s/p distributed by high level supply and return mixing ventilation with Ev ~1. At an assumed occupation density of 7.5 m2/person over the 1900 m2 office this was an occupancy of ~253 people providing a total 3.8 m3/s mechanical outdoor air supply available in the AHU for the Arup office including meeting rooms at design stage. This resulted in approximately 2 l/s/m2 ventilation rate which is IAQ Category I but 15 l/s/p is Category II which is the dominant factor.

At office fit-out design stage Arup reduced the floor occupancy to 180 staff resulting in an occupancy density of approx. 10 m2/person across the floor area. However, the outdoor air ventilation rate of 3.8 m3/s remained unchanged and did not include fan speed control, therefore the office fit-out design ventilation rate is approx. 21 l/s/p and 2 l/s/m2 which is IAQ Category 1 environment (unnecessarily?) greater than design requirements but likely beneficial to the office occupants.

Table 15 - Arup Office Cork Design Ventilation Analysis - Flowrate

Design Ventilation Analysis				
Stage	**Vent. Rate L/s/p**	**Vent. Rate L/s/m2**	**Ev**	**IAQ Category**
Design - Core & Shell	15	2	1	II
Design - Office Fit-out	21.1	2	1	I

For further enhanced ventilation and IAQ analysis, expected zone CO2 levels can be calculated using the presented adapted Method 2 (BS EN 16798-1) limit values for substance concentration formula. Using this formula the CO2 level expected for the specified design ventilation rate is estimated, and may be compared against the table of classified absolute indoor CO2 levels to categorise the design IAQ level. Note unit conversions are required for this formula calculation, and more details on these are provided in the IAQ calculator tool with this research and an extract included below.

Design Data	Ventilation Rate	Qh	21.1 l/s/p	0.0211 m3/s/p	Design Ventilation rate per person
	Ventilation Effectiveness	Ev	1 _		Assumed for High level low temp (< 8 degC dT) mixing ventilation
	Outdoor air CO2 levels	Co	400 ppm	720.00 mg/m3	Taken from outside CO2 sensor or sourced from local weather station
	Occupant Metabolic Rate		1.25 Met		Allowing for an average metabolic rate of 1.25 (70W/m2)
	CO2 generation rate	Gh	0.005 L/s/p	9.16 mg/(s.person)	Calculated per CIBSE Guide B2 with PV=nRT (at 21ºC, 1 atm)
	CO2 molecular weight		44.01 g/mol		Molecular weight of CO2
	Estimated Zone CO2 level	**Chi**	**641 ppm**	1154.17 mg/m3	Concentration (ppm) = 24.45 * mg/m3 / molecular weight

Based on the design data and calculation, an estimated design CO2 concentration of ~640ppm is expected which is an IAQ Category I classification.

Table 16 - Arup Office Cork Design Ventilation Analysis - CO2

Design Ventilation Analysis - CO2						
Stage	**Vent. Rate (Qh) l/s/p**	**CO2 Gen. Rate (Gh) l/s/p**	**Ev**	**Outdoor CO2 (Cho) ppm**	**Est. Design CO2 (Chi) ppm**	**IAQ Category**
Design - Office Fit-out	21.1	0.005	1	400	**640**	**I**

Resulting zone CO2 values will not be exact due to variances in occupant activity and outdoor CO2 levels however, operational measure values can be compared against a range (i.e. 640 ± 50ppm) to help identify if there are any significant variances between design and operation expectations.

Note design stage calculations may use design data in per person values, however for operational stage analysis absolute values should be used as below.

Operational stage measured CO2 data is required to compare to design data and this was achieved in the Arup office using a BPS Arc air quality monitor. The air quality monitor which records temperature, relative humidity, VOCs and CO2 among other IEQ factors is connected to a Grafana platform to visually display the data.

Figure 76 - Arup BPS Arc Air Quality Monitor in the Cork Office

Taking the last two fully operational 'normal' weeks pre-pandemic of March 2nd to March 15th as the analysis period, the following CO2 and VOC profiles were recorded. During occupied hours for the Cork office the average value measured for CO2 was ~750ppm, and for VOCs was 0.06ppm (~200 ug/m3) respectively. During peak occupancy the office CO2 levels are shown to regularly exceed 800ppm.

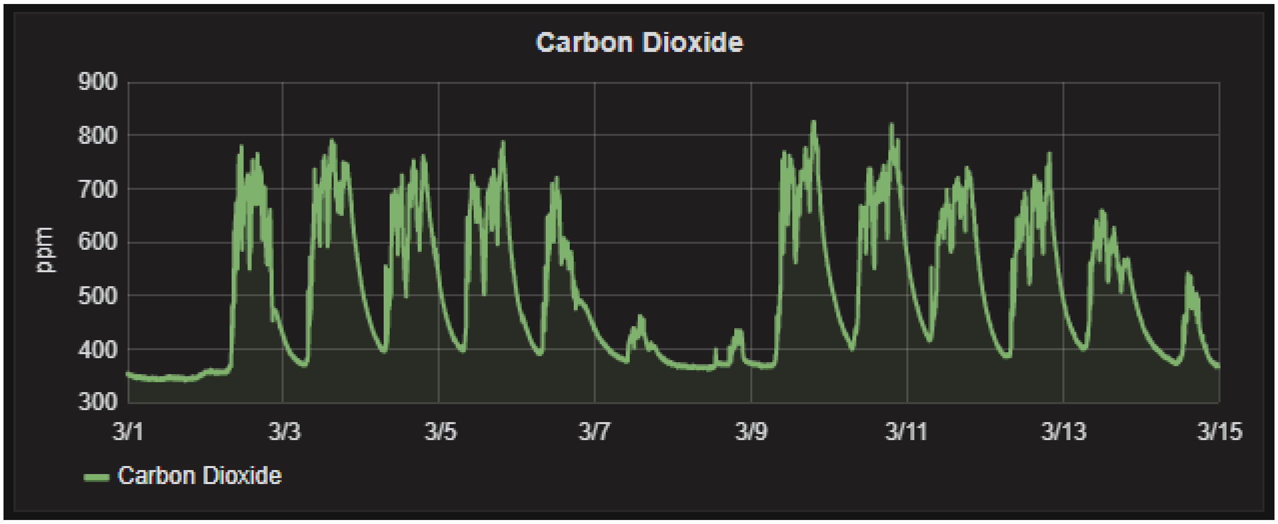


Figure 77 - Cork Office Operational CO2 Monitoring Values 2020

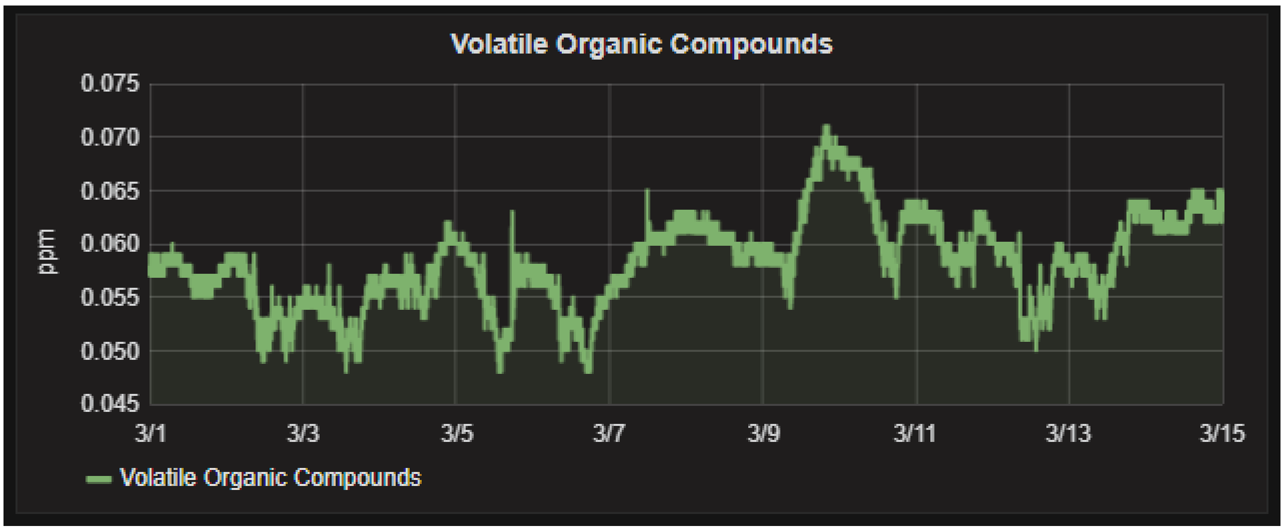


Figure 78 - Cork Office Operational VOCs Monitoring Values

While not an indication of poor IAQ as this still meets Category I IAQ class thresholds, this 800ppm measured operational CO2 value is 160 ppm greater than the calculated design CO2 value of 640 ppm, which is substantially outside the allowable range (max 690ppm) and may indicate an issue in the operation of the ventilation system that may need to be investigated further.

Taking this measured CO2 value as in the zone indoor concentration and using the BS EN 16798 Method 2 formula to calculate the corresponding ventilation rate the IAQ-calculated supply airflow is only 2.3 m3/s in the zone, a difference of 40%. Rearranging the same formula and using the measured operational ventilation rate and indoor CO2 value, the ventilation effectiveness is estimated to be 0.6, much lower than the 1 assumed for the high level mixing ventilation system applied in the office.

Operational measured space CO2 (ppm)	**800 ppm**
Operational space ventilation flowrate (m3/s)	**3.8 m3/s**

Space Data	Net Internal Area (NIA)	A	1900 m2		Building floor NIA
	Ceiling/ Breathing zone height	H	2 m		Space floor to ceiling height or breathing zone height - 2m (BS EN 16978
	Number of Occupants - people	n	180		Numbe rof people occupaying the space
	Volume	V	3800 m3		
Air Data	Outdoor air CO2 levels	Cho	400 ppm	720.00 mg/m3	Taken from outside CO2 sensor or sourced from local weather station
	Indoor Space CO2 levels	Chi	800 ppm	1440.01 mg/m3	Measured space return air CO2 levels
	Ventilation Effectiveness	Ev	1		Assumed for High level low temp (< 8 degC dT) mixing ventilation
	Actual Air supply rate	Q	3.8 m3/s	3800 L/s	Actual measured supply airflow to space
	Occupant Metabolic Rate		1.25 Met		Allowing for an average office metabolic rate of 1.25 (70W/m2)
	CO2 generation rate	Gh	0.005 L/s/p	9.16 mg/s/p	Calculated per CIBSE Guide B2 with PV=nRT (at 21ºC, 1 atm)
	CO2 molecular weight		44.01 g/mol		

Design		**Operational**		**Difference**
CO2 Calc.	**641.00 ppm**	**CO2 Meas.**	**800.00 ppm**	**159.00 ppm**
Q Design	**3.80 m3/s**	**Q Op.**	**3.80 m3/s**	**0.00 %**
		Q Calc.	**2.29 m3/s**	**-40 %**
Ev design	**1.0**	**Ev Calc**	**0.6**	**-0.4**
q_design	**21.1 l/s/p**	**q_actual**	**12.7 l/s/p**	**-8.4 l/s/p**
Design ACH	**3.60 ACH**	**Actual ACH**	**2.17 ACH**	**-1.43 ACH**

Recirculation % *	**40%**
Q_Calc / Q_Op.	**60%**

Figure 79 - Arup Cork Office Operational Ventilation Analysis Results 2020

These results may indicate that there is significant leakage of supply air and recirculation of exhaust air in the ventilation system, and/or the effectiveness of the ventilation system is compromised with airflow short circuiting[23] occurring. This poorer than expected ventilation performance is investigated further and tackled in the HVAC Measures section below.

The final ventilation adequacy analysis examines air exchange rate in an environment and its role in building resilience and IAQ. We have agreed that CO2 as a proxy for IAQ is acceptable, however measurement of CO2 cannot account for other HVAC based mitigation strategies such as filtration, local air cleaners and UVC disinfection strategies which remove or deactivate virus and other particle contaminants from the air but have no effect on CO2. The ASHRAE 62.1 IAQ procedure has adopted the effective air change rate (ACHe) metric to account for these mitigation strategies in IAQ based ventilation design. This ACHe and its calculation use recirculated air volumes and air cleaning efficiencies to approximate relative ventilation supply, and is detailed in the attached Equivalent Outdoor Air Calculator spreadsheet and summarised below.

[23] Short-circuiting is when the air moves from the air inlet to the exhaust without diluting contaminants due to obstacles or impediments to mixing of airflows.

Name of Space / AHU / Building	Units	Design	Operation_Actual
Area	Sq m	1900	1900
Average Ceiling / Breathing Zone Height	m	2	2
Volume	m3	3800	3800
Total Supply Air	m3/s	3.8	2.29
Total Outdoor Air	m3/s	3.8	2.29
Supply Air ACH	ACH	3.60	2.17
Outdoor Air ACH	ACH	3.60	2.17
Central AHU Filter MERV Rating	MERV	13	13
UVC Single Pass Inactivation	%	0.00%	0.00%
In Room Fan Air Cleaner (HEPA+)	CADR (m3/h)	0	0
Number of In Room Fan Air Cleaners (HEPA+)	Qty	0	0
Effective Air Changes Based on Technology			
ACH_OA	ACH	3.60	2.17
ACH_MERV filter in AHU	ACH	0.00	0.00
ACH_e,c	ACH	0.00	0.00
ACH_air cleaner	ACH	0.00	0.00
Sub-Total Effective ACH	ACH	3.60	2.17
Zone Air Distribution Effectiveness	Ez	1.0	1.0
Air Cleaner Position Effectiveness	Ezp_ac	1.0	1.0
Total Effective ACH_e		**3.60**	**2.17**

Figure 80 - Arup Cork Office Effective Air Change Results

ACHe is important metric in contamination removal and dilution, vital for good IAQ and the new normal building resilience objective. Based on the results, the design ventilation effective air change rate of 3.6 ACHe is greater than the Category II recommended value of 3 ACHe which is improving building resilience and general IAQ. However, with the previously identified issue with ventilation recirculation or effectiveness, the actual operation ventilation effective air change rate is closer to 2.17 ACHe, 38% below the IAQ Category II target value.

Table 17 - Arup Office Cork Design Ventilation Analysis - ACHe

Design Ventilation Analysis - ACHe					
Stage	**ACH_OA**	**ACH_f**	**ACH_e,c**	**ACHe**	**IAQ Category**
Design	3.6	0	0	3.6	**II**
Operational - Effective	2.17	0	0	2.17	**III**

This ACHe rate may be increased by increasing outside air flow rate, using local air cleaners or by resolving the identified ventilation system issue. This is explored further in the applicable HVAC measures for the Arup office.

HVAC Measures

Using the case study Arup Cork office building as a blueprint we analyse of the need and suitability of the previously distilled HVAC measures from best practice guidance, looking at their impact on air contaminants and virus transmission risk, while also considering their economic costs, ease of implementation, and impact on building sustainability as presented in the following table.

These distilled HVAC measures are listed below with their main analysis points while full summary details of each is provided previously in this report.

- **Ventilation System & Distribution Effectiveness** –
  - DOAS vs Recirculation ventilation systems
  - Mixing vs Displacement vs Personal ventilation distribution
- **Ventilation Rate & Operation** –
  - ‘Adequate’ ventilation achievement
  - Demand Controlled Ventilation (DCV) operation
  - Purge Ventilation
- **Temperature & Humidity** –
  - Acceptable temperature and humidity ranges
- **Air Filtration & Air Cleaning** –
  - Air filtrations levels
  - Air cleaning technologies
  - Local in-room air cleaners
- **IAQ Monitoring** –
  - CO2 monitoring
  - IAQ measurement
- **Mechanical Ventilation Heat Recovery (MVHR)** –
  - AHU sealing and pressure regimes (fan locations)
  - Thermal Wheel (TW) purge sectors

HVAC Measures	*Description*	*Impact Level*	*ROM* Cost*	*Ease of Implement-ation*	*Impact on Sustainability*
Ventilation System & Distribution Effectiveness	Unit is 100% Outside Air, no remediation recommended Ceiling mixing ventilation system with assumed Ev ~1. Ventilation analysis calculations indicated this may be closer to Ev of 0.6 due to possible air short circuiting. However, after further investigation potential air recirculation was found further in the ventilation system at AHU. Therefore ventilation distribution and effectiveness Ev ~1 adequate with no changes recommended at this stage.				
Ventilation Rate & Operation	The Office fit-out design ventilation rate is approx. 21 l/s/p and 2 l/s/m2 which is IAQ Category I environment, beyond design expectations for IAQ. In terms of overall sustainability and energy consumption, a reduction in supply airflow is recommended to return to design levels of ~15 l/s/p while maintaining a premium Category II IAQ environment	Med		Easy	Technically a decrease in IAQ but levels are unnecessarily high - expect minimal occupant comfort difference. Significant energy reduction at lower airflow rates
	Implement air purging and run the base-building centralised air system for min. 3 ACH between occupancies periods e.g. nightly.	Med	No capital cost. Increase in operational cost	Easy	Increase in overall energy consumption. Minimal if included in Ventilation Optimised start routine
	Additional fan speed control for Full Occupancy, Medium Occupancy & Low occupancy added to enable full ventilation when occupied but setback ventilation when unoccupied.	Med	Minimal capital cost. Decrease in operational cost (compared to previous)	Easy	Increased IAQ Reduced energy consumption in line with occupancy and IAQ requirements compared to CAV
Temperature & Humidity	Measured by the IAQ monitor, temperature and relative humidity were found to be within the recommended comfort and IAQ range, therefore no action recommended.				

HVAC Measures	*Description*	*Impact Level*	*ROM* Cost*	*Ease of Implement-ation*	*Impact on Sustainability*
Air Filtration & Air Cleaning	Add/Upgrade plenum FCU filters to F8/MERV14 levels to filter return recirculated air and increase effective air changes. Upgrade current G4 return air filter with F8/MERV14 filter to minimise potential carry-over leakage. Upgrade current F7/MERV13 Supply air filter to F8/MERV14 when replacement required for greater filtration efficiency (of outdoor air and any possible leaked air) at minimal energy penalty. In room local air cleaners not recommended in this case as any additional ACHe required expected to be achieved by filtration on FCUs	Med Med	~€15k capital cost. Minor increase in operational cost Minor capital cost. Minor increase in operational cost	Medium	Additional maintenance on AHU and FCUs filter required. Slight increase in overall energy consumption.
IAQ Monitoring	Install zonal and meeting room CO2 monitoring and dashboards	Low	~€5k	Easy	Increased awareness of IAQ and identification of any issues.
MVHR Upgrade	Measure Thermal Wheel (TW) EATR with AHU Manufacturer. Add TW CO2 & differential pressure sensors to confirm correct pressure regimes and leakage rates Upon inspection, significant TW sealing deficiencies in the AHU were identified . This with the negative pressure differential was reintroducing exhaust air into supply air. Recommended to upgrade AHU TW sealing, fan speed and pressure control. Purge sector is not recommended to be retrofitted as could induce greater sealing leakage.	High	~€50k Reduction in energy cost	Medium	Reduction in air leakage improving ventilation effectiveness, IAQ and energy efficiency

*Cost is an indicative rough-order-of-magnitude cost and refers to supply and installation costs only.

Results

Based on the review of available design data and documents, the on-site inspection and ventilation adequacy analysis which occurred in March 2020 the above HVAC measures were recommended for the Arup office in Cork.

The main, high impact measure was the MVHR upgrade. Upon inspection, significant thermal wheel sealing deficiencies in the AHU were identified . This with the negative pressure differential produced by the fans operation was reintroducing exhaust air into supply air (i.e. AHU short circuiting), providing explanation for the higher than expected CO2 levels within the office identified in the ventilation analysis.

The recommendation to upgrade AHU thermal wheel sealing, and to update the fan speed operation and differential pressure control was actioned in stages over the summer of 2020. A thermal wheel purge sector, although originally recommended in 2020, was not easily retrofitted into the unit so was not installed. Then after further research it is no longer recommended to be retrofitted as could induce greater sealing leakage in the AHU.

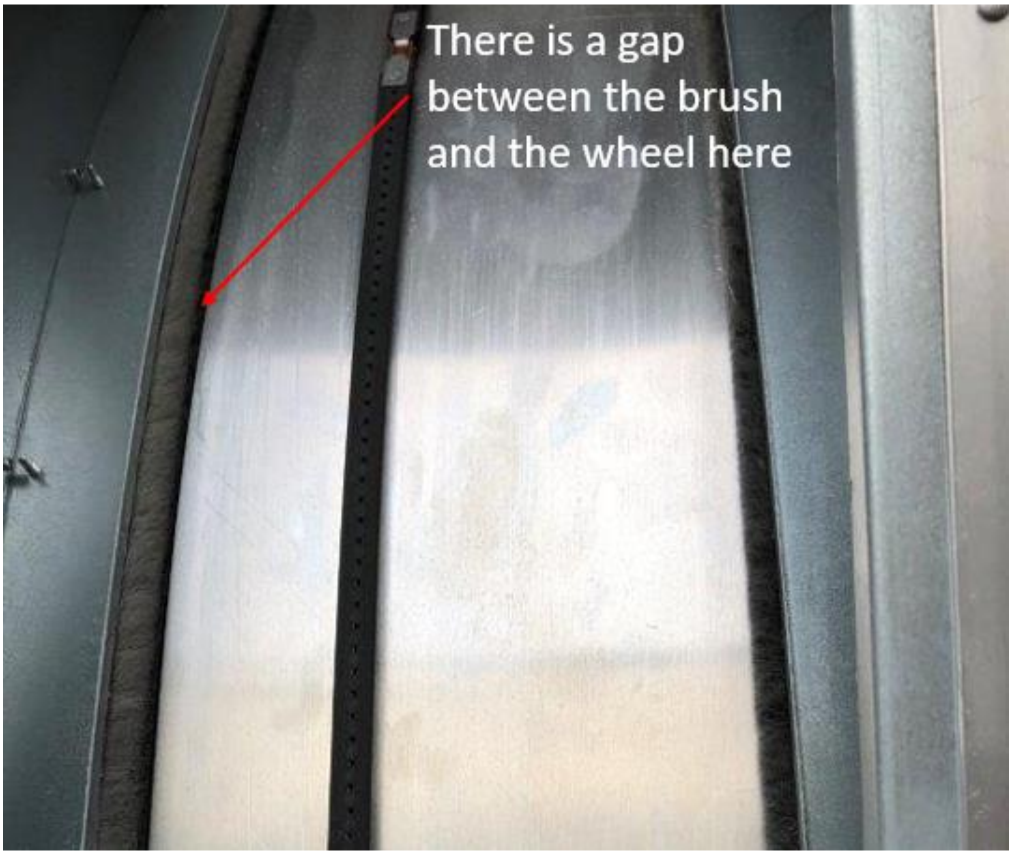


Figure 81 - Arup Cork Office AHU Thermal Wheel Sealing Leakage

Supply and exhaust air is modulated based on manual BMS input for fan speed - High, Medium, and Low, to match with occupancy rates typically known in advance due to new desk booking requirements in the office.

With the upgraded AHU sealing, air leakage and recirculation is greatly reduced, and therefore the high occupancy air supply rate may be reduced to original design levels without any reduction in IAQ. The pressure balance and positive pressure of ~50Pa is set to be maintained at design flows for supply and exhaust fans with an alarm raised if pressure differential drops to less than 25Pa to ensure any potential leakage occurs from supply to exhaust with no potential for cross-contamination.

For purge ventilation, the AHU is scheduled to operate 2 hours in advance of occupancy to ensure a minimum of 3 ACH as recommended. Additional upgrades to the control of the thermal wheel, and measurement of CO2 and pressure differentials across the AHU and filters were also implemented.

As of the 1st of October 2020, after the implementation of the above recommended measures the high occupancy supply airflow was 2.44 m3/s with a new office maximum capacity of 160 (when social distancing measures removed) providing an outside air ventilation rate of ~15 l/s/p as per design. This would result in an IAQ Category II environment (based on 15 l/s/p) or at an estimated CO2 value of ~740ppm (± 50ppm) a Category I environment.

Table 18 - Design Ventilation Analysis - CO2

Design Ventilation Analysis - CO2						
Stage	**Vent. Rate (Qh) l/s/p**	**CO2 Gen. Rate (Gh) l/s/p**	**Outdoor CO2 (Cho) ppm**	**Ev**	**Est. Design CO2 (Chi) ppm**	**IAQ Category**
Design - Office Fit-out	15	0.005	400	1	**739**	**I**

Although lower airflow rate, due to lower air leakage and recirculation and hence improved overall ventilation effectiveness, the IAQ remains at a minimum at Category II levels with no noticeable change to occupants, while estimated energy savings of 78,500 kWh per year have been implemented.

Occupancy rates during this period of October 2020 were low due to the state of COVID pandemic in Ireland at the time, however, taking a similar analysis period of March 6th – March 20th 2022 when occupancy was more akin to pre-pandemic levels the IAQ measurements were again taken as shown below.

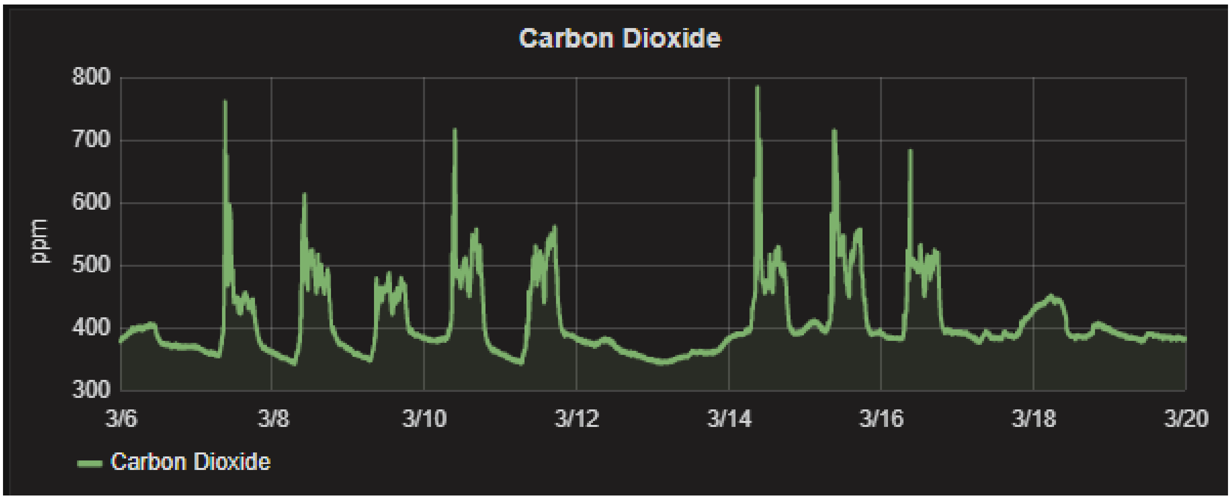


Figure 82 - Cork Office Operational CO2 Monitoring Values 2022

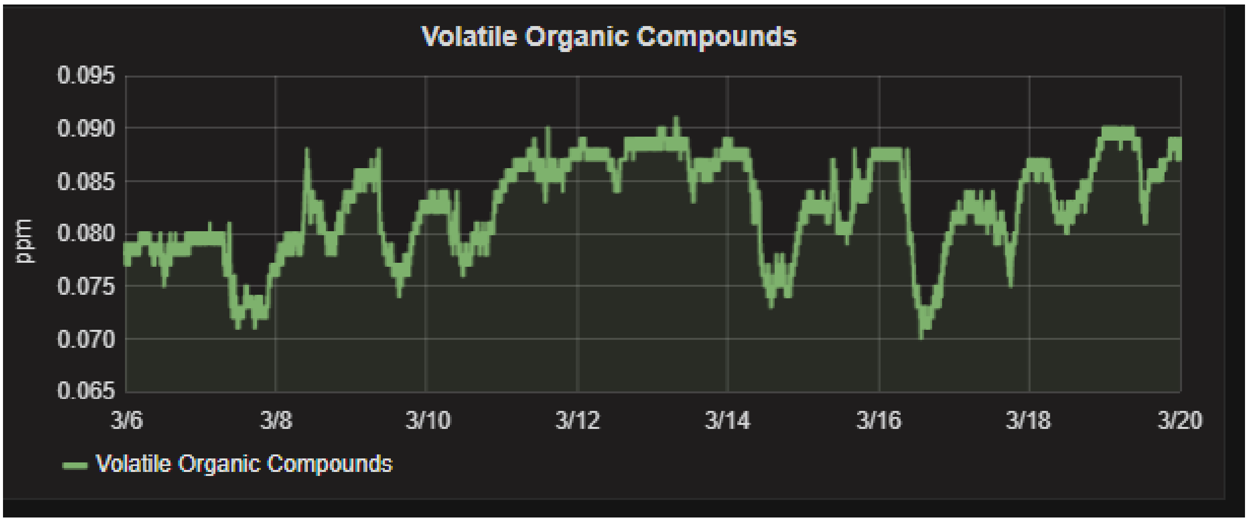


Figure 83 - Cork Office Operational VOCs Monitoring Values 2022

During occupied hours for the Cork office the average value measured for CO2 was ~550ppm, and for VOCs was 0.085ppm (~275 ug/m3) respectively. During peak morning occupancy, the office CO2 levels are shown to regularly achieve 750ppm. It is noted that VOCs levels are greater in the 2022 analysis period than previous but this may be attributed to the increased cleaning protocol applied in the office post pandemic. Again, taking this measured CO2 value as in the zone indoor concentration and using the Method 2 formula to calculate the corresponding ventilation rate the IAQ-calculated supply airflow is estimated at 2.33 m3/s in the zone, with an Ev of ~1.

This is an almost negligible difference and a radical improvement on the 2020 analysis indicating that the employed HVAC measures have had a significant benefit on the overall sustainability of the office.

Input	Fixed
Calculation	Comments

Operational measured space CO2 (ppm)	**750 ppm**
Operational space ventilation flowrate (m3/s)	**2.44 m3/s**

Space Data	Net Internal Area (NIA)	A	1900 m2	
	Ceiling/ Breathing zone height	H	2 m	
	Number of Occupants - people	n	160	
	Volume	V	3800 m3	
Air Data	Outdoor air CO2 levels	Cho	400 ppm	720.00 mg/m3
	Indoor Space CO2 levels	Chi	750 ppm	1350.01 mg/m3
	Ventilation Effectiveness	Ev	1	
	Actual Air supply rate	Q	2.44 m3/s	2440 L/s
	Occupant Metabolic Rate		1.25 Met	
	CO2 generation rate	Gh	0.005 L/s/p	9.16 mg/s/p
	CO2 molecular weight		44.01 g/mol	

Design		**Operational**		**Difference**
CO2 Calc.	**739.00 ppm**	**CO2 Meas.**	**750.00 ppm**	**11.00 ppm**
Q Design	**2.40 m3/s**	**Q Op.**	**2.44 m3/s**	**1.67 %**
		Q Calc.	**2.33 m3/s**	**-5 %**
Ev design	**1.0**	**Ev Calc**	**1.0**	**0.0**
q_design	**15.0 l/s/p**	**q_actual**	**14.5 l/s/p**	**-0.5 l/s/p**
Design ACH	**2.27 ACH**	**Actual ACH**	**2.20 ACH**	**-0.07 ACH**

Recirculation % *	**5%**
Q_Calc / Q_Op.	**95%**

Figure 84 - Arup Cork Office Upgraded HVAC Ventilation Analysis Results 2022

Case Study 2 - Education Facility, Singapore

The National University of Singapore (NUS) School of Design and Environment (SDE) latest building SDE4 is sited on a hill on the west of NUS campus in Singapore, Asia located in the Very Hot Humid (1A) climate zone.
Constructed in 2019, the six-story, 8,500 sqm educational building has a mixture of enclosed and open spaces with functions such as laboratories, teaching classrooms, design studios, a library, and administrative offices.

SDE4 is the first new-build net-zero energy building in Singapore in that it is designed to consume only as much energy as it produces, and acts as a living laboratory to demonstrate and explore human-centric approaches for integrated sustainable development. It is also the world's first university building to attain WELL Certified™ Gold, and first in Singapore to achieve the WELL™ Health-Safety Rating by the International WELL Building Institute (IWBI)

Figure 85 - NUS SDE4 Building, Singapore

HVAC System Summary

A summary of the HVAC system as of May 2022 with a focus on the building ventilation system is provided in table 19 below. The building was constructed in 2019 with all the existing HVAC equipment still in use today.

Table 19 - NUS SDE4 HVAC Summary Table

Item	Description	Notes
Plant	Centralised Air Handling Unit supporting Natural Ventilation & Ceiling Fans	Roof mounted AHU providing tempered air to mixed mode and mechanically ventilated spaces
Design IAQ Target	Category II	Leading educational facility
Type	Dedicated Outdoor Air Supply (DOAS)	Open Supply grilles in room, no return
Distribution	High Level Supply - VAV	Effectiveness (Ev) of ~1
Filtration	MERV 7 + MERV 14 grade	Bag filter type
Outside Air Provision	12.5 l/s/p 100%	Design occupancy density: ~4m2/person in mechanically ventilated areas
Outside Air as % of Supply Air	100%	Supply only with 'spill' air transfer to outside via natural ventilation grilles
Approx. Total Air Change Rate	~3 ACH	By mechanical ventilation, boosted by natural ventilation & ceiling fan mixing
Outside Air Modulation	Yes	Outside air is modulated based on manual BMS input for fan speed - High, Medium and Low
Economy Cycle / Heat Recovery	No	Not applicable for hybrid cooling model
Internal Temperature	27 °C	Singapore has relatively constant climate 1A year round
Humidity	Not controlled	Humid environment
Normal Hours of Base-Building HVAC Plant Operation	7am to 10 pm daily	May be shorter during weekends and holidays
Centralised Plant Cooling and Heating Capacity	Cooling provided by either full AC or hybrid cooling using ceiling fans No heating required	Campus centralised cooling circuit

NUS SDE4 has a uniquely designed HVAC systems specifically for the warm and humid Singaporean climate. Most zones are naturally ventilated (NV) including transitional (e.g., corridors), semi open spaces (e.g., plaza and terraces), and service rooms (e.g., toilets and storage). Many spaces adopt a hybrid cooling system (HC) that employs mechanical ventilation with both AC and ceiling fans with a design zone setpoint temperature of 27 degrees Celsius and elevated air movement via ceiling fans that help provide thermal comfort with higher setpoint temperatures. Other zones are either solely mechanically ventilated (MV) with tempered air from the AHU, or include traditional air-conditioning (AC). This helped SDE4 achieve its net-zero energy status by minimising HVAC energy consumption.

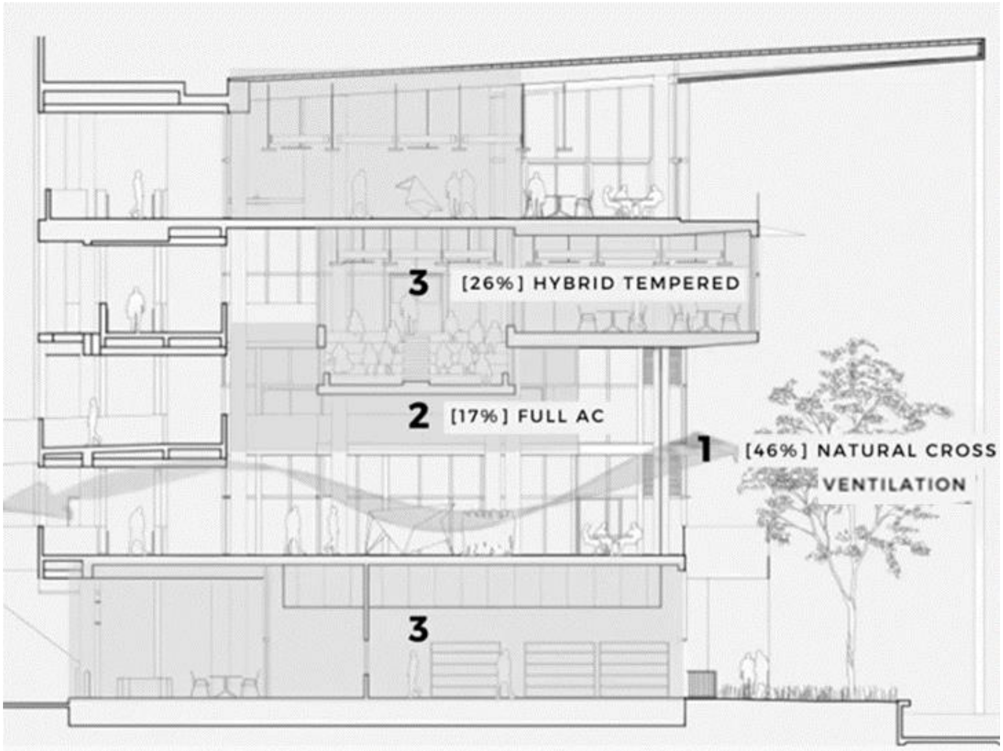


Figure 86 - SDE4 HVAC Strategy Breakdown

The supply only AHU located on the roof delivers 100% outside air to mechanically ventilated areas including hybrid and full AC spaces. The hybrid cooling system implemented in SDE4 is a single pass system that supplies the spaces with 100 per cent highly filtered outdoor fresh air at higher temperature and humidity, augmented with elevated air speed from IoT-enabled smart ceiling fans, controllable by occupants. The hybrid system is not only more efficient than conventional systems, but also provides better comfort levels.

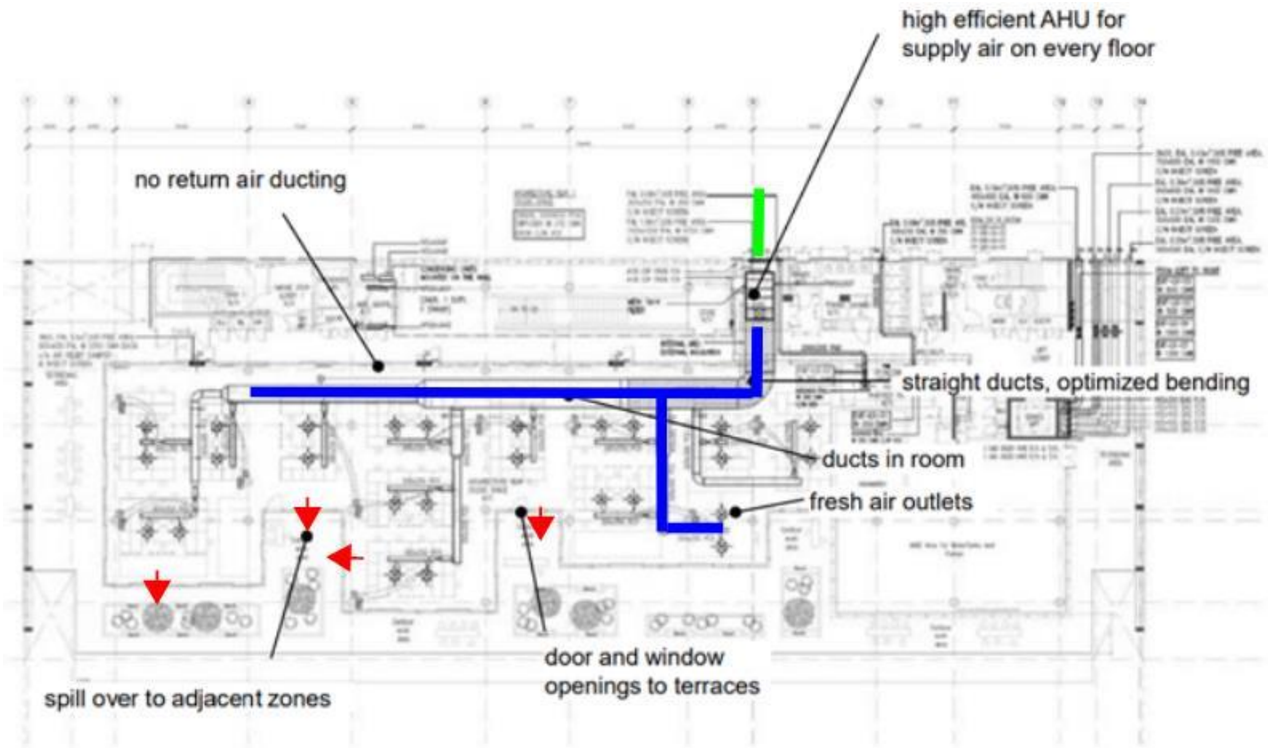


Figure 87 -- NUS SDE4 Air Layout

In the hybrid designs the operative temperature is between 26 °C and 29 °C; the humidity level is about 15 to 20 g/kg. The impact of higher temperature and humidity is compensated by elevated air speed from the ceiling fans. The mechanical ventilation system fresh air is supplied to the zones typically cooled to 18 °C air temperature. Supply air pressurizes the room and spills over to the hallways or other zones open to natural cross ventilation, minimizing infiltration. This allows a simplified window design as well as omitting any return air system.

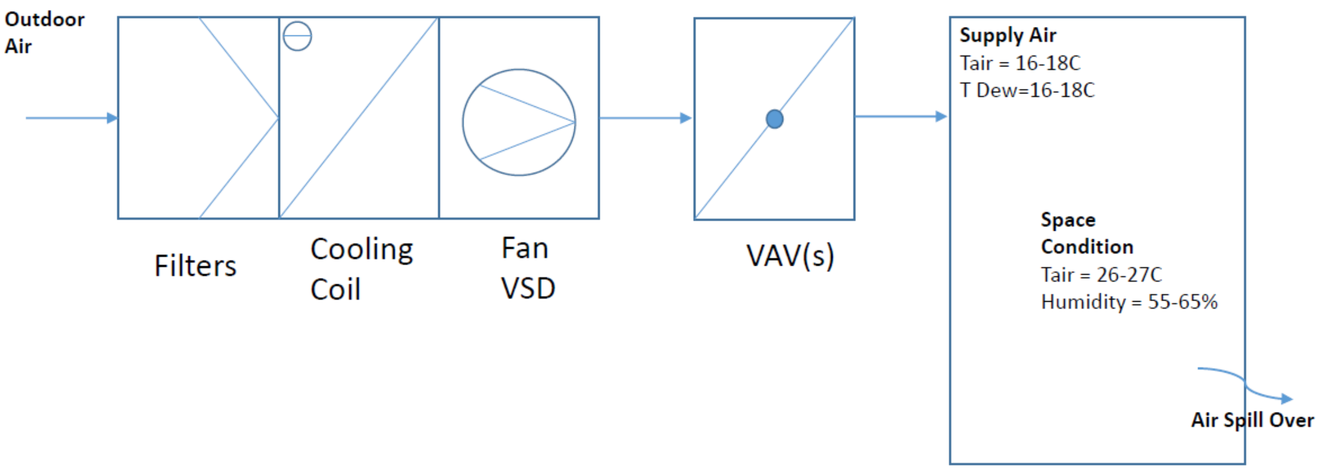


Figure 88 - NUS SDE4 HVAC Schematic

Ceiling fans are deployed with occupant adjustable air velocity speeds elevated in three steps: 0.3 to 0.7 to 1.2 m/s to meet comfort requirements. This is in line with limits for air speed of sedentary work (0.7 m/s) and maximum air speed under occupant control (1.2 m/s) according to ASHRAE Standard 55. Supplied air is varied through VAVs based on occupancy rates lowering to approx. 50% design occupancy and demand control ventilation strategies are in place to ensure that indoor carbon dioxide levels does not exceed 750ppm in mechanically ventilated zones. Indoor air quality is measured and tracked in the building at all times to ensure optimal air quality. There are currently no air cleaning devices utilised within the AHU or educational zones

Figure 89 - NUS SDE4 Mechanical Ventilation and Ceiling Fan, & IAQ Sensor photos

Ventilation Analysis

The NUS SDE4 building is a leading educational facility aiming to achieve IAQ II category or better in design. The building the world's first university building to attain WELL Certified™ Gold, and the open space, exposed thermal mass and natural finishes associated with the design provide confirmation that very low polluting materials were used and related credits achieved - therefore a very low polluting environment (BS EN16798) is applied, with the associated recommended ventilation rates provided below for reference.

Table 20 - Very Low Polluting Environment (BS EN16798) Recommended Ventilation Rates

Category	Rec. Ventilation Rate	
	l/s/p	l/s/m2
I	$\frac{15}{Ev}$	$\frac{1.5}{Ev}$
II	$\frac{10.5}{Ev}$	$\frac{1.05}{Ev}$
III	$\frac{6}{Ev}$	$\frac{0.6}{Ev}$
IV	$\frac{4.125}{Ev}$	$\frac{0.4125}{Ev}$

Many zones in SDE4 are naturally ventilated with detailed design consideration to achieve adequate cross ventilation for occupant comfort and contamination dilution. Focusing on these remaining zones which are mechanically ventilated the design allowed for 12.5 l/s/p distributed by high level supply with no return only 'spill over' to adjacent naturally ventilated or external environments. In the majority of these zones ceiling fans for increased air velocity are also operational creating full mixing conditions therefore a ventilation effectiveness Ev ~1 is assumed.

With an occupancy density of 4m2/person over 3,540m2 mechically ventilated floor area provides an occupancy of 890 people requiring 11.1 m3/s mechanical air supply. This resulted in approximately 3.1 l/s/m2 ventilation rate which is IAQ Category I, but 12.5 l/s/p is Category II which is the dominant factor.

Table 21 – NUS SDE4 Design Ventilation Analysis - Flowrate

Design Ventilation Analysis - Flowrates				
Stage	**Vent. Rate L/s/p**	**Vent. Rate L/s/m2**	**Ev**	**IAQ Category**
Design - MV Areas	12.5	3.1	1	**II**

For further enhanced ventilation and IAQ analysis, expected zone CO2 levels can be calculated using the presented adapted Method 2 (BS EN 16798-1) limit values for substance concentration formula. Using this formula the CO2 level expected for the specified design ventilation rate is estimated, and may be compared against the table of classified absolute indoor CO2 levels to categorise the design IAQ level. Note unit conversions are required for this formula calculation, and more details on these are provided in the IAQ calculator tool with this research and an extract included below.

Design Data	Ventilation Rate	Qh	12.5 l/s/p	0.0125 m3/s/p	Design Ventilation rate per person
	Ventilation Effectiveness	Ev	1 _		Assumed for High level low temp (< 8 degC dT) mixing ventilation
	Outdoor air CO2 levels	Co	400 ppm	720.00 mg/m3	Taken from outside CO2 sensor or sourced from local weather station
	Occupant Metabolic Rate		1.25 Met		Allowing for an average office metabolic rate of 1.25 (70W/m2)
	CO2 generation rate	Gh	0.005 L/s/p	9.16 mg/(s.person)	Calculated per CIBSE Guide B2 with PV=nRT (at 21ºC, 1 atm)
	CO2 molecular weight		44.01 g/mol		Molecular weight of CO2
	Estimated Zone CO2 level	**Chi**	**807 ppm**	1452.87 mg/m3	Concentration (ppm) = 24.45 * mg/m3 / molecular weight

Based on the design data and calculation, an estimated design CO2 concentration of ~810ppm is expected which is an IAQ Category II classification.

Table 22 – NUS SDE4 Design Ventilation Analysis – CO2

Design Ventilation Analysis - CO2						
Stage	**Vent. Rate (Qh) l/s/p**	**CO2 Gen. Rate (Gh) l/s/p**	**Outdoor CO2 (Cho) ppm**	**Ev**	**Est. Design CO2 (Chi) ppm**	**IAQ Category**
Design - Office Fit-out	12.5	0.005	400	1	**807**	**II**

Resulting zone CO2 values will not be exact due to variances in occupant activity and outdoor CO2 levels however, operational measure values can be compared against a range (i.e. 810 ± 50ppm) to help identify if there are any significant variances between design and operation expectations. Note design stage calculations may use design data in per person values, however for operational stage analysis absolute values should be used as below.

Operational stage measured CO2 data is required to compare to design data and this was achieved in the NUS SDE4 using the AIRTHINGS View Plus; a class-leading air-monitoring device which was used to record measurements of CO2 and VOCs in selected locations in the educational facility. Due to issues with Wi-Fi connection and security, the AIRTHINGS continuous monitoring platform was not available.

Figure 90 - NUS SDE4 AIRTHINGS Air Quality Sensor Measurement

Using this available point in time measurement, taken on Wednesday 11th May 2022 in the BEEHUB lab in SDE4, the measured CO2 value was ~650ppm and VOCs was 46 ug/m3 respectively during this occupancy period, both below the recommended limits.

This 650 ppm measured operational CO2 value meets Category I IAQ class threshold as is 110 ppm less than the calculated design CO2 expected range (min 760ppm). In this case it is no cause for concern as due to summer holidays and COVID measures the mechanically ventilated zone was only partly occupied compared to design levels, therefore the lower CO2 level is expected.

The final ventilation adequacy analysis examines air exchange rate in an environment and its role in building resilience and IAQ. We have agreed that CO2 as a proxy for IAQ is acceptable, however measurement of CO2 cannot account for other HVAC based mitigation strategies such as filtration, local air cleaners and UVC disinfection strategies which remove or deactivate virus and other particle contaminants from the air but have no effect on CO2. The ASHRAE 62.1 IAQ procedure has adopted the effective air change rate (ACHe) metric to account for these mitigation strategies in IAQ based ventilation design. This ACHe and its calculation use recirculated air volumes and air cleaning efficiencies to approximate relative ventilation supply, and is detailed in the attached Equivalent Outdoor Air Calculator spreadsheet and summarised below.

Name of Space / AHU / Building	Units	SDE4 MV
Area	Sq m	3540
Average Ceiling / Breathing Zone Height	m	3
Volume	m3	10620
Total Supply Air	m3/s	11.3
Total Outdoor Air	m3/s	11.3
Supply Air ACH	ACH	3.83
Outdoor Air ACH	ACH	3.83
Central AHU Filter MERV Rating	MERV	13
UVC Single Pass Inactivation	%	0.00%
In Room Fan Air Cleaner (HEPA+)	CADR (m3/h)	0
Number of In Room Fan Air Cleaners (HEPA+)	Qty	0
Effective Air Changes Based on Technology		
ACH_OA	ACH	3.83
ACH_MERV filter in AHU	ACH	0.00
ACH_e,c	ACH	0.00
ACH_air cleaner	ACH	0.00
Sub-Total Effective ACH	ACH	3.83
Zone Air Distribution Effectiveness	Ez	1.0
Air Cleaner Position Effectiveness	Ezp_ac	1.0
Total Effective ACH_e		**3.83**

Figure 91 - SDE4 Mechanical Ventilation (MV) Effective Air Change Results

ACHe is important metric in contamination removal and dilution, vital for good IAQ and the new normal building resilience objective. Based on the results, the design ventilation effective air change rate of 3.8 ACHe is greater than the Category II recommended value of 3 ACHe which is improving building resilience and general IAQ.

Table 23 – NUS SDE4 Design Ventilation Analysis - ACHe

Design Ventilation Analysis - ACHe					
Stage	**ACH_OA**	**ACH_f**	**ACH_e,c**	**ACHe**	**IAQ Category**
Design	3.83	0	0	3.83	**II**

The current design ventilation system can achieve adequate levels of resilient air exchange if required however it is postulated that the operation of the ceiling fans may have an effect on effective air change rates and ventilation effectiveness. This is explored further in the applicable HVAC measures for SDE4.

HVAC Measures

Using the case study SDE4 building as a blueprint we analyse of the need and suitability of the previously distilled HVAC measures from best practice guidance, looking at their impact on air contaminants and virus transmission risk, while also considering their economic costs, ease of implementation, and impact on building sustainability as presented in the following table.

These distilled HVAC measures are listed below with their main analysis points while full summary details of each is provided previously in this report.

- **Ventilation System & Distribution Effectiveness** –
  - DOAS vs Recirculation ventilation systems
  - Mixing vs Displacement vs Personal ventilation distribution
- **Ventilation Rate & Operation** –
  - 'Adequate' ventilation achievement
  - Demand Controlled Ventilation (DCV) operation
  - Purge Ventilation
- **Temperature & Humidity** –
  - Acceptable temperature and humidity ranges
- **Air Filtration & Air Cleaning** –
  - Air filtrations levels
  - Air cleaning technologies
  - Local in-room air cleaners
- **IAQ Monitoring** –
  - CO2 monitoring
  - IAQ measurement
- **Mechanical Ventilation Heat Recovery (MVHR)** –
  - AHU sealing and pressure regimes (fan locations)
  - Thermal Wheel (TW) purge sectors

HVAC Measures	*Description*	*Impact Level*	*ROM* Cost*	*Ease of Implement-ation*	*Impact on Sustainability*
Ventilation System & Distribution Effectiveness	Unit is 100% Outside Air, no remediation recommended High level supply with ceiling fans mixing ventilation system with assumed Ev ~1. Recommended to analyse the effect of ceiling fans on the ventilation effectiveness and effective air change rate to ensure suitable dilution and removal of contaminants, particularly virus particles.	Low	Low capital cost for CFD analysis or similar	Easy to complete analysis. Changes to ceiling fan operation may be difficult to action	Confirmation of IAQ. Possible increased cooling energy consumption if ceiling fans need to be altered
Ventilation Rate & Operation	The SDE4 design ventilation rate is approx. 12.5 l/s/p and 3.1 l/s/m2 which is IAQ Category II environment, achieving design expectations for IAQ. The operational ventilation rate is also achieving expectations for IAQ. Naturally ventilated spaces achieve cross ventilation. Implement air purging and run the base-building centralised air system for min. 3 ACH between occupancies periods e.g. nightly. Supplied air is varied through VAVs based on occupancy rates lowering to approx. 50% design occupancy and demand control ventilation strategies are in place to ensure that indoor carbon dioxide levels does not exceed 750ppm in mechanically ventilated zones. No recommendations	Med	No capital cost. Increase in operational cost	Easy	Increase in overall energy consumption. Minimal if included in Ventilation Optimised start routine
Temperature & Humidity	Measured by the IAQ monitor, temperature and relative humidity were found to be within the recommended comfort and IAQ range for the given environment, therefore no action recommended.				

HVAC Measures	*Description*	*Impact Level*	*ROM* Cost*	*Ease of Implement-ation*	*Impact on Sustainability*
Air Filtration & Air Cleaning	The current MERV7 + MERV14 2-stage filter is more than adequate and does not require upgrading at this time In room local air cleaners not recommended in this case as target resilience ACHe achieved by mechanical ventilation supply				
IAQ Monitoring	Several zonal and classroom CO2 monitoring and dashboards installed, including a wellbeing learning trail provided. Additional IAQ monitors with colour coded feedback / dashboards for increased awareness is recommended.	Low	~€5k	Easy	Increased awareness of IAQ and identification of any issues.
MVHR Upgrade	No MVHR onsite or required.				

Results

Based on the review of available design data and documents, the on-site inspection and ventilation adequacy analysis which occurred in May 2022 the above HVAC measures were recommended for the NUS SDE4 building in Singapore.

Considering SDE4 is a leading educational facility with WELL Gold certification and human-centric design it is not surprising that there are limited HVAC measures recommended. This case study was more chosen to learn from a renowned, exemplar case study building in a tropical climate rather than identify issues. Nonetheless based on the analysis some HVAC measures were recommended, the highest impact of which is ventilation operation – night purging measure to improve IAQ and resilience by boosting absolute contamination removal between occupancy periods which are relatively long compared to typical buildings. This can be implemented into the building BMS operational schedule relatively easily with almost no capital cost and minimal increase in operational costs and energy consumption.

The current MERV7 + MERV14 2-stage filter is more than adequate and does not require upgrading at this time. While the additional IAQ monitors and display are not crucial, and it is noted that the National University of Singapore has been recently trialling Spacematch in the SDE4 and SDE2 building on the campus. Spacematch is an online platform with AI enhanced spatial recommendation engine that suggest suitable workspaces to building occupants based on comfort preferences. Currently monitoring temperature, humidity, and noise this can be expanded to included CO2 and VOCs or others if applicable to improve IAQ awareness and occupant comfort.

Figure 92 - NUS Spacematch Platform - Credit Clayton Miller, NUS

One of the fundamental aspects of the leading cooling and ventilation design of SDE4 is the ceiling fans and increased air velocity. The effect of this on occupant comfort is well studied and reported using NUS SDE4 as a case study [24] [25] [26] however, the effect of the ceiling fans on ventilation effectiveness and contamination removal, or in particular virus spread is less studied.

In one recent study from NUS [27] the effects of ceiling fans on airborne transmission in an air-conditioned space were analysed by experimentally and numerically investigating the steady-state aerosol transmission characteristics in a full-size room using a dedicated outdoor air system coupled with ceiling fans, representative of the SDE4 ventilation strategy. The results indicated that the ceiling fans generated local air movement and mixed air within the space, and a higher operating speed contributed to a more uniform concentration distribution providing better mixing validating the ventilation effectiveness of ~1. Additionally, from this NUS research it is demonstrated that with better dispersion of the aerosols, the ceiling fan operation reduced the concentrations at the exposed person's breathing zone by more than 20%. Therefore it is concluded that the ceiling fans show the potential to reduce the cross-infection risk in an air-conditioned space.

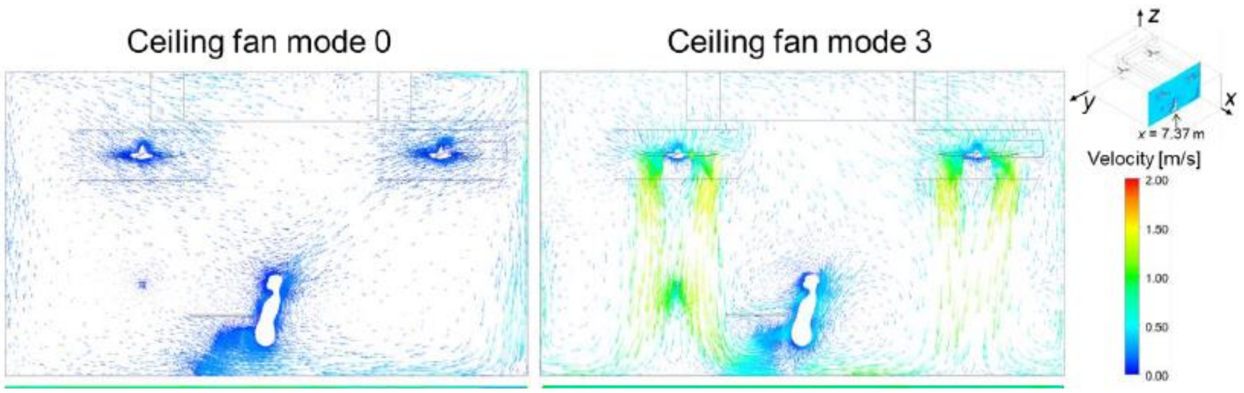


Figure 93 – CFD Image extract from 'Effects of ceiling fans on airborne transmission in an air-conditioned space', Wenxin Li et al

[24] Humans-as-a-Sensor for Buildings—Intensive Longitudinal Indoor Comfort Models, Prageeth Jayathissa,Matias Quintana, Mahmoud Abdelrahman, Clayton Miller, Building and Urban Data Science (BUDS) Lab, National University of Singapore (NUS), Singapore 117566, Singapore. https://www.mdpi.com/2075-5309/10/10/174/htm

[25] Spacematch: Using Environmental Preferences to Match Occupants to Suitable Activity-Based Workspaces, Tapeesh Sood1, Patrick Janssen and Clayton Miller, Front. Built Environ., 30 July 2020 Sec. Indoor Environment. https://doi.org/10.3389/fbuil.2020.00113

[26] The SDE4 Learning Trail: Crowdsourcing occupant comfort feedback at a net-zero energy building, Tapeesh Sood, Matias Quintana, Prageeth Jayathissa, Mahmoud AbdelRahman and Clayton Miller. https://iopscience.iop.org/article/10.1088/1742-6596/1343/1/012141

[27] Effects of ceiling fans on airborne transmission in an air-conditioned space, Wenxin Li et al., Building and Environment · July 2021. https://www.researchgate.net/publication/351099958

Case Study 3 - Commercial Office, Melbourne - Australia

161 Collins Street is established heritage commercial building located on the prime corner of Collins and Russell Streets in Melbourne, Australia in the Mixed Humid climate zone 4A. A historic neo-renaissance building originally constructed in 1928, it has most recently undergone extensive refurbishment in 2018. The refurbished building comprises 10 storeys of commercial space providing approx. 38,000 sqm of commercial office space and approx. 3600 sqm of retail space on the lower levels.
The building is an A-grade building with current NABERS Energy rating of 4 stars.

Figure 94 - 161 Collins Street Building, Melbourne, Australia

HVAC System Summary

A summary of the HVAC system with a focus on the building ventilation system is provided in table 24 below.

Table 24 – 161 Collins Street HVAC Summary Table

Item	*Description*	*Notes*
Plant	Centralised Air Handling Units	6 no. AHUs located on roof serving office floors
Design IAQ Target	Category II	Premium Commercial Office
Type	Recirculation Variable Air Volume (low temperature)	VAV boxes located on office floors
Distribution	High Level Supply & Return Mixing	Effectiveness (Ev) ~1
Filtration	F8 grade	Bag filter type
Outside Air Provision	8 L/s/person	Design occupancy density: 10 m^2/person Actual occupancy density: Similar to design[3].
Outside Air as % of Supply Air	~24%	AHU P.1 and P.3 which serve perimeter zones ~ 10% outside air. AHU P.2, P.4, P.5 and P.6 serve internal zones have ~ 30% outside air.
Approx. Total Air Change Rate	~3 ACH	Total air exchange
Outside Air Modulation	Yes	Outside air is modulated based on room temperature VAV strategy. No CO_2 sensors
Economy Cycle / Heat Recovery	Yes	Air Recirculation Economiser
Internal Temperature	24°C (Summer) 20°C (Winter)	N/A
Humidity	Not controlled	No humidity sensors
Normal Hours of Base-Building Air-Conditioning Plant Operation	8am to 6 pm Weekdays	N/A
Centralised Plant Cooling and Heating Capacity	3670 kW (Cooling) 3600 kW (Heating)	2 no. 1186 kW VS chillers & 1 no. 1300 kW chillers 2 no 1800 kW boilers

The building has most recently undergone extensive refurbishment in 2018 which included major works on the HVAC systems. The main relevant HVAC works in the context of this report from the above refurbishment are:

- Refurbishment of the existing Air Handling Units (AHUs) incl. cleaning of existing AHU coils, filter replacements and refurbishment of the AHU supply air fans.
- Extensive reconfiguration of the AHUs and on-floor VAV systems to resemble contemporary low-temp VAV systems. This included replacement of the existing fan-assisted VAV boxes with new VAV boxes on most commercial office floors.
- Rezoning of commercial office floors whereby the centralised AHUs serve in perimeter/internal configuration.

The six recently refurbished centralised AHUs are located on roof and supply air to ten office floors via risers distributed throughout the floor. Air returns to the centralised air distribution system via separate return air risers as shown on the air layout drawing below.

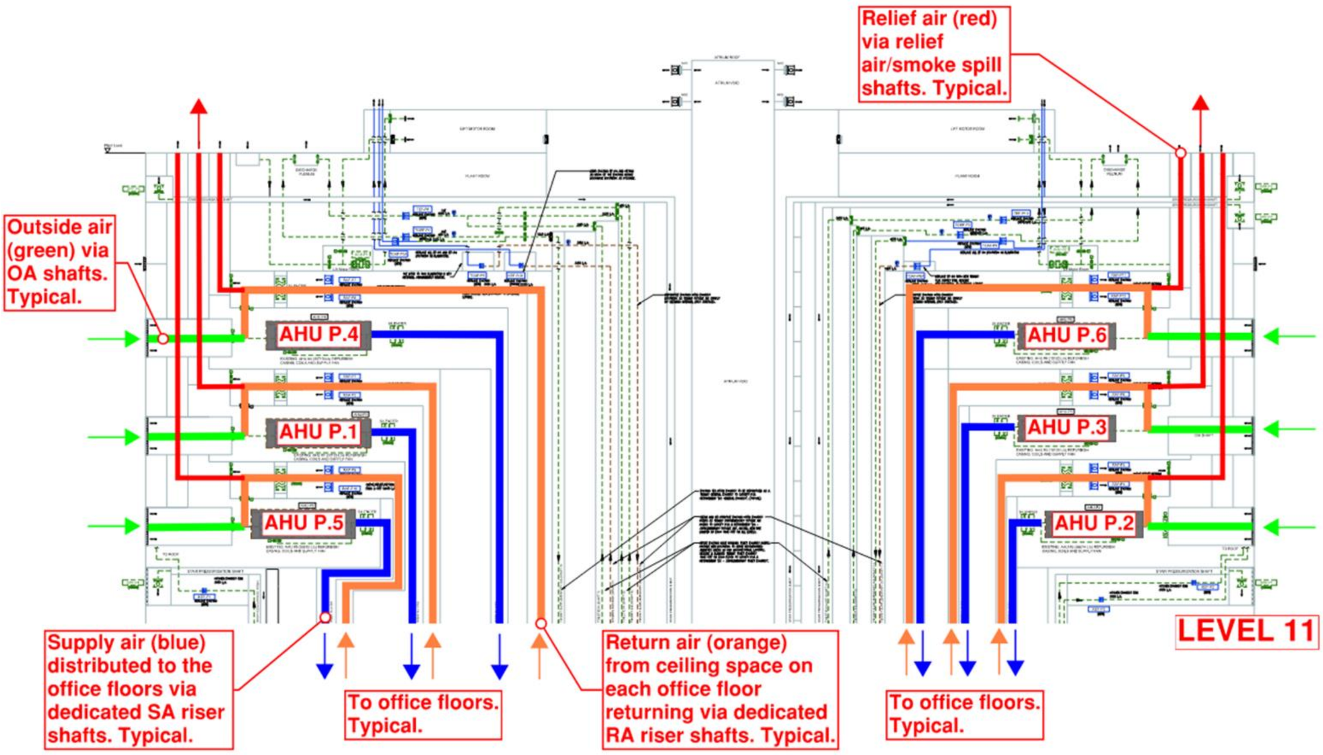


Figure 95 - 161 Collins Street Air Layout

AHUs incorporate chilled and heating hot water coils with chilled and heating hot water supplied from the central thermal plant. There are tenant supplementary air systems such as tenant outside air and tenant general exhaust systems available for connections on the office floors.

Supply air consists of a mix of filtered outside air and return air. Outside air quantity is currently modulated using mixing damper based on calculated supply air temperature, and supply air is modulated via AHU fan VSD and VAV boxes based on room temperature control with a minimum setting of 30% and 100pa AHU fan pressure. The AHUs are capable of economy cycle (100% outside air), and full recirculation during occasions of external contamination events such as wildfires.

The supply air system serving the office floors is a low-temperature VAV system with each VAV box serving no more than 85 sqm (perimeter zone) and 120 sqm (internal zone) respectively. Supply ventilation is distributed from high level via ceiling mounted swirl grilles in co-ordinated locations, and return air extracted from eggcrate plenum return grilles in the ceiling. Linear slot diffusers in reception and meeting room areas provide more architecturally discreet air exchange in these areas. There are currently no air cleaning devices utilised within the AHU or commercial space.

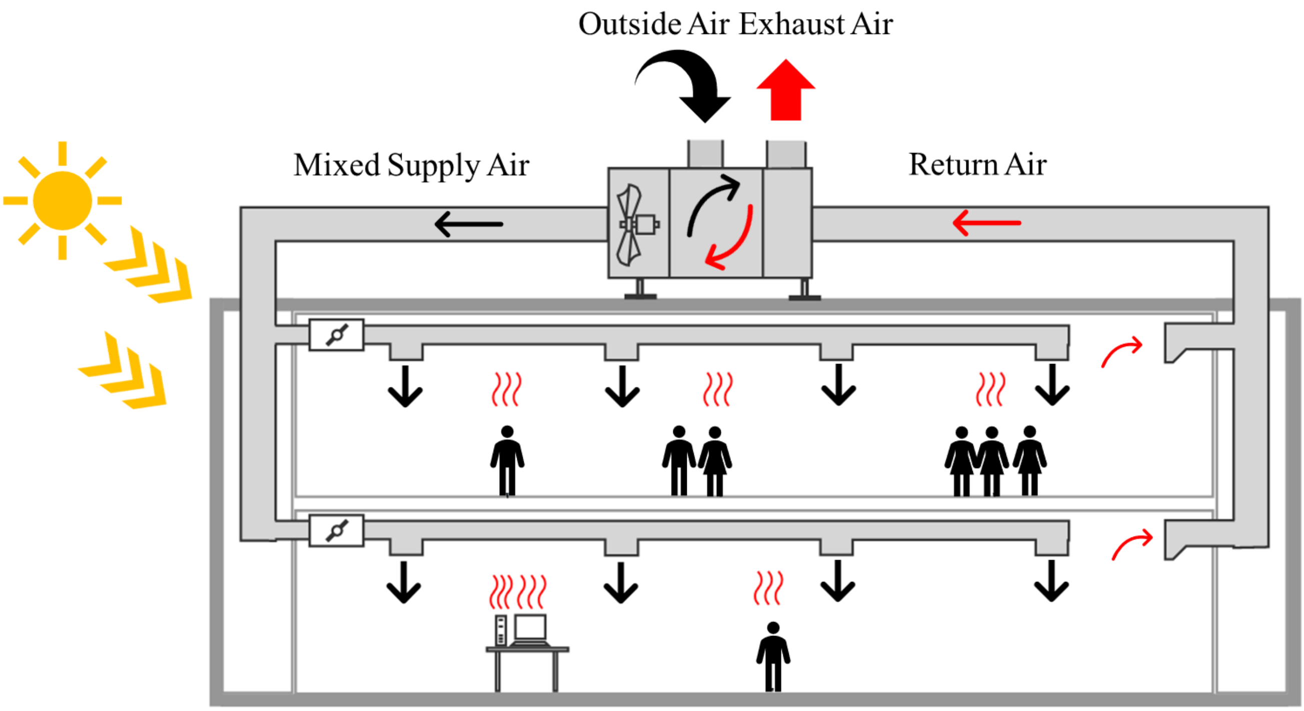


Figure 96 - 161 Collins Street HVAC Schematic

Ventilation Analysis

The 161 Collins building is mostly a premium commercial office space aiming to achieve IAQ II category or better in design. The building, which is an A-grade building with current NABERS Energy rating of 4 stars, and clearly designed and built to a high specification, has no confirmation that very low polluting materials was used therefore a typical low polluting environment (BS EN16798) is assumed, with the associated recommended ventilation rates provided below for reference.

Table 25 - Typical Low Polluting Environment (BS EN16798) Recommended Ventilation Rates

Category	Rec. Ventilation Rate	
	l/s/p	l/s/m2
I	$\frac{20}{Ev}$	$\frac{2}{Ev}$
II	$\frac{14}{Ev}$	$\frac{1.4}{Ev}$
III	$\frac{8}{Ev}$	$\frac{0.8}{Ev}$
IV	$\frac{5.5}{Ev}$	$\frac{0.55}{Ev}$

Focusing on the commercial office zones which are mechanically ventilated the design allowed for 8 l/s/p distributed by high level supply and return mixing ventilation with Ev ~1. With an occupancy density of ~10m2/person over 38,000m2 mechically ventilated floor area provides an occupancy of 3,800 people requiring 30.4 m3/s outdoor air supply over the 10 floors, not inlcuding recirculated air.
This resulted in approximately 0.8 l/s/m2 ventilation rate which is IAQ Category III and 8 l/s/p is also Category III.

Table 26 – 161 Collins Street Design Ventilation Analysis - Flowrates

Design Ventilation Analysis - Flowrates				
Stage	**Vent. Rate L/s/p**	**Vent. Rate L/s/m2**	**Ev**	**IAQ Category**
Design - Commercial Office	8	0.8	1	**III**

For further enhanced ventilation and IAQ analysis, expected zone CO2 levels can be calculated using the presented adapted Method 2 (BS EN 16798-1) limit values for substance concentration formula. Using this formula the CO2 level expected for the specified design ventilation rate is estimated, and may be compared against the table of classified absolute indoor CO2 levels to categorise the design IAQ level. Note unit conversions are required for this formula calculation, and more details on these are provided in the IAQ calculator tool with this research and an extract included below.

Design Data	Ventilation Rate	Qh	8 l/s/p	0.008 m3/s/p	Design Ventilation rate per person
	Ventilation Effectiveness	Ev	1 _		Assumed for High level low temp (< 8 degC dT) mixing ventilation
	Outdoor air CO2 levels	Co	400 ppm	720.00 mg/m3	Taken from outside CO2 sensor or sourced from local weather station
	Occupant Metabolic Rate		1.25 Met		Allowing for an average office metabolic rate of 1.25 (70W/m2)
	CO2 generation rate	Gh	0.005 L/s/p	9.16 mg/(s.person)	Calculated per CIBSE Guide B2 with PV=nRT (at 21°C, 1 atm)
	CO2 molecular weight		44.01 g/mol		Molecular weight of CO2
	Estimated Zone CO2 level	**Chi**	**1036 ppm**	1865.11 mg/m3	Concentration (ppm) = 24.45 * mg/m3 / molecular weight

Based on the design data and calculation, an estimated design CO2 concentration of ~1035ppm is expected which is just over the threshold of an IAQ Category III classification.

Table 27 – 161 Collins Street Design Ventilation Analysis – CO2

Design Ventilation Analysis - CO2						
Stage	**Vent. Rate (Qh) l/s/p**	**CO2 Gen. Rate (Gh) l/s/p**	**Outdoor CO2 (Cho) ppm**	**Ev**	**Est. Design CO2 (Chi) ppm**	**IAQ Category**
Design - Office	8	0.005	400	1	**1036**	**III**

Resulting zone CO2 values will not be exact due to variances in occupant activity and outdoor CO2 levels however, operational measure values can be compared against a range (i.e. ~1035 ± 50ppm) to help identify if there are any significant variances between design and operation expectations. Note design stage calculations may use design data in per person values, however for operational stage analysis absolute values should be used as below.

Operational stage measured CO2 data is required to compare to design data and this was achieved in the 161 Collins Street case study using the AIRTHINGS View Plus; a class-leading air-monitoring device which was used to record measurements of CO2 and VOCs in selected locations in the educational facility. Due to issues with Wi-Fi connection and security, the AIRTHINGS continuous monitoring platform was not available.

Figure 97 – 161 Collins Street AIRTHINGS Air Quality Sensor Measurement

Using this available point in time measurement, taken on Wednesday 18th May 2022 in 161 Collins Street level 2 office area, the measured CO2 value was ~760ppm and VOCs was 253 ug/m3 respectively during this occupancy period, both below the recommended limits.

This 760 ppm measured operational CO2 value meets Category I IAQ class threshold and is 275 ppm less than the calculated design CO2 value of 1035 ppm, which is significantly less than the expected range (min 985ppm). In this case it is no cause for concern as due to the tenants current Work From Home (WFH) practices and COVID measures the mechanically ventilated zone was only partly occupied compared to design levels therefore, the lower CO2 level is somewhat expected, although this is a significant deviation. It is proposed that the additional air exchange related to the recirculated air also included in the mechanical ventilation is also lower the CO2 rate which is not taken into account in the calculation.

Investigating this further and allowing for the lower occupancy rate, and as a result of the ventilation modulation strategy lower ventilation rate to the minimum 30% (0.9 m3/s for the floor) we can calculate the IAQ based expected ventilation rate using the BS EN 16798 Method 2 formula.

Taking this measured CO2 value of 760ppm as in the zone indoor concentration and using the BS EN 16798 Method 2 formula to calculate the corresponding ventilation rate, the result is 1.41 m3/s, an improvement of 57% over operational outdoor ventilation rate as detailed below.

Operational measured space CO2 (ppm)	**760 ppm**
Operational space ventilation flowrate (m3/s)	**0.9 m3/s**

Space Data	Net Internal Area (NIA)	A	3800 m2		Building floor NIA
	Ceiling/ Breathing zone height	H	2 m		Space floor to ceiling height or breathing zone height - 2m (BS EN 1697[8]
	Number of Occupants - people	n	100		Numbe rof people occupaying the space
	Volume	V	7600 m3		
Air Data	Outdoor air CO2 levels	Cho	400 ppm	720.00 mg/m3	Taken from outside CO2 sensor or sourced from local weather station
	Indoor Space CO2 levels	Chi	760 ppm	1368.01 mg/m3	Measured space return air CO2 levels
	Ventilation Effectiveness	Ev	1		Assumed for High level low temp (< 8 degC dT) mixing ventilation
	Actual Air supply rate	Q	0.9 m3/s	900 L/s	Actual measured supply airflow to space
	Occupant Metabolic Rate		1.25 Met		Allowing for an average office metabolic rate of 1.25 (70W/m2)
	CO2 generation rate	Gh	0.005 L/s/p	9.16 mg/s/p	Calculated per CIBSE Guide B2 with PV=nRT (at 21ºC, 1 atm)
	CO2 molecular weight		44.01 g/mol		

Design		**Operational**		**Difference**
CO2 Calc.	**1035.00 ppm**	**CO2 Meas.**	**760.00 ppm**	**##### ppm**
Q Design	**3.00 m3/s**	**Q Op.**	**0.90 m3/s**	**-70.00 %**
		Q Calc.	**1.41 m3/s**	**57 %**
Ev design	**1.0**	**Ev Calc**	**1.6**	**0.6**
q_design	**30.0 l/s/p**	**q_actual**	**14.1 l/s/p**	**-15.9 l/s/p**
Design ACH	**1.42 ACH**	**Actual ACH**	**0.67 ACH**	**-0.75 ACH**

Figure 98 – 161 Collins Street Operational Ventilation Analysis Results 2022

This result may indicate that even accounting for the lower occupancy rate within the office space the IAQ is substantially better than the design outdoor air flowrates analysis on their own would indicate. This may be due to higher percentage outdoor air being supplied than indicated on system, or the additional air exchange related to the recirculated air included in the ventilation supply but not the above calculations.

The final ventilation adequacy analysis examines air exchange rate in an environment and its role in building resilience and IAQ. We have agreed that CO2 as a proxy for IAQ is generally acceptable, however measurement of CO2 cannot account for other HVAC based mitigation strategies such as filtration, local air cleaners and UVC disinfection strategies which remove or deactivate virus and other particle contaminants from the air but have no effect on CO2. The ASHRAE 62.1 IAQ procedure has adopted the effective air change rate (ACHe) metric to account for these mitigation strategies in IAQ based ventilation design. This ACHe and its calculation use recirculated air volumes and air cleaning efficiencies to approximate relative ventilation supply, and is detailed in the attached Equivalent Outdoor Air Calculator spreadsheet and summarised below.

Name of Space / AHU / Building	Units	161 CS Design
Area	Sq m	3800
Average Ceiling / Breathing Zone Height	m	2
Volume	m3	7600
Total Supply Air	m3/s	9
Total Outdoor Air	m3/s	3
Supply Air ACH	ACH	4.26
Outdoor Air ACH	ACH	1.42
Central AHU Filter MERV Rating	MERV	14
UVC Single Pass Inactivation	%	0.00%
In Room Fan Air Cleaner (HEPA+)	CADR (m3/h)	0
Number of In Room Fan Air Cleaners (HEPA+)	Qty	0
Effective Air Changes Based on Technology		
ACH_OA	ACH	1.42
ACH_MERV filter in AHU	ACH	2.70
ACH_e,c	ACH	0.00
ACH_air cleaner	ACH	0.00
Sub-Total Effective ACH	ACH	4.12
Zone Air Distribution Effectiveness	Ez	1.0
Air Cleaner Position Effectiveness	Ezp_ac	1.0
Total Effective ACH_e		**4.12**

Figure 99 – 161 Collins Street Effective Air Change Results

ACHe is important metric in contamination removal and dilution, vital for good IAQ and the new normal building resilience objective. Based on the results, the design ventilation effective air change rate of 4.1 ACHe is greater than the Category II recommended value of 3 ACHe which is improving building resilience and general IAQ.

Table 28 - 161 Collins Street Design Ventilation Analysis – ACHe

Design Ventilation Analysis - ACHe					
Stage	**ACH_OA**	**ACH_f**	**ACH_e,c**	**ACHe**	**IAQ Category**
Design	1.42	2.7	0	4.12	**II**

This IAQ classification of Category II is more representative of the occupant comfort experienced and premium office feel provided by 161 Collins street. Therefore further investigation of the 'Ventilation Analysis' calculations with recirculation type systems to ensure they are truly representative may be required. What is accurate is that the current design ventilation system can achieve adequate levels of resilient air exchange if required based on the above results.

HVAC Measures

Using the case study 161 Collins Street office building as a blueprint we analyse of the need and suitability of the previously distilled HVAC measures from best practice guidance, looking at their impact on air contaminants and virus transmission risk, while also considering their economic costs, ease of implementation, and impact on building sustainability as presented in the following table.

These distilled HVAC measures are listed below with their main analysis points while full summary details of each is provided previously in this report.

- **Ventilation System & Distribution Effectiveness** –
  - DOAS vs Recirculation ventilation systems
  - Mixing vs Displacement vs Personal ventilation distribution
- **Ventilation Rate & Operation** –
  - ‘Adequate’ ventilation achievement
  - Demand Controlled Ventilation (DCV) operation
  - Purge Ventilation
- **Temperature & Humidity** –
  - Acceptable temperature and humidity ranges
- **Air Filtration & Air Cleaning** –
  - Air filtrations levels
  - Air cleaning technologies
  - Local in-room air cleaners
- **IAQ Monitoring** –
  - CO2 monitoring
  - IAQ measurement
- **Mechanical Ventilation Heat Recovery (MVHR)** –
  - AHU sealing and pressure regimes (fan locations)
  - Thermal Wheel (TW) purge sectors

HVAC Measures	*Description*	*Impact Level*	*ROM* Cost*	*Ease of Implement-ation*	*Impact on Sustainability*
Ventilation System & Distribution Effectiveness	Recirculation Variable Air Volume (VAV) AHUs can be operated in economy / outdoor air only mode (100% fresh air) depending on AHU spare thermal capacity, or full recirculation mode for resilience in external public health emergency. This dual operation is useful so no permanent upgrade recommended however, current AHU air modulation strategy is complex and a review is recommended. Ceiling mixing ventilation system with assumed Ev ~1 therefore ventilation distribution and effectiveness adequate with no changes recommended at this stage.	Low	Minimal capital cost for air modulation strategy review	Easy	Improvement in IAQ and building resilience available from Recirculation VAV AHU Relatively small capital cost and possible operational cost increase
Ventilation Rate & Operation	Recommended that Recirculation Variable Air Volume (VAV) AHUs minimum outside air quantity be increased to 10.5 – 14 l/s/p depending on AHU spare thermal capacity.	High	~$20k Increase in operational cost	Medium	Increase in energy consumption but can be managed in extreme weather conditions. Improvement in IAQ and occupant comfort & productivity
	Implement air purging and run the base-building centralised air system for min. 3 ACH between occupancies periods e.g. nightly.	Med	No capital cost. Increase in operational cost	Easy	Increase in overall energy consumption. Minimal if included in Ventilation Optimised start or free night cooling routine
	Upgrade current AHU air modulation control strategy to ensure recommended outdoor air rates and/or IAQ levels are achieved.	Med	Minimal capital cost. Decrease in operational cost (compared to previous)	Easy	Increased IAQ Relatively small capital cost and operational cost increase
Temperature & Humidity	Measured by the IAQ monitor, temperature and relative humidity were found to be within the recommended comfort and IAQ range, therefore no action recommended.				

HVAC Measures	*Description*	*Impact Level*	*ROM* Cost*	*Ease of Implement-ation*	*Impact on Sustainability*
Air Filtration & Air Cleaning	Current F8/MERV14 maximise filtration efficiency at minimal energy penalty and therefore no upgrade recommended. Note - upgrading F8/MERV14 filters to F9/MERV15/16 possible but would only achieve ~0.1 ACHe additional but at relatively large energy penalty. Filtration alone achieves adequate air cleaning and effective air changes; however UV may be considered for extra resilience but is not recommended in this case In room local air cleaners not recommended in this case as target resilience ACHe achieved by mechanical ventilation supply.				
IAQ Monitoring	Install zonal and meeting room IAQ monitoring and dashboards, including CO2, temperature, relative humidity, and VOCs.	Low	~€20k	Easy	Increased awareness of IAQ and identification of any issues.
MVHR Upgrade	Recirculation AHU using mixing box is the heat recovery in this ventilation system. Return air purposely reintroduced into supply air stream so no leakage consideration. Air filtration and cleaning strategy deemed adequate for this recirculation system therefore no upgrade recommended. May be possible to replace Recirculation Mixing box section with heat recovery element such as thermal wheel but based on this research study is not recommended at this time.				

Results

Based on the review of available design data and documents, the on-site inspection and ventilation adequacy analysis which occurred in May 2022 the above HVAC measures were recommended for the 161 Collins Street, Melbourne, Australia.

161 Collins Street is a recently renovated, leading premium commercial office space and therefore as would be expected there are limited HVAC measures recommended. This case study provides an insight into a recirculation type ventilation system in a commercial building in South Australia with consideration for external public health emergency (wildfire smoke) in the design and operation.

The main, high impact measure recommended is the increase in outdoor air supply rates to align with recommendations identified in this report.

Outdoor air supply rates of 10.5l/s/p to 14 l/s/p should be sufficient for the desired Category II environment taking into account the relatively low recorded VOCs values. The higher 14 l/s/p air flow rates should be focused on AHUs serving larger higher occupancy office areas such as AHU P4 & AHU P6. These higher outdoor air rates can be achieved by reducing the mixing damper recirculation percentage and maintaining the required minimum VSD flowrate and duct pressure. The AHU air modulation control strategies should be updated to reflect this. Allowances may be made in temperature extremes to increase recirculation rates to accommodate the limited thermal capacities on some AHUs.

AHU ventilation operation procedures at the same time can be updated to include the night purging measure to improve IAQ and resilience by boosting absolute contamination removal between occupancy periods. This can be implemented into the building BMS operational schedule relatively easily with almost no capital cost and minimal increase in operational costs and energy consumption.

The installation of IAQ monitors measuring CO2 and VOCs is recommended to increase awareness of IAQ across the office space. Established and calibrated sensors may be used for updated demand controlled ventilation strategies in the future if desired.

It is worth noting that while an upgrade of the existing F8/MERV14 filters is possible, in this case it is not recommended as the marginal increase in filtration efficiency in ACHe of ~0.1 is not necessary and would result in an unproportional increase in energy demand. An onsite photo of the existing bag type F8/MERV14 filters in a selected AHU is shown below.

At the time of writing of this report no recommended measures were implemented and therefore cannot be directly analysed. However, taking into account the recent post pandemic changes in occupancy rates and greater than required effective air change rate capability within 161 Collins Street the classification of the indoor air quality as Category II is merited. This can be further enhanced by implementing the above recommended HVAC measures.

As concluded above, further investigation of the 'Ventilation Analysis' calculations with recirculation type systems to ensure they are truly representative of IAQ conditions experienced by occupants may be required

Figure 100 - 161 Collins Street AHU Filters

Case Study 4 - Commercial Office & Retail, Sydney - Australia

20 Martin Place is located on a busy plaza in the heart of Sydney's central business district, a Warm Humid (3A) climate zone of Australia. The 21-story commercial building was originally built in 1974, but a full redevelopment of this existing antiquated building was completed in 2015. During this refurbishment all building services and facades were replaced which helped the building to achieve the 5 Star NABERS Energy rating it holds today. The 20-floor commercial office space has a nominal building area of approx. 19,000 m^2 NIA not including the lower-level retail space.

Figure 101 - 20 Martin Place, Sydney, Australia

HVAC System Summary

A summary of the HVAC system with a focus on the building ventilation system is provided in table 29 below. The building has most recently undergone extensive refurbishment in 2015 which included a full redevelopment of the HVAC system.

Table 29 - 20 Martin Place HVAC Summary Table

Item	Description	Notes
Plant	Centralised Air Handling Units	4 no. AHUs located on L21 (roof) serving office floors L2 to L20
Design IAQ Target	Category II	Premium Commercial Office
Type	Dedicated Outdoor Air Supply (DOAS)	VAV boxes centre zone CAV & Active chilled beams perimeter zone
Distribution	High Level Supply & Return Mixing	Effectiveness (Ev) of 1 ??
Filtration	G4 + F6 grade	Panel + bag filter type
Outside Air Provision	18.75 L/s/person	Design occupancy density: 10 m^2/person
Outside Air as % of Supply Air	100%	N/A
Approx. Total Air Change Rate	~3 ACH	N/A
Outside Air Modulation	Centre zone only	To achieve VAV temperature control
Economy Cycle / Heat Recovery	No	N/A
Internal Temperature	24°C (Summer) 21°C (Winter)	N/A
Humidity	40-70%	No direct RH control provided, uses cooling coil performance
Normal Hours of Base-Building Air-Conditioning Plant Operation	7am to 6pm Weekdays	N/A
Centralised Plant Cooling and Heating Capacity	2150 kW (Cooling) 1300 kW (Heating)	1 no. 350 kW variable speed chiller and 2 no. 900 kW chillers 2 no. 650 kW boilers

Four no. centralised DOAS AHUs located on roof supply 100% outside air to nineteen office floors via risers distributed throughout the floor. 2 no. pressure controlled variable air volume AHUs provide varying high levels of supply air to centre zones via VAV boxes, and 2 no. constant air volume AHUs provide constant (during occupied hours) supply air to perimeter and meeting zones through active chilled beams. Each AHU includes a 2 stage G4 + F6 filters section, coiling coil, heating coil and, variable or constant speed fan for supply air, operated with a supply air temperature and static pressure setpoint control.

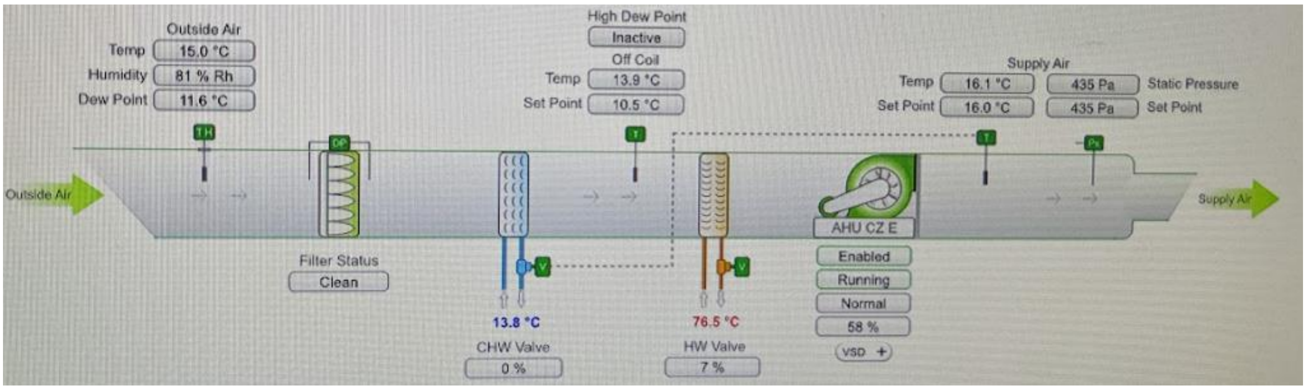


Figure 102 - 20 Martin Place AHU BMS Graphic

Air relieves to outside via separate relief air / smoke exhaust fan risers, with no mechanical heat recovery included. Refer to air schematic below for additional information. AHUs incorporate chilled and heating hot water coils with chilled and heating hot water supplied from the central thermal plant. There are tenant supplementary air systems such as tenant 100% outside air which is currently underutilised, and tenant general exhaust systems available for connections on the office floors.

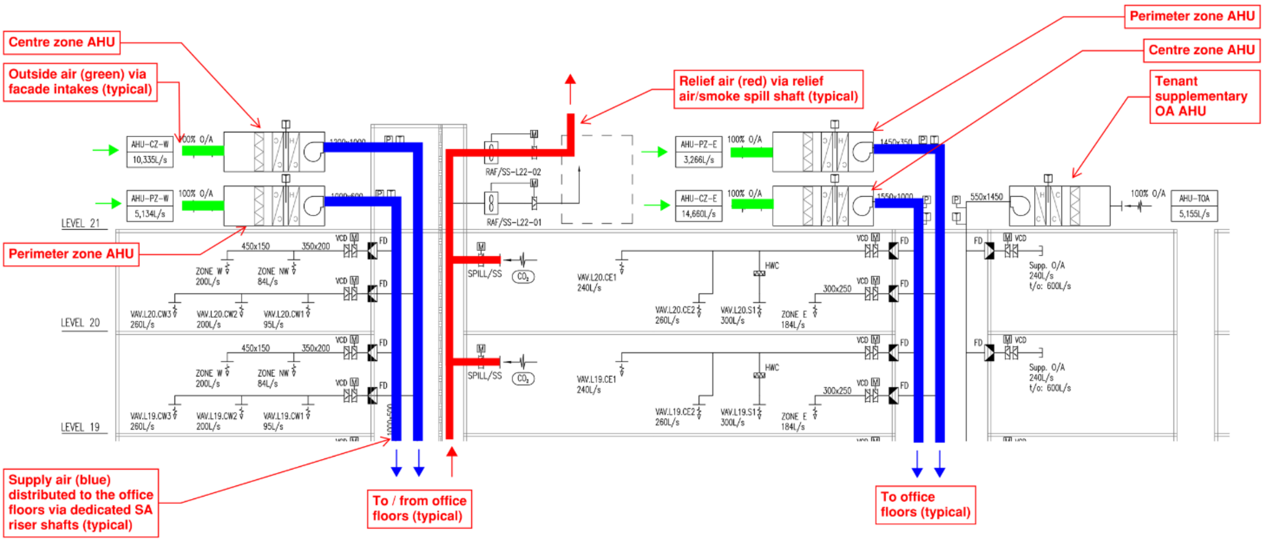


Figure 103 – 20 Martin Place Air Layout

The centre zone supply ventilation is distributed from high level ceiling mounted small swirl grilles in co-ordinated locations. Active chilled beams with linear diffusers in perimeter zones and meeting room areas provide ventilation and air conditioning. Exhaust air is extracted from eggcrate plenum return grilles in the ceiling.

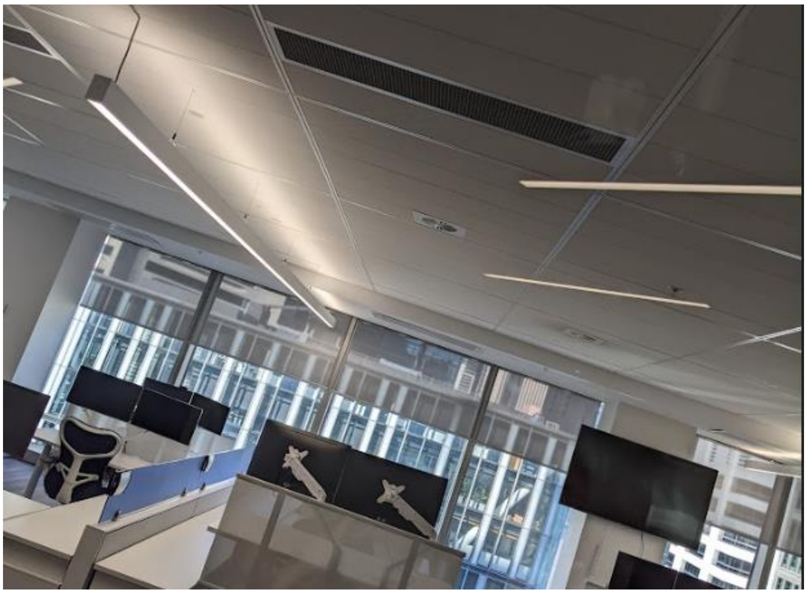


Figure 104 - 20 Martin Place Office Ceiling Supply & Extract grilles

The overall supply air system serving the office floors is a low-temperature VAV system for centre zones, and CAV active chilled beams for the perimeter zones. Each chilled beam / VAV box serves no more than 85 sqm (perimeter zone) and 120 sqm (internal zone) respectively. Exhaust air is extracted through a dedicated fan unit with no air recirculation or heat recovery. There are currently no air cleaning devices utilised within the AHU or office zones.

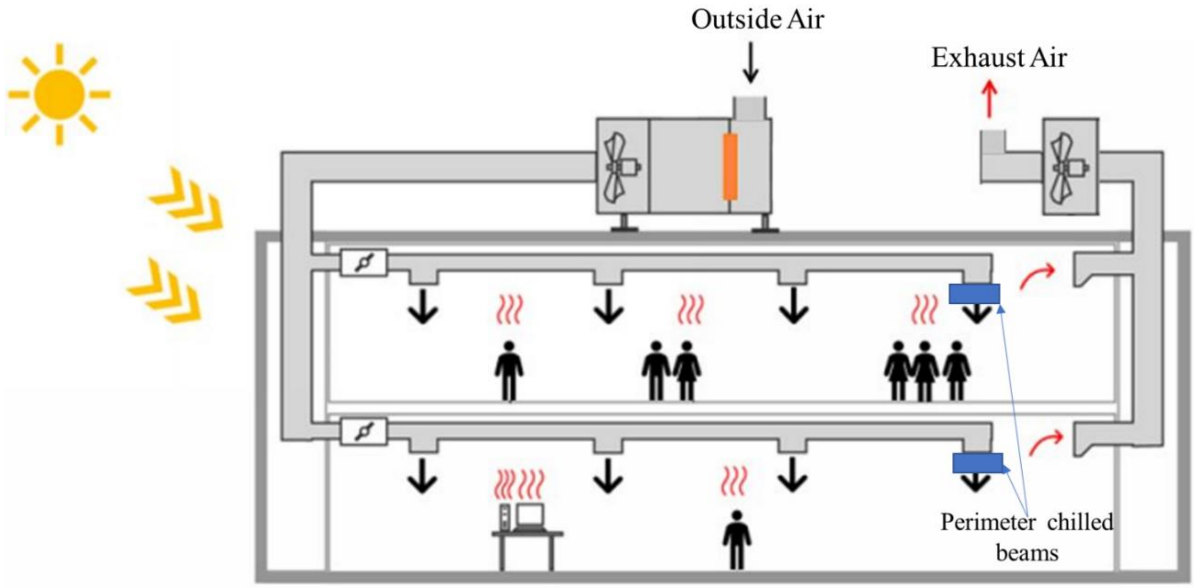


Figure 105 – 20 Martin Place HVAC Schematic

Ventilation Analysis

The 20 Martin Place building is majority a premium commercial office space aiming to achieve IAQ II category or better in design. The fully refurbished building has current 5 Star NABERS Energy rating, and is currently pursuing WELL Health and Safety rating. Clearly designed and refurbished to a high specification, there was however no confirmation that very low polluting materials were used and therefore a typical low polluting environment (BS EN16798) is assumed, with the associated recommended ventilation rates provided below for reference.

Table 30 - Typical Low Polluting Environment (BS EN16798) Recommended Ventilation Rates

Category	Rec. Ventilation Rate	
	l/s/p	l/s/m2
I	$\frac{20}{Ev}$	$\frac{2}{Ev}$
II	$\frac{14}{Ev}$	$\frac{1.4}{Ev}$
III	$\frac{8}{Ev}$	$\frac{0.8}{Ev}$
IV	$\frac{5.5}{Ev}$	$\frac{0.55}{Ev}$

Focusing on the commercial office zones which are mechanically ventilated the design allowed for 18.75 l/s/p distributed by high level supply mixing ventilation with Ev ~1. With an occupancy density of ~10m2/person over 19,000 m2 mechically ventilated floor area provides an occupancy of 1,900 people requiring 35.6 m3/s mechanical air supply over the 19 floors .

This resulted in approximately 1.9 l/s/m2 ventilation rate which is IAQ Category II and 18.75 l/s/p is also Category II, but both very close to Category I class.

Table 31 – 20 Martin Place Design Ventilation Analysis - Flowrates

Design Ventilation Analysis - Flowrates				
Stage	**Vent. Rate L/s/p**	**Vent. Rate L/s/m2**	**Ev**	**IAQ Category**
Design - Commercial Office	18.75	1.9	1	**II**

For further enhanced ventilation and IAQ analysis, expected zone CO2 levels can be calculated using the presented adapted Method 2 (BS EN 16798-1) limit values for substance concentration formula. Using this formula the CO2 level expected for the specified design ventilation rate is estimated, and may be compared against the table of classified absolute indoor CO2 levels to categorise the design IAQ level. Note unit conversions are required for this formula calculation, and more details on these are provided in the IAQ calculator tool with this research and an extract included below.

Design Data	Ventilation Rate	Qh	18.75 l/s/p	0.01875 m3/s/p	Design Ventilation rate per person
	Ventilation Effectiveness	Ev	1		Assumed for High level low temp (< 8 degC dT) mixing ventilation
	Outdoor air CO2 levels	Co	400 ppm	720.00 mg/m3	Taken from outside CO2 sensor or sourced from local weather station
	Occupant Metabolic Rate		1.25 Met		Allowing for an average office metabolic rate of 1.25 (70W/m2)
	CO2 generation rate	Gh	0.005 L/s/p	9.16 mg/(s.person)	Calculated per CIBSE Guide B2 with PV=nRT (at 21°C, 1 atm)
	CO2 molecular weight		44.01 g/mol		Molecular weight of CO2
	Estimated Zone CO2 level	**Chi**	**671 ppm**	1208.58 mg/m3	Concentration (ppm) = 24.45 * mg/m3 / molecular weight

Based on the design data and calculation, an estimated design CO2 concentration of ~671ppm is expected which is well under the threshold of an IAQ Category I classification.

Table 32 – 20 Martin Place Design Ventilation Analysis – CO2

Design Ventilation Analysis - CO2						
Stage	**Vent. Rate (Qh) l/s/p**	**CO2 Gen. Rate (Gh) l/s/p**	**Outdoor CO2 (Cho) ppm**	**Ev**	**Est. Design CO2 (Chi) ppm**	**IAQ Category**
Design - Office	18.75	0.005	400	1	**671**	**I**

Resulting zone CO2 values will not be exact due to variances in occupant activity and outdoor CO2 levels however, operational measure values can be compared against a range (i.e. ~670 ± 50ppm) to help identify if there are any significant variances between design and operation expectations. Note design stage calculations may use design data in per person values, however for operational stage analysis absolute values should be used as below.

Operational stage measured CO2 data is required to compare to design data and this was achieved in the 20 Martin Place case study using the AIRTHINGS View Plus; a class-leading air-monitoring device which was used to record measurements of CO2 and VOCs in selected locations in the educational facility. Due to issues with Wi-Fi connection and security, the AIRTHINGS continuous monitoring platform was not available.

Figure 106 – 20 Martin Place AIRTHINGS Air Quality Sensor Measurement

Using this available point in time measurement, taken on Wednesday 25th May 2022 in 20 Martin Place level 20 office area, the measured CO2 value was ~608ppm and VOCs was 181 ug/m3 respectively during this occupancy period, both below the recommended limits.

This 610 ppm measured operational CO2 value meets Category I IAQ class threshold, and is ~60 ppm less than the calculated design CO2 value of ~670 ppm, which is just over the limit of the expected range (min 620ppm). Again this lower value is expected also as due to the tenants current Work From Home (WFH) practices and COVID measures the mechanically ventilated zone was only partly occupied compared to design levels.

Investigating this further and allowing for the lower occupancy rate of about half with 45 people on the floor, and as a result of the ventilation modulation strategy lower ventilation rate with the VSD recorded at 58% (~1 m3/s for the floor) we can calculate the IAQ based expected ventilation rate using the BS EN 16798 Method 2 formula.

Taking this measured CO2 value of 610ppm as in the zone indoor concentration and using the BS EN 16798 Method 2 formula to calculate the corresponding ventilation rate, the result is 1.09 m3/s, a marginal improvement of 6% over operational outdoor ventilation rate as detailed below which suggest the system is operating well as designed.

Operational measured space CO2 (ppm)	**610 ppm**
Operational space ventilation flowrate (m3/s)	**1.03313 m3/s**

Space Data	Net Internal Area (NIA)	A	950 m2		Building floor NIA
	Ceiling/ Breathing zone height	H	2 m		Space floor to ceiling height or breathing zone height - 2m (BS EN 1697[illegible]
	Number of Occupants - people	n	45		Numbe rof people occupaying the space
	Volume	V	1900 m3		
Air Data	Outdoor air CO2 levels	Cho	400 ppm	720.00 mg/m3	Taken from outside CO2 sensor or sourced from local weather station
	Indoor Space CO2 levels	Chi	610 ppm	1098.01 mg/m3	Measured space return air CO2 levels
	Ventilation Effectiveness	Ev	1		Assumed for High level low temp (< 8 degC dT) mixing ventilation
	Actual Air supply rate	Q	1.033125 m3/s	1033.1 L/s	Actual measured supply airflow to space
	Occupant Metabolic Rate		1.25 Met		Allowing for an average office metabolic rate of 1.25 (70W/m2)
	CO2 generation rate	Gh	0.005 L/s/p	9.16 mg/s/p	Calculated per CIBSE Guide B2 with PV=nRT (at 21ºC, 1 atm)
	CO2 molecular weight		44.01 g/mol		

Design		**Operational**		**Difference**
CO2 Calc.	**670.00 ppm**	**CO2 Meas.**	**610.00 ppm**	**-60.00 ppm**
Q Design	**1.78 m3/s**	**Q Op.**	**1.03 m3/s**	**-42.00 %**
		Q Calc.	**1.09 m3/s**	**6 %**
Ev design	**1.0**	**Ev Calc**	**1.1**	**0.1**
q_design	**39.6 l/s/p**	**q_actual**	**24.2 l/s/p**	**-15.3 l/s/p**
Design ACH	**3.38 ACH**	**Actual ACH**	**2.07 ACH**	**-1.31 ACH**

Figure 107 – 20 Martin Place Operational Ventilation Analysis Results 2022

The final ventilation adequacy analysis examines air exchange rate in an environment and its role in building resilience and IAQ. We have agreed that CO2 as a proxy for IAQ is generally acceptable, however measurement of CO2 cannot account for other HVAC based mitigation strategies such as filtration, local air cleaners and UVC disinfection strategies which remove or deactivate virus and other particle contaminants from the air but have no effect on CO2. The ASHRAE 62.1 IAQ procedure has adopted the effective air change rate (ACHe) metric to account for these mitigation strategies in IAQ based ventilation design. This ACHe and its calculation use recirculated air volumes and air cleaning efficiencies to approximate relative ventilation supply, and is detailed in the attached Equivalent Outdoor Air Calculator spreadsheet and summarised below.

Name of Space / AHU / Building	Units	20 MP Design
Area	Sq m	950
Average Ceiling / Breathing Zone Height	m	2
Volume	m3	1900
Total Supply Air	m3/s	1.78125
Total Outdoor Air	m3/s	1.78125
Supply Air ACH	ACH	3.38
Outdoor Air ACH	ACH	3.38
Central AHU Filter MERV Rating	MERV	12
UVC Single Pass Inactivation	%	0.00%
In Room Fan Air Cleaner (HEPA+)	CADR (m3/h)	0
Number of In Room Fan Air Cleaners (HEPA+)	Qty	0
Effective Air Changes Based on Technology		
ACH_OA	ACH	3.38
ACH_MERV filter in AHU	ACH	0.00
ACH_e,c	ACH	0.00
ACH_air cleaner	ACH	0.00
Sub-Total Effective ACH	ACH	3.38
Zone Air Distribution Effectiveness	Ez	1.0
Air Cleaner Position Effectiveness	Ezp_ac	1.0
Total Effective ACH_e		**3.38**

Figure 108 – 20 Market Place Effective Air Change Results

ACHe is important metric in contamination removal and dilution, vital for good IAQ and the new normal building resilience objective. Based on the results, the design ventilation effective air change rate of 3.4 ACHe is greater than the Category II recommended value of 3 ACHe which is improving building resilience and general IAQ.

Table 33 – 20 Martin Place Design Ventilation Analysis – ACHe

Design Ventilation Analysis - ACHe					
Stage	**ACH_OA**	**ACH_f**	**ACH_e,c**	**ACHe**	**IAQ Category**
Design	3.38	0	0	3.38	**II**

The current design ventilation system can achieve adequate levels of resilient air exchange if required however, the ventilation strategy to prevent external contamination introduction into the building during an external public health emergency such as a wildfire is not clear. This is explored further in the applicable HVAC measures for 20 Martin Place.

HVAC Measures

Using the case study 20 Martin Place office building as a blueprint we analyse of the need and suitability of the previously distilled HVAC measures from best practice guidance, looking at their impact on air contaminants and virus transmission risk, while also considering their economic costs, ease of implementation, and impact on building sustainability as presented in the following table.

These distilled HVAC measures are listed below with their main analysis points while full summary details of each is provided previously in this report.

- **Ventilation System & Distribution Effectiveness** –
  - DOAS vs Recirculation ventilation systems
  - Mixing vs Displacement vs Personal ventilation distribution
- **Ventilation Rate & Operation** –
  - 'Adequate' ventilation achievement
  - Demand Controlled Ventilation (DCV) operation
  - Purge Ventilation
- **Temperature & Humidity** –
  - Acceptable temperature and humidity ranges
- **Air Filtration & Air Cleaning** –
  - Air filtrations levels
  - Air cleaning technologies
  - Local in-room air cleaners
- **IAQ Monitoring** –
  - CO2 monitoring
  - IAQ measurement
- **Mechanical Ventilation Heat Recovery (MVHR)** –
  - AHU sealing and pressure regimes (fan locations)
  - Thermal Wheel (TW) purge sectors

HVAC Measures	*Description*	*Impact Level*	*ROM* Cost*	*Ease of Implement-ation*	*Impact on Sustainability*
Ventilation System & Distribution Effectiveness	Unit is 100% Outside Air, no remediation recommended Ceiling mixing ventilation system with assumed Ev ~1 therefore ventilation distribution and effectiveness adequate with no changes recommended at this stage.				
Ventilation Rate & Operation	The 20 Martin Place design ventilation rate is approx. 18.75 l/s/p and 1.9 l/s/m2 which is IAQ Category II environment, achieving design expectations for IAQ. The operational ventilation rate is also achieving expectations for IAQ. Naturally ventilated spaces achieve cross ventilation. Implement air purging and run the base-building centralised air system for min. 3 ACH between occupancies periods e.g. nightly. Supplied air is varied through VAVs based on temperature control which appears to be working effectively for IAQ based on the ventilation analysis. Consideration for Demand Controlled Ventilation strategy to maintain IAQ levels may increase building sustainability and resilience	Med	No capital cost. Increase in operational cost.	Easy	Increase in overall energy consumption. Minimal if included in Ventilation Optimised start or free night cooling routine
Temperature & Humidity	Measured by the IAQ monitor, temperature and relative humidity were found to be within the recommended comfort and IAQ range for the given environment, therefore no action recommended.				

HVAC Measures	*Description*	*Impact Level*	*ROM* Cost*	*Ease of Implement-ation*	*Impact on Sustainability*
Air Filtration & Air Cleaning	Current G4 and F6/MERV12 2-stage filter system appears suitable for current ventilation system and operation. Recommended to investigate possibility upgrading AHU and filter sections to accept HEPA or highest possible grade filters for temporary installation in case of an external public health emergency (e.g. wildfire smoke) to maintain building ventilation and improve resilience Design ventilation alone achieves adequate air cleaning and effective air changes so no additional air cleaning recommended. In room local air cleaners not required but may provide additional resilience in case of external public health emergency or ventilation issue.	Low	TBC	Hard	Temporarily increase energy consumption in emergency circumstances, Improve building resilience
IAQ Monitoring	Current temperature, RH and return air CO2 sensors BMS based only. Recommended to install zonal and meeting room IAQ monitoring and dashboards, including VOCs.	Low	~€20k	Easy	Increased awareness of IAQ and identification of any issues.
MVHR Upgrade	No MVHR onsite with separate supply and extract systems. Recommended to investigate feasibility of a run-around coil or similar mechanical heat recovery system to maximise energy efficiency and reduce ventilation heating and cooling demand	Low	TBC		Feasibility study require but proposed MVHR would increase environmental sustainability and decrease operation costs with no adverse effect on IAQ

Results

Based on the review of available design data and documents, the on-site inspection and ventilation adequacy analysis which occurred in May 2022 the above HVAC measures were recommended for the 20 Martin Place, Sydney, Australia.

20 Martin Place is a recently fully refurbished, leading premium commercial office space and therefore as would be expected there are limited HVAC measures recommended. This case study provides an insight into a DOAS type ventilation system in a commercial building in South-East Australia taking consideration for external public health emergency (wildfire smoke) in the design and operation. Based on the analysis some HVAC measures were recommended, the highest impact of which is ventilation operation – night purging measure to improve IAQ and resilience by boosting absolute contamination removal between occupancy periods. This can be implemented into the building BMS operational schedule relatively easily with minimal capital cost and increase in operational costs and energy consumption.

The most impactful measure on building resilience is the recommendation to investigate the possibility of upgrading the AHU and filter sections to accept HEPA or highest possible grade filters for temporary installation in case of an external public health emergency (e.g. wildfire smoke). The current 2 stage filters are suitable for typical operation however, it is noted that the filter housing and AHU fans may be able to accommodate adapted HEPA filters which for the DOAS system which would help achieve adequate ventilation and IAQ during wildfire events that effect Sydney with external smoke particles and their attached odorous gases. If HEPA filters installation cannot be allowed for, F9/MERV16 is recommended with filters available to be installed onsite at all times in case of a wildfire warning.

Filtration Standard Used				Estimated Smoke Filtration Efficiency (%)
AS1324.1 (2001)	EN779 (2012)	ASHRAE 52.2 (2017)	EN1822 (2009)	
F4/F5	G4	MERV7-9	N/A	<20%
F5	M5	MERV10	N/A	20-35%
F6	M6	MERV11-12	N/A	35-50%
F7	F7	MERV13	N/A	50-65%
F8	F8	MERV14	N/A	65-80%
F9	F9	MERV15-16	N/A	80-90%
N/A	N/A	N/A	E11	95-98%
N/A	N/A	N/A	H14	99%+

Figure 109 -Filter Standards Estimated Fire Smoke Removal Efficiencies – Airpure Australia

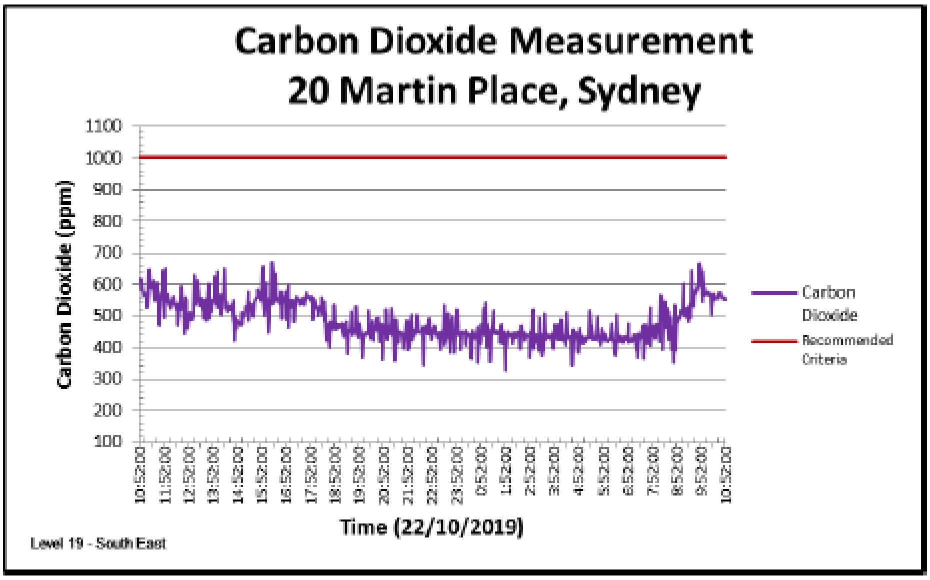
Smoke is one of the most difficult particles sizes to catch as it is 0.3 – 0.5 microns in size and generally fits within the PM1 - PM2.5 category. If air filters are not of a high enough efficiency to remove smoke particles, this will lead to a significant amount of smoke being noticed inside buildings. As highlighted in figure 109 above from Airpure Australia, smoke with its smaller particle size has filtration efficiencies of filter groups different to that of typical or virus contaminants as detailed earlier in this report. In addition to smoke, bushfires also produce odorous gases such as oxides of nitrogen (NOx) and volatile organic compounds (VOC). These odorous gases are chemically bound to smoke particles, which means that they can be removed along with the smoke with effective particulate filtration. The recommended HEPA of F9/MERV16 will capture the majority of the smoke particles and the odour attached to the smoke particles. The addition of the gaseous filters placed after the particulate air filters should also be considered as these will help adsorb the remaining odorous gases.

Building environmental sustainability and energy efficiency may be improved with the implementation of a run-around coil or similar MVHR system if viable and therefore a feasibility study investigating this is recommended. A run around coil system could recover heat or coolth from the current separate supply and exhaust systems without any possible cross contamination concerns, but typically at lower efficiencies than other heat recovery options. The FläktGroup ECONET® premium run around coil system may achieve higher efficiencies if required.

Figure 110 - FläktGroup ECONET® premium run around coil system

For indoor air quality the installation of zonal IAQ monitors and visible dashboards (beyond the BMS) to occupants is recommended to increase awareness of IAQ across the office space. Established and calibrated CO2 sensors may be used for updated demand controlled ventilation strategies in the future if desired.

Overall, the IAQ in 20 Martin Place is of a high standard and deserving of its Category II classification environment, and has been for some time. According to a pre-pandemic IAQ audit report in October 2019 provided by the building's facilities management, airborne respirable dust and microbiology, carbon dioxide, carbon monoxide, ozone, formaldehyde and hydrocarbon levels were all measured to be acceptable and well within the recommended limits. This analysis along with that audit has validated the effectiveness of the 20 Martin Place ventilation system in maintaining high IAQ levels.



Acceptable carbon dioxide concentration between 400ppm – 650 ppm during working hours (i.e. air conditioning system operating).

Figure 111 – 20 Martin Place Pre-pandemic IAQ Audit CO2 levels graph

Case Study 5 - Commercial Office, Brisbane - Australia

70 Eagle Street is located in the highly desirable 'Golden Triangle' business district of Brisbane, a city in Eastern Australia covered by a Hot Humid (2A) climate zone. Constructed in 2009 as part of the Central Plaza development, the 14-storey building has 13 floors of office space with retail on the ground level and total NLA floor area of approximately 11,000m^2.

The building has not undergone any major refurbishment or modification works since it was completed.

Figure 112 - 70 Eagle Street, Brisbane, Australia

HVAC System Summary

A summary of the HVAC system with a focus on the building ventilation system is provided in table 34 below.

Table 34 - 70 Eagle Street HVAC Summary Table

Item	Description	Notes
Plant	Centralised Air Handling Units	4 no. AHUs located in L14 plant room serving office floors L1 to L13
Design IAQ Target	Category II	Premium Commercial Office
Type	Recirculation Variable Air Volume (low temperature)	VAV boxes located on office floors
Distribution	High Level Supply & Return Mixing	Effectiveness (Ev) of 1 ??
Filtration	F6 grade	Bag filter type
Outside Air Provision	8 L/s/person	Design occupancy density: 10 m^2 per person
Outside Air as % of Supply Air	~ 15%	AHU outside air percentages vary between 7% to 19%
Approx. Total Air Change Rate	~ 7 ACH	N/A
Outside Air Modulation	Demand control	CO2 and VOC sensors in AHU return air plenum
Economy Cycle / Heat Recovery	Yes	Enabled when outside ambient temperature and enthalpy are below that of the return air
Internal Temperature	23°C	N/A
Humidity	Not controlled	N/A
Normal Hours of Base-Building Air-Conditioning Plant Operation	6:30 –18:00 Weekdays (Summer) 7:00 – 18:00 Weekdays (Winter)	Optimum start: ~30 minutes earlier if required
Centralised Plant Cooling and Heating Capacity	1,500 kW (Cooling)	3 no. 500 kW water-cooled chillers Heating via on-floor perimeter electric duct heaters

The building in its current fit out was completed in 2008 with a single tenant and no major refurbishments or changes to air conditioning systems have been undertaken since.

Four centralised single-zone VAV AHUs located in the level 14 plant room supply air to 13 office floors via two risers. AHU-1 also serves the ground floor lift lobby. Air returns to the AHUs via two blockwork return air risers with subducts as shown on the air layout drawing below.

AHUs incorporate chilled water coils with chilled water supplied from three water-cooled chillers. Heating is provided only via electric duct heaters within perimeter zone VAV boxes.

Façade louvres are provided on each floor for connection of tenant supplementary air systems, with some floors connecting packaged air conditioning units for additional ventilation and thermal capacity.

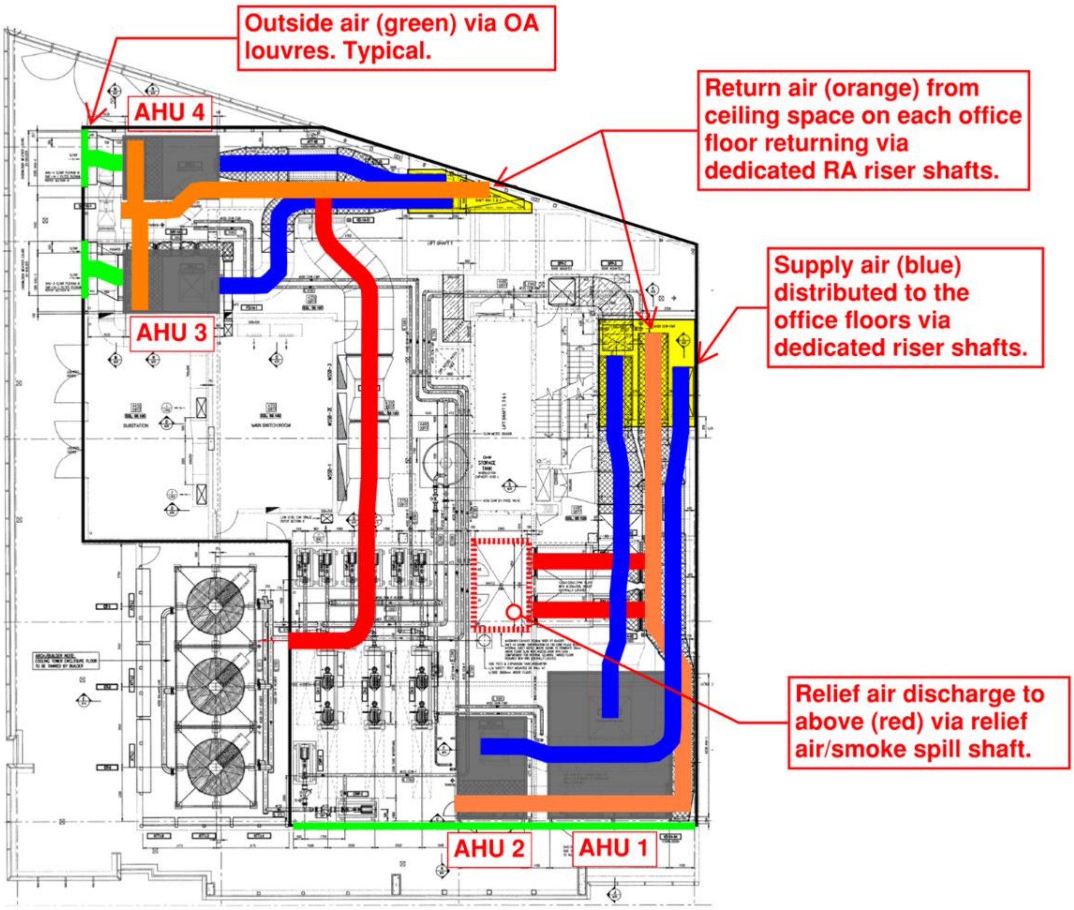


Figure 113 – 70 Eagle Street Air Layout

Supply air consists of a mix of filtered outside air and return air. Outside air quantity is currently modulated using mixing damper based on outside ambient temperature and enthalpy, and supply air is modulated via AHU fan VSD and VAV boxes based on supply temperature control and CO2 level demand control (although CO2 modulation control was disabled at the time of visit due to recommended guidance) with a minimum setting of 30% and 180pa AHU fan pressure. The AHUs are capable of economy cycle, and full air recirculation during occasions of external contamination events such as wildfires.

The supply air system serving the office floors is a low-temperature VAV system with each VAV box serving no more than 85 sqm (perimeter zone) and 120 sqm (internal zone) respectively. Supply ventilation is distributed from high level via ceiling mounted swirl grilles in co-ordinated locations, and return air extracted from eggcrate plenum return grilles in the ceiling. There are currently no air cleaning devices utilised within the AHU or commercial space.

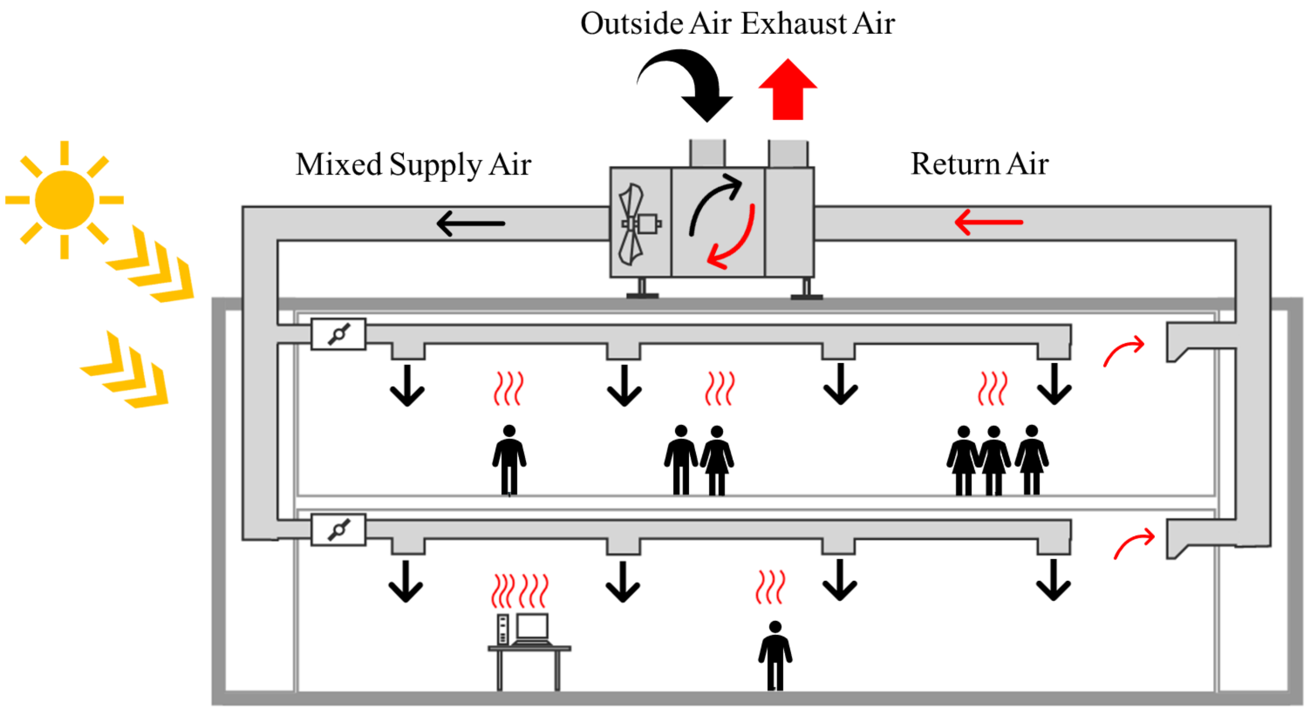


Figure 114 – 70 Eagle Street HVAC Schematic

Ventilation Analysis

The 70 Eagle Street building is mostly a premium commercial office space aiming to achieve IAQ II category or better in design. The building and ventilation systems appear to be well maintained, clean and in good condition, and clearly designed and built to a high specification, but no confirmation that very low polluting materials were used in construction was available, therefore a typical low polluting environment (BS EN16798) is assumed, with the associated recommended ventilation rates provided below for reference.

Table 35 - Typical Low Polluting Environment (BS EN16798) Recommended Ventilation Rates

Category	Rec. Ventilation Rate	
	l/s/p	l/s/m2
I	$\frac{20}{Ev}$	$\frac{2}{Ev}$
II	$\frac{14}{Ev}$	$\frac{1.4}{Ev}$
III	$\frac{8}{Ev}$	$\frac{0.8}{Ev}$
IV	$\frac{5.5}{Ev}$	$\frac{0.55}{Ev}$

Focusing on the commercial office zones which are mechanically ventilated the design allowed for 8 l/s/p distributed by high level supply and return mixing ventilation with Ev ~1. With an occupancy density of ~10m2/person over 11,000m2 mechically ventilated floor area provides an occupancy of 1,100 people requiring 8.8 m3/s outdoor air supply over the 13 floors, not inlcuding recirculated air.
This resulted in approximately 0.8 l/s/m2 ventilation rate which is IAQ Category III and 8 l/s/p is also Category III.

Table 36 – 70 Eagle Street Design Ventilation Analysis - Flowrates

Design Ventilation Analysis - Flowrates				
Stage	**Vent. Rate L/s/p**	**Vent. Rate L/s/m2**	**Ev**	**IAQ Category**
Design - Commercial Office	8	0.8	1	**III**

For further enhanced ventilation and IAQ analysis, expected zone CO2 levels can be calculated using the presented adapted Method 2 (BS EN 16798-1) limit values for substance concentration formula. Using this formula the CO2 level expected for the specified design ventilation rate is estimated, and may be compared against the table of classified absolute indoor CO2 levels to categorise the design IAQ level. Note unit conversions are required for this formula calculation, and more details on these are provided in the IAQ calculator tool with this research and an extract included below.

Design Data	Ventilation Rate	Qh	8 l/s/p	0.008 m3/s/p	Design Ventilation rate per person
	Ventilation Effectiveness	Ev	1 _		Assumed for High level low temp (< 8 degC dT) mixing ventilation
	Outdoor air CO2 levels	Co	400 ppm	720.00 mg/m3	Taken from outside CO2 sensor or sourced from local weather station
	Occupant Metabolic Rate		1.25 Met		Allowing for an average office metabolic rate of 1.25 (70W/m2)
	CO2 generation rate	Gh	0.005 L/s/p	9.16 mg/(s.person)	Calculated per CIBSE Guide B2 with PV=nRT (at 21°C, 1 atm)
	CO2 molecular weight		44.01 g/mol		Molecular weight of CO2
	Estimated Zone CO2 level	**Chi**	**1036 ppm**	1865.11 mg/m3	Concentration (ppm) = 24.45 * mg/m3 / molecular weight

Based on the design data and calculation, an estimated design CO2 concentration of ~1035ppm is expected which is just over the threshold of an IAQ Category III classification.

Table 37 – 70 Eagle Street Design Ventilation Analysis – CO2

Design Ventilation Analysis - CO2						
Stage	**Vent. Rate (Qh) l/s/p**	**CO2 Gen. Rate (Gh) l/s/p**	**Outdoor CO2 (Cho) ppm**	**Ev**	**Est. Design CO2 (Chi) ppm**	**IAQ Category**
Design - Office	8	0.005	400	1	**1036**	**III**

Resulting zone CO2 values will not be exact due to variances in occupant activity and outdoor CO2 levels however, operational measure values can be compared against a range (i.e. ~1035 ± 50ppm) to help identify if there are any significant variances between design and operation expectations. Note design stage calculations may use design data in per person values, however for operational stage analysis absolute values should be used as below.

Operational stage measured CO2 data is required to compare to design data and this was achieved in the 70 Eagle Street case study using the AIRTHINGS View Plus; a class-leading air-monitoring device which was used to record measurements of CO2 and VOCs in selected locations in the educational facility. Due to issues with Wi-Fi connection and security, the AIRTHINGS continuous monitoring platform was not available.

Figure 115 – 70 Eagle Street AIRTHINGS Air Quality Sensor Measurement

Using this available point in time measurement, taken on Wednesday 1st June 2022 in 70 Eagle Street level 2 office area, the measured CO2 value was ~490ppm and VOCs was 60 ug/m3 respectively during this period, both below the recommended limits.

This 490 ppm measured operational CO2 value is essentially similar to outside air values allowing for some measurement inaccuracy and residual concentrations of an internal environment. Of course this is significantly less than the expected range (min 985ppm) but in this case is expected as due to the tenants current Work From Home (WFH) practices and COVID measures the area was sparsely occupied other than transient staff. This makes the operational ventilation analysis redundant. In addition, the usual CO2 based demand controlled ventilation that would scale back outdoor air ventilation based on CO2 levels (connected to occupancy) was disabled as per the COVID related guidance at the time, therefore outdoor air ventilation rate remained high even with almost zero occupancy. The total ventilation supply air flowrate is also high during the operating period. The final ventilation adequacy analysis examines air exchange rate in an environment and its role in building resilience and IAQ. We have agreed that CO2 as a proxy for IAQ is generally acceptable, however measurement of CO2 cannot account for other HVAC based mitigation strategies such as filtration, local air cleaners and UVC disinfection strategies which remove or deactivate virus and other particle contaminants from the air but have no effect on CO2.

The ASHRAE 62.1 IAQ procedure has adopted the effective air change rate (ACHe) metric to account for these mitigation strategies in IAQ based ventilation design. This ACHe and its calculation use recirculated air volumes and air cleaning efficiencies to approximate relative ventilation supply, and is detailed in the attached Equivalent Outdoor Air Calculator spreadsheet and summarised below.

Name of Space / AHU / Building	Units	70 ES Design
Area	Sq m	850
Average Ceiling / Breathing Zone Height	m	2
Volume	m3	1700
Total Supply Air	m3/s	4.5
Total Outdoor Air	m3/s	0.677
Supply Air ACH	ACH	9.53
Outdoor Air ACH	ACH	1.43
Central AHU Filter MERV Rating	MERV	12
UVC Single Pass Inactivation	%	0.00%
In Room Fan Air Cleaner (HEPA+)	CADR (m3/h)	0
Number of In Room Fan Air Cleaners (HEPA+)	Qty	0
Effective Air Changes Based on Technology		
ACH_OA	ACH	1.43
ACH_MERV filter in AHU	ACH	6.75
ACH_e,c	ACH	0.00
ACH_air cleaner	ACH	0.00
Sub-Total Effective ACH	ACH	8.18
Zone Air Distribution Effectiveness	Ez	1.0
Air Cleaner Position Effectiveness	Ezp_ac	1.0
Total Effective ACH_e		**8.18**

Figure 116 – 70 Eagle Street Effective Air Change Results

ACHe is important metric in contamination removal and dilution, vital for good IAQ and the new normal building resilience objective. Based on the results, the design ventilation effective air change rate of 8.2 ACHe is greater than the Category II recommended value of 3 ACHe, and in fact the Category I recommended value of 6 ACHe so id therefore first class in building resilience and general contamination dilution. This IAQ classification of Category II is more representative of the occupant comfort experienced and premium office feel provided by 70 Eagle street.

Table 38 – 70 Eagle Street Design Ventilation Analysis – ACHe

Design Ventilation Analysis - ACHe					
Stage	**ACH_OA**	**ACH_f**	**ACH_e,c**	**ACHe**	**IAQ Category**
Design	1.43	6.75	0	8.18	**I**

HVAC Measures

Using the case study 70 Eagle Street office building as a blueprint we analyse of the need and suitability of the previously distilled HVAC measures from best practice guidance, looking at their impact on air contaminants and virus transmission risk, while also considering their economic costs, ease of implementation, and impact on building sustainability as presented in the following table.

These distilled HVAC measures are listed below with their main analysis points while full summary details of each is provided previously in this report.

- **Ventilation System & Distribution Effectiveness** –
  - DOAS vs Recirculation ventilation systems
  - Mixing vs Displacement vs Personal ventilation distribution
- **Ventilation Rate & Operation** –
  - ‘Adequate’ ventilation achievement
  - Demand Controlled Ventilation (DCV) operation
  - Purge Ventilation
- **Temperature & Humidity** –
  - Acceptable temperature and humidity ranges
- **Air Filtration & Air Cleaning** –
  - Air filtrations levels
  - Air cleaning technologies
  - Local in-room air cleaners
- **IAQ Monitoring** –
  - CO2 monitoring
  - IAQ measurement
- **Mechanical Ventilation Heat Recovery (MVHR)** –
  - AHU sealing and pressure regimes (fan locations)
  - Thermal Wheel (TW) purge sectors

HVAC Measures	*Description*	*Impact Level*	*ROM* Cost*	*Ease of Implement-ation*	*Impact on Sustainability*
Ventilation System & Distribution Effectiveness	Recirculation Variable Air Volume (VAV) AHUs can be operated in economy / outdoor air only mode (100% fresh air) depending on AHU spare thermal capacity, or full recirculation mode for resilience in external public health emergency. This dual operation is useful so no permanent upgrade recommended. Ceiling mixing ventilation system with assumed Ev ~1 therefore ventilation distribution and effectiveness adequate with no changes recommended at this stage.				High IAQ and building resilience available from Recirculation VAV AHU
Ventilation Rate & Operation	Recommended that Recirculation Variable Air Volume (VAV) AHUs minimum outside air quantity be increased to 10.5 – 14 l/s/p depending on AHU spare thermal capacity.	High	~$20k Increase in operational cost.	Medium	Increase in energy consumption but can be managed in extreme weather conditions. Improvement in IAQ and occupant comfort & productivity
	Implement air purging and run the base-building centralised air system for min. 3 ACH between occupancies periods e.g. nightly.	Med	No capital cost. Increase in operational cost.	Easy	Increase in overall energy consumption. Minimal if included in Ventilation Optimised start or free night cooling routine
	Re-enable AHU CO2 demand controlled air modulation strategy to ensure recommended outdoor air rates and/or IAQ levels are achieved.	Med	Minimal capital cost. Decrease in operational cost (compared to previous)	Easy	Increased IAQ Relatively small capital cost and operational cost increase
Temperature & Humidity	Measured by the IAQ monitor, temperature and relative humidity were found to be within the recommended comfort and IAQ range, therefore no action recommended.				

HVAC Measures	*Description*	*Impact Level*	*ROM* Cost*	*Ease of Implement-ation*	*Impact on Sustainability*
Air Filtration & Air Cleaning	Upgrade current F6/MERV12 supply air filter to F8/MERV14 when replacement required for greater filtration efficiency of outdoor air at minimal energy penalty for greater building resilience Filtration alone achieves adequate air cleaning and effective air changes; however UV may be considered for extra resilience and may improve cooling coil performance by limiting fouling. In room local air cleaners not recommended in this case as target resilience ACHe achieved by mechanical ventilation supply.	Med	Minor capital cost. Minor increase in operational cost ~$60k. Negligible increase in operational cost.	Medium Hard	Additional maintenance on AHU and FCUs filter required. Slight increase in overall energy consumption. Greater building resilience. Small improvement in IAQ and cooling efficiency. Greater building resilience. Additional maintenance on AHU
IAQ Monitoring	Install zonal and meeting room IAQ monitoring and dashboards, including CO2, temperature, relative humidity, and VOCs.	Low	~€20k	Easy	Increased awareness of IAQ and identification of any issues.
MVHR Upgrade	Recirculation AHU using mixing box is the heat recovery in this ventilation system. Return air purposely reintroduced into supply air stream so no leakage consideration. Air filtration and cleaning strategy deemed adequate for this recirculation system therefore no upgrade recommended. May be possible to replace Recirculation Mixing box section with heat recovery element such as thermal wheel but based on this research study is not recommended at this time.				

Results

Based on the review of available design data and documents, the on-site inspection and ventilation adequacy analysis which occurred in June 2022 the above HVAC measures were recommended for the 70 Eagle Street, Brisbane, Australia.

70 Eagle Street is a leading premium commercial office space and therefore as would be expected there are limited HVAC measures recommended. This case study provides an insight into a recirculation type ventilation system in a commercial building in the warm and humid East Australian climate.

The main, high impact measure recommended is the increase in outdoor air supply rates to align with recommendations identified in this report. Outdoor air supply rates of 10.5l/s/p to 14 l/s/p should be sufficient for the desired Category II environment taking into account the relatively low recorded VOCs values. The higher 14 l/s/p air flow rates should be focused on AHUs serving floors without tenant outdoor air supply systems. These higher outdoor air rates can be achieved by reducing the mixing damper recirculation percentage and maintaining the required minimum VSD flowrate and duct pressure. The AHU air modulation control strategies should be updated to reflect this. In addition, the currently disabled CO2 based demand control strategy is recommended to be re-enabled to assist in achieving the building IAQ targets while maximising energy efficiency and cost savings.

At the same time AHU ventilation operation procedures can be updated to include the night purging measure to improve IAQ and resilience by boosting absolute contamination removal between occupancy periods. This can be implemented into the building BMS operational schedule relatively easily with almost no capital cost and minimal increase in operational costs and energy consumption.

The installation of IAQ monitors measuring CO2 and VOCs is recommended to increase awareness of IAQ across the office space. Established and calibrated sensors may be used for updated demand controlled ventilation strategies in the future if desired.

The upgrading of the AHU filters to F8/MERV 14 from the current F6/MERV12 filters when replacement is due is recommended as will increase the contaminant removal efficiency with minimal energy penalty.

This level of filtration alone achieves adequate air cleaning and effective air changes; however it is recommended to consider the installation of an Ultra-Violet (UV) germicidal radiation system in the AHU adjacent to the cooling coils. This will improve building resistance and IAQ by deactivating certain airborne contaminants including potential virus particles, and enhance AHU cooling coil performance by eliminating coil fouling maximising heat transfer for greater energy efficiency, a significant benefit in the warm humid climate of Brisbane.

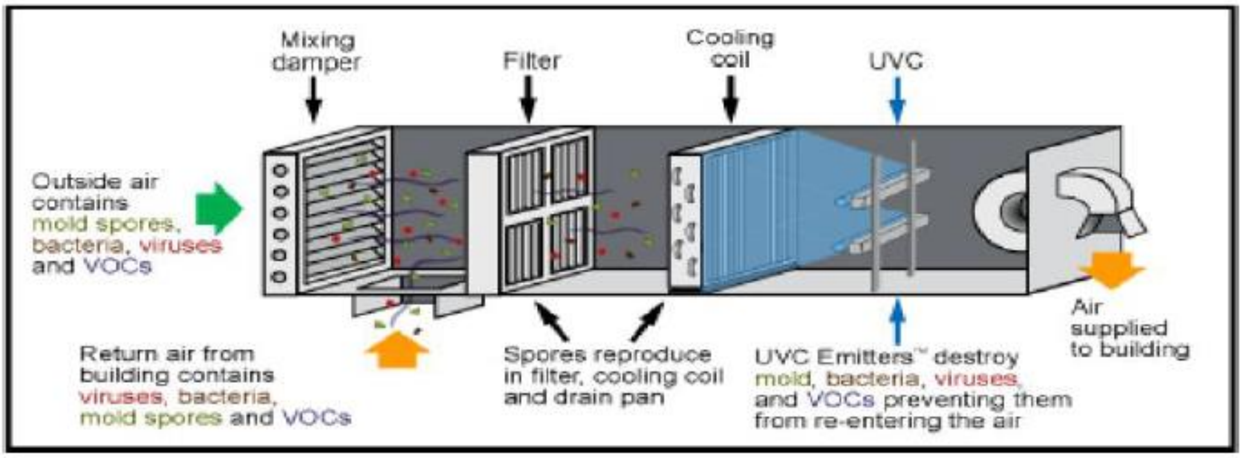


Figure 117 – Diagram of AHU UV system

At the time of writing of this report no recommended measures were implemented and therefore cannot be directly analysed. However, taking into account the recent post pandemic changes in occupancy rates and greater than required effective air change rate capability within 70 Eagle Street the classification of the indoor air quality as Category II at a minimum is merited. This can be further enhanced by implementing the above recommended HVAC measures.

Conclusions & Recommendations

After over 2-years (albeit intermittent) research the conclusions and recommendations of this study have changed massively and several times over the period as my, and societies, collective knowledge on the topics covered here grows. From this plethora of ever-updating and growing research I have tried to distill the main conclusions and recommendations below.

It is clear that indoor air quality has become one of the central topics for building designer and operators of late, and I have incorporated IAQ under the umbrella term of sustainability for my research. Typically climate change has seen a focus on the environmental aspects of sustainable building design, although with the effects of the COVID-19 pandemic and increased awareness of the importance IAQ on occupant comfort and safety, the 'people' aspect of sustainability has become more central in sustainable building design while still respecting the 'planet' and 'profit' pillars.

This renewed focus on IAQ has expanded our knowledge on air pollutants including viruses, TVOCs and particulate matter to name a few. Surprisingly however there is no definite health guidance on air contaminants limits, despite great work by the WHO, which I believe requires greater research and standardisation across the industry.

Similarly, recommended minimum ventilation levels differ across regulations with significant variations. However from my research this is less of a concern, as different levels of indoor air quality environments are acceptable across the industry - depending on multiple factors including occupant expectations or needs. Nevertheless, I believe an updated standardised means to classify and compare building ventilation and IAQ levels is a necessity, and BS EN 16798 provides a methodology for this which forms the basis of my main recommendation below.

Of the 3 proposed BS EN 16798 ventilation methodologies I conclude that the single prescriptive ventilation rates is the simplest, and the most preferred method amongst engineers polled for this research. Therefore, Method 3 - predefined ventilation air flow rates albeit adapted to account for ventilation system effectiveness, is seen as most applicable for the future of design ventilation specification. Validation of ventilation specification can be further enhanced using an adapted Method 2 (BS EN 16798-1) limit values for substance concentration formula to calculate the estimated zone IAQ level using CO2 as the chosen known contaminant.

The ventilation distribution strategy and its inherent effectiveness is a key, and often overlooked, aspect of ventilation. The high-level mixing ventilation strategy remains the modern industry standard, however the effectiveness and energy load benefits of displacement ventilation systems, and more recently personal ventilation systems, although perhaps not commercially acceptable yet, have reintroduced these strategies into the building design and sustainability agendas.

A ventilation filtration strategy can help protect building users from major outdoor sources of pollution and strike the right balance between indoor air quality and energy efficiency in the ventilation system. For mechanical filtration, filter efficiency is arguably the most important factor of its performance. As a result, consistency in values in application for any future early stage design IAQ and ventilation calculations, particularly in terms of effective air change and clean air delivery rates (CADR), is required in my opinion. Therefore as part of my recommendations below I provide average calculated values across the main filtration ratings that cover the key contaminants of concern.

In terms of air cleaning or purification devices, I believe based on my research that there is not sufficient evidence at this stage to support the use of air purification devices outside of UVC in commercial environments for IAQ purposes. There may be some limited use of air cleaners, particularly in-room located technologies, in unventilated areas such as elevators or some meeting rooms but this singly will not provide good IAQ in the long-term.

IAQ monitoring has seen a renaissance in post pandemic building design, and is now a requirement in the most recent UK Part F regulations. Typically, IAQ monitoring by measuring CO2 has been widely accepted as an indicator of ventilation, with CO2 typically a good proxy of IAQ in most cases. However, increased awareness of wellness has expanded our consideration beyond just CO2 to other contaminants. For a more robust IAQ perspective measuring CO2, Total volatile organic compounds (TVOC), temperature, relative humidity, fine particulate matter (PM2.5) and even NO2 could be used as a more holistic way to approach IAQ and may be presented in a single metric using an Indoor Air Quality Index (IAQI), particularly with communication and colour coding of values and their significance for IAQ.

Across the HVAC best practice guidance literature reviewed for this research, I conclude that the measures and advice specified agrees that certain HVAC measures can be beneficial and are recommended, but specifics do vary across institution. Many of these recommendations were issued in sole consideration of virus risk transmission, and so not in greater consideration of the overall effect on building operation and sustainability (now incorporating IAQ and resilience. As a result some of these measures may not align with my recommendations below.

Several building certification and rating systems also address ventilation design and operation with recommended measures with 5 reviewed as part of this research. Each does address IAQ consideration in design using their own methodology, however common across the 3 main studied building standards of WELL, LEED, and BREEAM are the expensive certification costs, which are inaccessible to many projects. Consequently the standards themselves, and their useful IAQ enhancing measures are often disregarded. On the other hand, information on these standards specific measures and their implementation is often freely accessible online (which greatly helped this research). Therefore, I believe greater education and knowledge of these useful measures, which are detailed in the recommendations below, should be employed across the industry as then they can be considered and included in building design and operation without the need for expensive certification of projects.

Not all guidance measures, or even this research’s recommendations, are required or suitable for all projects. Appropriate HVAC measures for buildings should be assessed on case-by-case basis and consider the effectiveness of each measure, costs and ease of implementation, impact on energy performance, and occupant comfort for the building. This is demonstrated in the case study building analysis of this research.

The overarching aim of this research was to summarise the latest best practice design guidance in HVAC building services, with a focus on ventilation, and analyse the impact of this guidance on selected case study buildings sustainability performance. I believe this was achieved with the objectives of classifying ‘adequate ventilation, distilling applicable IAQ measures, and presenting the research recommendations for the future ‘new normal’ of commercial ventilation realised below.

Based on the results of these objectives the below recommendations are proposed.
Implementation of these recommendations will improve the sustainability and resilience of commercial building environments, and may prevent the need for ‘reflex’ building guidance and design decisions during future public health emergencies.

Recommendations

Based on the analysis conducted as part of this research, I believe an updated approach to commercial building ventilation design is required to enhance building IAQ and resilience in the new normal.

The main recommendation relates to the classification and specification of ventilation in design, and its verification in building operation.

'Adequate' Ventilation - Classification & Specification

Classification of 'adequate' ventilation for a commercial environment was a key objective of this report and was or even is no easy task. Fortunately, the latest BS EN 16798-1 provides some guidance on this with an updated categorisation of adequate levels of Indoor Environmental Quality (IEQ), which we can simplify to IAQ as we are focusing on ventilation, based on the level of expectation of building occupants as summarised below: -

Table 39 – IEQ-IAQ Categories Level of Expectation & Explanation

Category	Level of expectation	Explanation
IEQ_I	High	Should be selected for occupants with special needs (children, elderly, persons with disabilities).
IEQ_{II}	Medium	The normal level used for design and operation.
IEQ_{III}	Moderate	Will still provide an acceptable environment. Some risk of reduced performance of the occupants.
IEQ_{IV}	Low	Should only be used for a short time of the year or in spaces with very short time of occupancy.

BS EN 16798-1 also provides recommended ventilation rates based on these categories and building pollution levels. These form the basis of my adequate ventilation classifications however; I do recommend they are adapted to include ventilation effectiveness for design ventilation specification to account for the characteristics of the distribution system in early stage design.

As a result, it is recommended for a typical building and design process (i.e. those not taking into account building source pollution limitation), or those premium commercial buildings aiming for LEED or WELL building certification using the current standards, to use below outdoor ventilation rates taking the greater of l/s/p or l/s/m2 value.

Table 40 - Typical Low Polluting Environment (BS EN16798) Recommended Ventilation Rates

Category	Rec. Ventilation Rate	
	l/s/p	l/s/m2
I	$\frac{20}{Ev}$	$\frac{2}{Ev}$
II	$\frac{14}{Ev}$	$\frac{1.4}{Ev}$
III	$\frac{8}{Ev}$	$\frac{0.8}{Ev}$
IV	$\frac{5.5}{Ev}$	$\frac{0.55}{Ev}$

For low polluting buildings which have minimised sources of internal pollution and followed guidance in specifying low emission internal building materials, for example WELL Materials X06 feature, or LEED EQ credit on Low-Emitting Materials, I recommend the following ventilation rates for each design category.

Table 41 - 'Very Low' Polluting Environment (BS EN16798) Recommended Ventilation Rates

Category	Rec. Ventilation Rate	
	l/s/p	l/s/m2
I	$\frac{15}{Ev}$	$\frac{1.5}{Ev}$
II	$\frac{10.5}{Ev}$	$\frac{1.05}{Ev}$
III	$\frac{6}{Ev}$	$\frac{0.6}{Ev}$
IV	$\frac{4.125}{Ev}$	$\frac{0.4125}{Ev}$

This design stage IAQ classification and specification can be further enhanced using an adapted Method 2 (BS EN 16798-1) limit values for substance concentration formula to calculate the estimated zone IAQ level - using CO2 as the chosen known contaminant in this case. Using this formula the CO2 level expected for the specified design ventilation rate is estimated, and may be compared against the below table of classified absolute indoor CO2 levels to categorise the design IAQ level, as demonstrated in this reports building case study analysis.

Table 42 - BS EN 16798 Recommended Absolute CO2 Level Category(ppm)

Category	Absolute CO2 Level ppm CO2
I	< 800
II	< 1000
III	< 1500
IV	< 2000

One of the main benefits of this calculation is that the estimated design CO2 levels provide verifiable values (+/- 50ppm) that can then be used to validate achievement of the zone design target IAQ Category using the ventilation rates specified, and its effectiveness during operation, with significant deviations in site measured CO2 rates compared to design values highlighting any potential issues in ventilation delivery.

For greater building contamination dilution and resilience, enhanced effective air change (ACHe) rates are recommended, but no such guidance is provided in BS EN 16798. However, American CDC guidance has indicated that for a well-mixed room >6 ACH can remove 99% of contaminants in space, 3 ACH can remove 95% of contaminants, 2 ACH can remove 86% of contaminants, and 1 ACH can remove 63% of contaminants in a space respectively, assuming zero concentration of the contaminant in ventilation air and the contamination source is controlled. This is the basis of my recommended design target air exchange rates for each IAQ category below.

Table 43 – Recommended Effective Air Change Rate based on BS EN 16798 Standard

Category	Rec. ACH ACHe
I	≥6
II	≥3
III	≥2
IV	≥1

For typical low polluted buildings aiming for category II – IV IAQ design relatively low additional air changes of 0.2 – 0.4 ACH (~8% - 25% additional ventilation) is recommended. However, for very low polluted buildings aiming for category II – IV IAQ design significantly more ventilation air exchange (~50%) is required to achieve recommended resilient air change rates for contaminant removal, despite the buildings generally being less polluted in normal operation.
In both cases, buildings aiming for category I IAQ design require almost a doubling of existing ventilation air exchange rate.

Table B.1. Air changes/hour (ACH) and time required for airborne-contaminant removal by efficiency *		
ACH § ¶	Time (mins.) required for removal 99% efficiency	Time (mins.) required for removal 99.9% efficiency
2	138	207
4	69	104
6+	46	69
8	35	52
10+	28	41
12+	23	35
15+	18	28
20	14	21
50	6	8

Figure 118 - American CDC Estimated Time Required for Contamination Dilution per ACH range

BS EN 16798 is a frequently reference standard throughout this report as I agree with many of its proposals. However, in contrast to BS EN 16798 and some other standards, I recommend that the distinction between adapted and non-adapted person should be removed. The adaptability of an occupant to bio-effluents (odour, CO2) over the longer term, in my opinion, should not be an allowable criteria to reduce the design ventilation rate, particularly considering the impact on IAQ and possible COVID-19 or virus transmission. Its inclusion in standards also creates confusion on acceptable ventilation rates. Categorised ventilation rates should be absolute with allowances only for pollution control rather than occupant tolerance.

Despite my contradicting of BS EN 16798 above, in general I did not want to stray too far from the standard recommendations and values as these have been well researched and validated by professionals more qualified than myself.

However, from my own research I believe that the ‘very low polluted’ buildings outside air flow rate recommendations (below) are suitable to achieve the required IAQ in modern commercial office design taking source pollution risk mitigation into account.

And those premium office buildings, who typically prefer to aim for the highest classifications can target the Category I IAQ class achieving superior air quality and occupant comfort while maintaining strong overall sustainability principles.

Table 44 - Research Classified Recommended Adequate Ventilation Rates for Commercial Buildings in the New Normal

Category	Rec. Ventilation Rate	
	l/s/p	l/s/m2
I	$\frac{15}{Ev}$	$\frac{1.5}{Ev}$
II	$\frac{10.5}{Ev}$	$\frac{1.05}{Ev}$
III	$\frac{6}{Ev}$	$\frac{0.6}{Ev}$
IV	$\frac{4.125}{Ev}$	$\frac{0.4125}{Ev}$

These lower ventilation rates reiterate the importance of source pollution limitation as directed in CIBSE TM64, as this can greatly reduce the recommended ventilation rate as a very low polluting building to achieve the same IAQ level, resulting in more sustainable ventilation.

In summary, it is recommended that the general commercial office ventilation adequacy can be classified at design stage using the proposed updated BS EN 16798 IAQ categories, and the corresponding design ventilation rate accounting for ventilation effectiveness be specified. It may also be validated in operation stage using the adapted Method 2 (BS EN 16798-1) limit values for substance concentration formula to calculate the estimated zone IAQ level using CO2 as the chosen known contaminant and comparing it to operational CO2 measurements. Enhanced commercial ventilation and IAQ adequacy for the new normal to achieve greater building resilience should take into account zone effective air changes, and target adequate contamination dilution rates in the form of ACHe in line with the desired design IAQ category as outlined above.

This recommended approach is not being proposed as a perfect solution, and further research and development is required as noted in the case study analysis of this report. The main intention of this research recommended approach is the update the way in which we consider ventilation in buildings in the future, with the goal of designing for IAQ, not ventilation rates. It is important to strike a balance between the benefits of ventilation against issues such as energy, cost, and occupant comfort.

HVAC Guidance Measures

Based on my research the main recommendations are summarised as;

- **Ventilation System & Distribution Effectiveness** - Despite the majority of guidance literatures preference for DOAS, recirculation type systems with suitable filtration (and in some cases UVC) is an appropriate ventilation system once minimum outdoor air rates are maintained. Effective air distribution is critical to building design, and it is likely that well mixed, ceiling based ventilation will achieve this, but research indicates that displacement type ventilation systems will realise 20-50% greater ventilation effectiveness, and lower energy demand. Personal ventilation systems may achieve even greater effectiveness in the future.
- **Ventilation Rate & Operation** - 'Adequate' ventilation is recommended across the guidance documents but with no consensus on the definition of 'adequate ventilation' or how it is demonstrated in building operation - something I hope is rectified above. However based on this research, and in contrast to most guidance documents, well designed and commissioned ventilation systems, including DCV systems, should operate as normal to achieve the desired IAQ, while ensuring minimum ventilation levels are maintained to achieve desired air changes for contaminant removal. For 'purge ventilation' between occupancies it is recommended to achieve a minimum of 3 ACH which can achieve >95% contaminant removal, and this can also be incorporated into ventilation 'optimum start' procedures if applicable.
- **Temperature & Humidity** - have relatively little effect on COVID-19 in the comfort range of occupancy, but recommended to maintain temperature in usual climate comfort range, and relative humidity between 40-70% to minimise the risk of microbial growth, as well as promoting the health and comfort of occupants.
- **Air Filtration & Air Cleaning** – There are different recommendations by industry bodies on the level of filtration required, however, research indicates that MERV13-14 (F7-F8) offered the best value balancing pollution removal and risk of virus infection with energy penalty and operating costs, and are therefore recommended for future commercial building design.

For air cleaning technologies, UV is the dominant technology in guidance documents and based on my research the only consideration for UV technology in the AHU system or ducts is to irradiate wet downstream cooling coil and drain pan surfaces in warm and humid environments where coils are wet for long periods, as this will reduce coil fouling while achieving additional air cleaning improving the overall sustainability.

Few guidance documents reference other air cleaning technologies specifically, and any available guidance recommends caution and comprehensive verification if selecting one of these newer, unproven technologies.

Most guidance suggest that local air cleaning (UV based) and filtration (HEPA) may be beneficial for reducing air pollution and virus transmission risk in some spaces with low ventilation rates, but do not replace outdoor air ventilation.

Local in-room air cleaners may also help achieve higher effective ACH where required.

- **IAQ Monitoring** - CO2 monitoring has been widely accepted as an indicator of ventilation, and it should continue to do so as CO2 measurements may also be used to help verifying ventilation effectiveness and supply rates during building operation. However, for future commercial building design in the new normal it is recommended that building based contaminants such as TVOCs, and possible external contaminants such as PMs, should also be monitored and dash-boarded for a more wholistic measurement and awareness of IAQ.
- **Mechanical Ventilation Heat Recovery (MVHR)** – MVHR is essential to sustainably achieving the indoor environmental quality required by occupants and should not be turned off or bypassed unless the climate allows for it. Airstream cross contamination and virus transmission risk may be minimised using suitable AHU fan locations and pressure regimes, and adequate sealing. For most commercial applications (IAQ II – IV), based on my research, I am not recommending installing a purge sector as this increases OACF with minimal reduction is cross contamination, and can also introduce a sealing point of weakness.

Building upon these recommended measures, the importance of ventilation effectiveness and its consideration cannot be understated. Figure 118 overleaf reiterates the importance of supply air temperature, velocity, and inlet and outlet location in the variability of ventilation effectiveness values.

Table 6-4 Zone Air Distribution Effectiveness

Air Distribution Configuration	E_z
Well-Mixed Air Distribution Systems	
Ceiling supply of cool air	1.0
Ceiling supply of warm air and floor return	1.0
Ceiling supply of warm air 15°F (8°C) or more above space temperature and ceiling return	0.8
Ceiling supply of warm air less than 15°F (8°C) above average space temperature where the supply air-jet velocity is less than 150 fpm (0.8 m/s) within 4.5 ft (1.4 m) of the floor and ceiling return	0.8
Ceiling supply of warm air less than 15°F (8°C) above average space temperature where the supply air-jet velocity is equal to or greater than 150 fpm (0.8 m/s) within 4.5 ft (1.4 m) of the floor and ceiling return	1.0
Floor supply of warm air and floor return	1.0
Floor supply of warm air and ceiling return	0.7
Makeup supply outlet located more than half the length of the space from the exhaust, return, or both	0.8
Makeup supply outlet located less than half the length of the space from the exhaust, return, or both	0.5
Stratified Air Distribution Systems (Section 6.2.1.2.1)	
Floor supply of cool air where the vertical throw is greater than or equal to 60 fpm (0.25 m/s) at a height of 4.5 ft (1.4 m) above the floor and ceiling return at a height less than or equal to 18 ft (5.5 m) above the floor	1.05
Floor supply of cool air where the vertical throw is less than or equal to 60 fpm (0.25 m/s) at a height of 4.5 ft (1.4 m) above the floor and ceiling return at a height less than or equal to 18 ft (5.5 m) above the floor	1.2
Floor supply of cool air where the vertical throw is less than or equal to 60 fpm (0.25 m/s) at a height of 4.5 ft (1.4 m) above the floor and ceiling return at a height greater than 18 ft (5.5 m) above the floor	1.5
Personalized Ventilation Systems (Section 6.2.1.2.2)	
Personalized air at a height of 4.5 ft (1.4 m) above the floor combined with ceiling supply of cool air and ceiling return	1.40
Personalized air at a height of 4.5 ft (1.4 m) above the floor combined with ceiling supply of warm air and ceiling return	1.40
Personalized air at a height of 4.5 ft (1.4 m) above the floor combined with a stratified air distribution system with nonaspirating floor supply devices and ceiling return	1.20
Personalized air at a height of 4.5 ft (1.4 m) above the floor combined with a stratified air distribution system with aspirating floor supply devices and ceiling return	1.50

Figure 119 – Detailed Ventilation Effectiveness Table (ASHRAE 62.1)

These Ev values can play an important role in the design and sustainability of a building as in theory the higher the ventilation effectiveness the lower the total supply air quantity (and associated fan energy, air conditioning load and ductwork size). Consideration and design of air diffuser velocities to minimise draughts and maintain good IEQ should be sufficient consideration to maintain good ventilation effectiveness and manage virus transmission risk.

In terms of air filtration, which will play a key role in future building ventilation design and resilience, air filter efficiency is the crucial parameter for consideration, and therefore requires consistency in its design, specification, and application.

Air filter efficiency have been tested and categorised across 3 different standards - ASHRAE MERV Filter Rating, EN779 Filter Rating and ISO 16890 Filter Rating, all of which are used and referred to across different countries and building standards, although ISO 16890 is the most recent and globally applicable standard.

Based on the mean distribution of the main contaminants of concern, including viruses, particle sizes across several studies the average calculated filtration efficiency values for mechanical filters across each rating system is provided below.

Table 45 - Recommended Standardised Filtration Efficiency Table

ASHRAE MERV Filter Rating	EN779 Filter Rating	ISO 16890 Filter Rating	Est. Filter Effiency (%)
1	G1	ISO Coarse < 50%	< 15%
2	G2	ISO Coarse < 50%	< 15%
3			< 15%
4			16.80%
5	G3	ISO Coarse > 50%	26.55%
6			32.45%
7	G4	ISO Coarse > 50%	41.13%
8			55.57%
9	M5	ePM10 > 50%	62.00%
10			64.65%
11	M6	ePM2.5 > 50%	72.86%
12		ePM10 > 60%	83.39%
13	F7	ePM1 > 50%	89.93%
		ePM2.5 > 65%	
		ePM10 > 80%	
14	F8	ePM1 > 70%	94.94%
		ePM2.5 > 80%	
		ePM10 > 90%	
15	F9	ePM1 > 80%	96.18%
		ePM2.5 > 90%	
		ePM10 > 95%	
16		ePM1 > 85%	97.40%
		ePM2.5 > 95%	
		ePM10 > 95%	
HEPA +	HEPA +	HEPA +	> 99%
ULPA +	ULPA +	ULPA +	100%

These average calculated values can provide consistency in application for any future early stage design IAQ and ventilation calculations. These can be updated or replaced by manufacturer filter information once available if required.

Research indicates that MERV13-14 (F7-F8) offered the best value balancing pollution removal and risk of virus infection with energy penalty and operating costs, and are therefore recommended for future commercial building design.

Additionally, air filtration should follow EN 16798-3:2017 guidance, and aligns with above recommendation as typically a minimum F7/MERV 13 filter is an acceptable filter grade to achieve a high level of IAQ while maximising sustainability.

Table 46 - EN 16798-3:2017 Air Class and Recommended Filtration Levels

Outdoor Air Quality		Indoor Air Quality				
		SUP 1 (Very low concentrations of PMs and/or gases)	**SUP 2** (Low concentrations of PMs and/or gases)	**SUP 3** (Medium concentrations of PMs and/or gases)	**SUP 4** (High concentrations of PMs and/or gases)	**SUP 5** (Very High concentrations of PMs and/or gases)
ODA 1 (only temporarily dusty, e.g. pollen)	(P)	M5 + F7	F7	F7	F5	-
	(G)	Gas filter recommended	-	-	-	-
ODA 2 (high concentrations of particulate matter and/or gaseous pollutants)	(P)	F7 + F7	M5 + F7	F7	F7	M5
	(G)	Gas filter required	Gas filter recommended	-	-	-
ODA 3 (very high concentrations of dust and gases)	(P)	F7 + F9	F7 + F7	M6+F7	F7	F7
	(G)	Gas filter required	Gas filter required	Gas filter recommended	-	-
Filter classes defined according to EN 779 Gas filtration should be considered if design SUP quality is above design ODA quality. Dimensioning should be done in accordance with EN ISO 10121-1 and EN ISO 10121-2. Further consideration on gas filtration is given in CEN/TR 16798-4						

For air cleaning, AHU based or in-duct UV disinfection systems are recommended only in warm humid climates when located adjacent to cooling coils, as this can reduce coil fouling while achieving additional air cleaning improving the overall sustainability. As noted above, other air cleaning technologies, while may be beneficial to building resilience, are only recommended in limited circumstances where benefits and IAQ improvement outweigh any technological concerns if applicable.

Where high ventilation rates for effective air changes are required this can increase duct sizes, energy and space planning requirements which can be offset by the use of in-room air cleaners. Local air cleaners are also recommended in areas where it is difficult to achieve the recommended effective air changes or ventilation rates. Systems should be certified and equipped with HEPA or minimum F8/MERV 14 filters, and be positioned close to occupants to maximise its effectiveness. Air cleaner capacity should at least cover the gap between the minimum requirement and the measured ventilation rate as indicated by the device clean air delivery rate (CADR).

Energy impacts of air cleaning devices depends on many factors as discussed in the Air Infiltration and Ventilation Centre paper titled 'The Concept for Substituting Ventilation by Gas Phase Air Cleaning' and is unfortunately beyond the capability of this research but is a topic that requires further investigation.

In terms of ventilation systems, there are some inherent IAQ advantages related to DOAS with heat recovery. However, in my opinion a suitably filtered recirculation type system with the recommended minimum supply of 'outside' air (based on desired category) is an acceptable ventilation system for 'new normal' operation, and 100% outside air is not a design requirement.

Additionally, if the current ventilation strategy is well designed to provide adequate ventilation to meet occupant and building level requirements there should be no need to disable control strategies such as DCV in the future.

A programmed air purging (or air flushing) between occupancies of 3-6 ACH (depending on designed risk or IAQ level) is recommended as will help remove any buildup of contaminants from the previous day and during unoccupied hours, can be done in conjunction with any optimal start or night-cooling strategy if applicable. Air purging can also provide a uniform CO2 level indoor environment for CO2 sensor fault detection and self-correction as all the CO2 sensors should equal to the CO2 concentration of the ambient air with full outdoor air purge ventilation. In extreme temperatures or for dominant recirculation ventilation strategies an alternative approach of 100% return air ventilation so that all CO2 sensors should have a same reading in the end to identify sensor faults or drift, with the flushing effect provided by the air cleaning strategy of the system.

For central MVHR systems, it is recommended to request and consider the estimated EATR and OACF value at design operating conditions to ensure it is to a satisfactory level. All Eurovent certified manufacturers of rotary heat exchangers provide proven EATR and OACF values for different conditions. According to EN 16798-3:2017 OACF (left) and EATR (right) at nominal conditions and nominal air volume flow of the heat recovery section shall be classified according to the table below.

	OACF	
Class	Outdoor to exhaust air	Extract to supply air
1	1,03	0,97
2	1,05	0,95
3	1,07	0,93
4	1,10	0,9
5	Not classified	

Figure 120 - EN 16798-3:2017 OACF Classifications

Public Health Emergencies - Wildfires

Consideration for building resilience external public health emergencies, such as wildfires and the related smoke but could cover any external source, is a necessity in some regions and is recommended in all buildings.

Wildfires in particular, and the resulting smoke were responsible for the temporary closure of businesses and schools across Australia and California respectively. But even in Europe there are on average 65,000 wildfires every year, and research has shown that smoke from forest fires can linger in the atmosphere for weeks as it spreads, and can even become more toxic with time. Therefore, it should be a consideration for nearly every building design in the future based on our current climate degradation direction, no matter what the location.

This consideration may be in the form of an emergency response plan in which particular consideration to ventilation for operation during the design phase is essential. For example from the case studies presented, the storing onsite of HEPA or MERV15/16 filters for emergency use is recommended. Additionally, a positive pressure, full recirculation ventilation control strategy for recirculation AHUs in wildfire smoke scenarios will limit wildfire smoke infiltration as a short term strategy.

There is no literature specifically examining the issue of infiltration of wildfire smoke particles into buildings and this may need to be addressed to be prepared for future events. ASHRAE Guideline 44P *Protecting Building Occupants from Smoke During Wildfire and Prescribed Burn Events* which is still in development is however a useful resources on preparing buildings for wildfires.

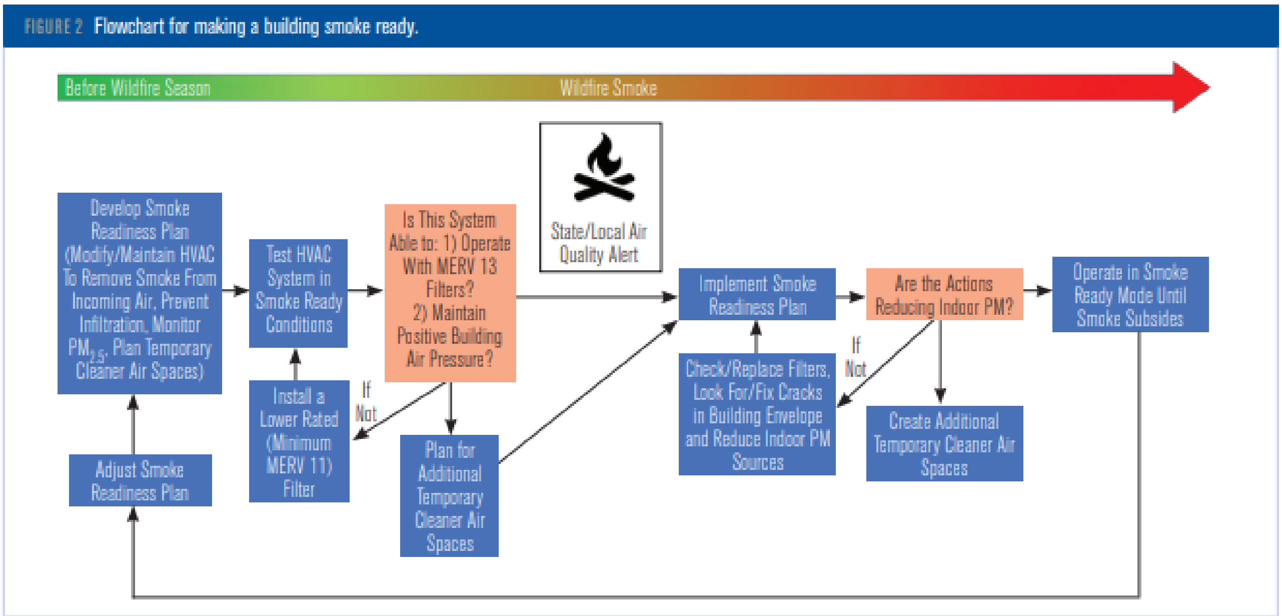


Figure 121 – Flowchart for Making a Building Smoke Ready (ASHRAE Guideline 44P)

Building Certification Measures

Based on the completed summary review, and my opinion on ‘useful measures’, it is recommended that WELL Building standard ventilation or ‘Air’ features, and the Community C03 – Emergency Preparedness, and Materials X06 - VOC Restrictions features be included and considered as part of the building design process. It is not expected every feature will be required or applicable to all projects, and particular features for example recommending increase in ventilation rates (A06), openable windows (A07) and UVGI air cleaning (A14) should be analysed specifically taking into account the overall building sustainability, ventilation strategy and IAQ plan, but all are recommended to be considered.

LEED is a forerunner in terms of materials and low emissions specifications with the EQ Credit on Low-Emitting Materials (V4.1), and the Materials and Resources credit Building Product Disclosure and Optimization - Material Ingredients credits particularly useful in minimising building source pollution, and improving IAQ and sustainability. Therefore, it is recommended that the design team be familiar with these credits and consider them as part of the design process also.

From BREEAM, the Hea 02 Indoor Air Quality (IAQ) plan credit requires an IAQ plan covering acceptable pollution levels (IAQ category), ventilation strategies, IAQ monitoring & testing, contamination sources removal etc. which is recommended to be implemented for all projects at early stage design and communicated with the clients.

I do not however agree with all LEED and WELL IAQ related credits, as buildings targeting and achieving LEED & WELL building standard credentials by reducing building source pollution and maximising ventilation system effectiveness are still being required to provide additional outdoor ventilation (30% – 60%) over regulations regardless of the IAQ achieved at the regulations rate. Taking into account overall sustainability and the energy penalty of surplus outdoor air, the option to reduce indoor pollution sources at the lower design flowrate to achieve the required IAQ should also be encouraged.

Therefore, taking into account above, it is recommended based on this research that these useful measures all be incorporated into the future of commercial building ventilation design

Updated Design Approach – New Normal

To take into account the recommend updated approach to ventilation specification and classification, and the additional recommended HVAC measures detailed above, an updated overall ventilation design approach is recommended.

This updated approach mainly effects early stage design but has facets over the building life cycle. It requires early consideration of the ventilation strategy and agreeing the approach with the client and the wider design team, which is key to the delivery of systems that successfully address occupant health and wellbeing.

At early stage concept design, an IAQ category target should be set, and details of the various air distribution strategies with different ventilation effectiveness communicated to clients and wider project team. The building ventilation strategy should be informed by an accurate evaluation of both outdoor and indoor sources of pollution: site location is a critical component in determining filtration and intake /exhaust location, and an understanding of occupancy profiles, materials specifications and processes taking place inside the buildings (e.g. cooking, printing, etc.) is necessary. Adequate ventilation is of paramount importance in achieving optimal indoor air quality, but it is also important to recognise other aspects such as materials selection, cleaning products, and mould and leak prevention.

All projects should produce an IAQ plan at early stage in line with BREEAM HEA02 prerequisite and outlined by Guidance Note GN06 and Appendix G. The IAQ plan and design ventilation documentation should include information relating to the following;

- Design method used, and IEQ/IAQ category targeted for the design
- Specified design ventilation airflow rates, and the applied occupancy and calculation schedules
- Ventilation system and distribution strategy with its estimated ventilation effectiveness
- Pollutant sources have been identified and processes used to eliminate or decrease those sources
- Air filtration and cleaning requirements
- Public health emergency plan (see WELL Community C03 – Emergency Preparedness feature)
- IAQ pollutant limit expectations and associated proposed material specification considerations
- Commissioning plan
- Operation, control, and maintenance considerations

Indoor air quality is affected by procurement, construction and handover procedures as well as the ongoing operation and maintenance of the building. Liaising with design team early to minimise indoor pollutants through material specifications can reduce the ventilation requirement for the desired IAQ level and improve overall building sustainability. Attention should be paid at construction stage that these specified materials are installed, and that planned construction pollution prevent measures are implemented.

A key step to ensuring the energy performance of our buildings is to how we designed (modelled) is to monitor performance in operation and compare to design. In order to do this for IAQ we would need a simple measurable design parameter (similar to kWh in energy performance) to verify design targets are achieved. This is currently generally done using air flow measurements (l/s) on commissioning stage. However this does not account for the effectiveness of the distribution system, building changes in the operation phase, and is not easily communicable as a parameter of IAQ to indicate performance. The proposed above adapted Method 2 calculation and ventilation specification approach can be used at handover stage to overcome this.

In operation, post occupancy evaluations and ongoing commissioning using the adapted Method 2 CO_2 levels will help monitor and maintain desired IAQ levels, while effective maintenance procedures for filters and ventilation equipment will maximise efficiency and results.

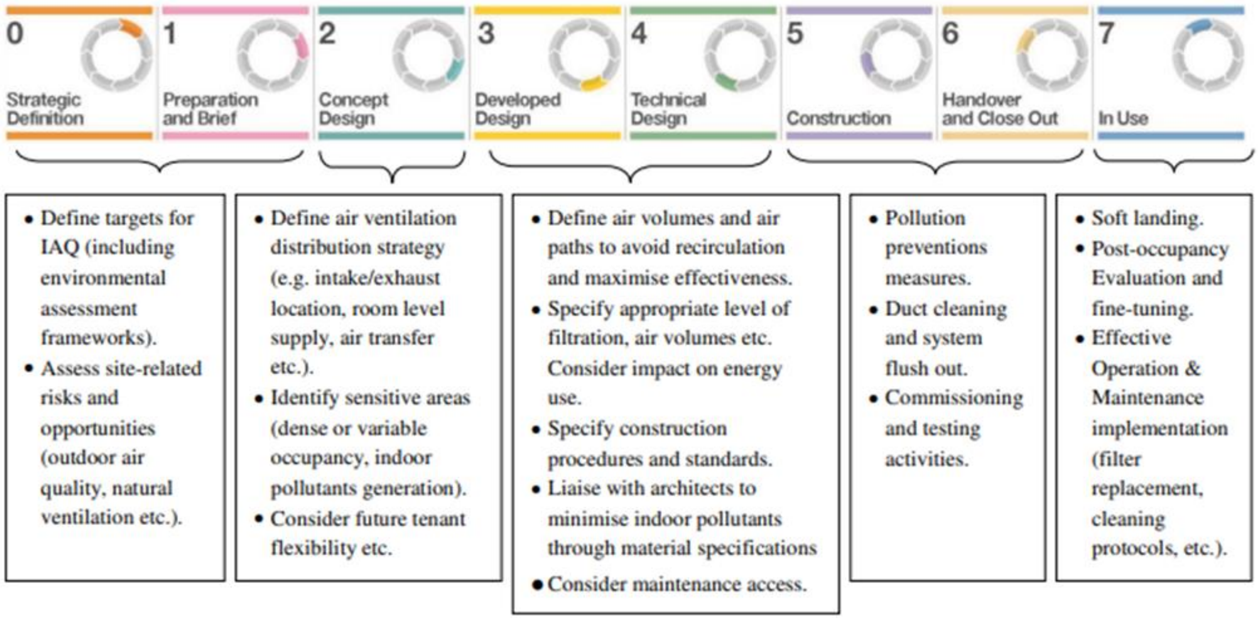


Figure 122 - Recommended Updated Design Approach Process Graphic

It is my belief that once this updated approach is applied correctly, which can be assisted and confirmed using the CIBSE TM61 – 64 guidance as a basis, building resilience and operation will be optimised in case of any future public health emergency or likewise, without the need for future ‘reflex’ guidance documents.

CIBSE TM 61 – 64 and Other Resources

The latest CIBSE TM61 -64 bundle (2020) is a recommend must have reference for all future building designs in the new normal;

CIBSE TM61: Operational performance of buildings engineering controls are recommended to be considered on all projects

CIBSE TM62: Operational Performance - Surveying occupant satisfaction recommended to be used as reference for any POE surveys requirements. This can inform and engage occupants during operation, and help review and improve operation based on data and feedback.

CIBSE TM63: Operational Performance - Building performance modelling and calibration for evaluation of energy in-use is based on energy modelling but may be possible it can be used for any indoor IAQ modelling calibration if required.

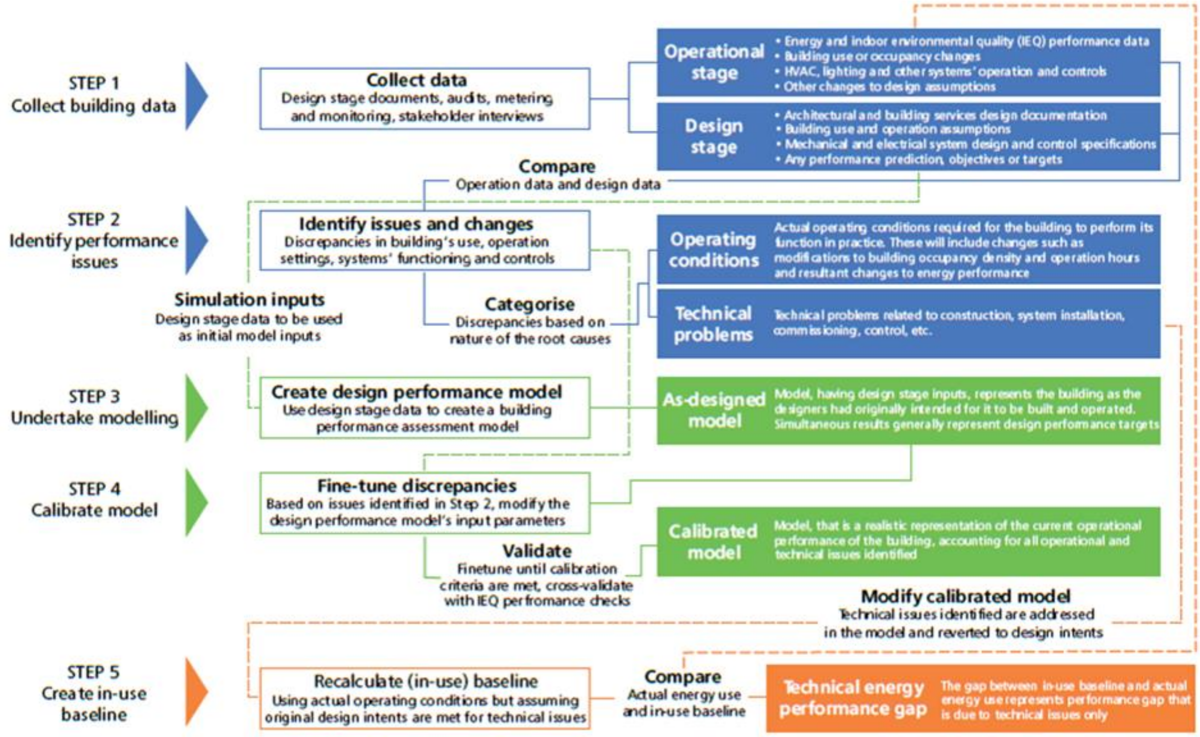


Figure 123 - CIBSE TM63 Building performance modelling and calibration for evaluation flowchart

TM64: Operational Performance - Indoor air quality – Emissions sources and mitigation measures is an excellent source of building activity specific IAQ information including emission sources, key pollutants, and possible mitigation measures for future design.

Further to this, the USA EPA Clean Air in Buildings Challenge (March 2022) provides basic principles and general actions recommended to improve indoor air quality (IAQ) in buildings and reduce the risk of airborne spread of viruses and other contaminants.

Key actions outlined in the Clean Air in Buildings Challenge include:

- Create a clean indoor air action plan,
- Optimize fresh air ventilation,
- Enhance air filtration and cleaning, and
- Conduct community engagement, communication, and education.

The document also includes a great list of additional resources for further information, many of which have been referenced throughout this report.

There is also a multitude of recommended guidance is available on IAQ for buildings in operation such as the BESA 'Buildings as Safe Havens' practical guide.

While the Coronavirus (COVID-19) response resources from ASHRAE and others is a highly recommended resource for COVID specific mitigation measures.

Finally, detailed guidance on improving IAQ in buildings I recommend the Indoor Air Quality Guide developed by AHSRAE and several leading American built environment bodies which expertly develops 8 IAQ objectives over 700 pages on best practices for design, construction, and commissioning of buildings.

It is noteworthy that the existing guidelines for the calculation of outside air ventilation rates are based on the assumptions that the air outside the building is 'fresh' and that the pollutant load is inside the building. For buildings in city areas or adjacent to busy roads the quality of the outside air needs to be assessed, as this can also be a source of pollutants. Where specific problems are anticipated, an air quality survey should be undertaken. This should include measurements at likely times of peak pollution.

The on-site measurement of outdoor air quality and continued into operation is recommended if possible. However, available national or regional measurements may provide useful design information if required. Operational outdoor air quality systems in buildings should consider sharing data with others on public such as purple air platform for example - to monitor air quality overtime and update filtration strategy if required according to pollution levels if applicable.

I feel obliged to advise that not all of these research recommendations are suitable for all projects. Appropriate measures should be assessed on case-by-case basis and consider the effectiveness of each measure, costs and ease of implementation, impact on energy performance, and thermal comfort for the building as demonstrated in the case study building analysis of this research.

Appendices