AIRBODS

FINDINGS AND GUIDANCE FOR AIRBORNE INFECTION RESILIENCE

CIBSE

In Partnership

NOTES FROM THE AUTHORS

AUTHORS

The whole of the AIRBODS team contributed to this guide through their rich tapestry of papers, reports, presentations and articles. The following members of its guidance and dissemination team (Work Package 4) have collated the document:

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Additional Events Research Programme funding through DCMS.

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PREFACE

AIRBODS began on a Friday afternoon in April 2020, deep into lockdown, online. People all over the world were ill, confused, frustrated and very uncertain of what the future held. A multi-disciplinary group of researchers with many years' experience of ventilation decided they must act, and thus AIRBODS was born.

AIRBODS (Airborne Infection Reduction through Building Operation and Design for SARS-CoV-2) received funding from the Engineering and Physical Sciences Research Council (EPSRC) and the Department for Digital, Culture, Media and Sport (DCMS). The priority was to work fast, responding initially to the acute need for advice on how to safely operate buildings during a pandemic from the point of view of ventilation and fresh air distribution. The team did this through a combination of field studies, experimental work, modelling and focus group discussions with building operators.

Although the priority was to offer guidance for those making decisions in response to the spread of Covid-19, the work was conducted in such a way as to ensure the learning could be applied far more extensively. It now offers a basis on which the AIRBODS team can develop the techniques further, equipping us with the knowledge and know-how in the event of future pandemics and enabling us to ensure buildings are a healthy place to work, live and socialise.

This has, without doubt, been the most exciting, fastest moving project I have worked on, which took us to Ascot, the World Snooker Championships, the Brit Awards and the FA Cup final! It has been a privilege to lead such a committed, experienced team, all striving for the same goal: to make buildings healthier for their users.

This guidance was launched at Breathe, Loughborough University on March 22nd, 2023.

A free download is available on the publications page of the AIRBODS website.

https://www.airbods.org.uk/publications

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CONTENTS

EXECUTIVE SUMMARY

AIRBODS team collecting their winner's trophy for the Learning and Development category at the CIBSE Building Performance Awards 2023. They were also Highly Commended in the Building Performance Champion category.
https://www.cibse.org/what-s-on/cibse-building-performance-awards-2023/winners-2023

This guidance provides insights into airborne infection risks and proposes mitigation measures to improve airborne infection resilience of indoor and semi-outdoor spaces. In some poorly-ventilated and/or highly occupied spaces, the provision of increased ventilation performance can be the key to reducing airborne infection risk down to 'acceptable' (although currently undefined) levels.

This is a complex area of study with many areas of uncertainty that form the basis of ongoing research. That said, the AIRBODS programme, in the context of the global research efforts associated with the COVID-19 pandemic, has generated a sound basis for improving airborne infection resilience. Key aspects of the guide with its many recommendations include:

- Experiments carried out in a test chamber showing how screens can improve or, even, worsen airborne infection risk.
- Field studies undertaken as part of the Events Research Programme which underpinned the opening up of the UK hospitality sector in summer of 2021. Good practice advice is provided on how to drive high resolution CO_2 and microbiological studies and then appropriately interpret results.
- Analytical models were developed to understand how infection risk, using a mass balance approach with many different parameters, might be mitigated in some circumstances when compared to reference spaces. These models were then developed into a 'full building' tool which can be downloaded as part of this guidance.
- Computational fluid dynamics (CFD) models were developed to provide insights into the physics of droplets or aerosols at microscale. Following completion of a test chamber validation exercise, models were developed to investigate breathing or coughing mannequins at single human moving towards audience or crowd scale. Local ventilation effectiveness and associated airborne infection risk aspects of some real spaces may significantly differ from assumed 'fully-mixed' equivalent spaces. This, along with a number of other issues, will form part of ongoing research activities.
- Focus groups were also used to provide some wider context and support some of our recommendations.

AIRBODS has produced a repository of data and modelling methods with the mindset of enabling building professionals to inform their design and operation decisions towards improving airborne infection resilience in their buildings.

1

AIRBODS: AN INTRODUCTION

ABOUT AIRBODS

THE AIRBODS RESEARCH PROGRAMME
Led by Prof Malcolm Cook.
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THE ENVIRONMENTAL STUDY, PART OF THE EVENTS RESEARCH PROGRAMME
Led by Dr Liora Malki-Epshtein,
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AIRBODS website: www.airbods.org.uk

This photo is of a graduation ceremony held at Loughborough University during the pandemic. All participants were masked and there were high levels of natural ventilation. Additional measures included shorter duration ceremony with reduced overall occupancy levels.

The AIRBODS Research Programme kicked off in March 2021 and ended in December 2022. The programme was supported by over 20 academic researchers and industrial consultants over its 22-month funding period, It was initiated following an early realisation that the COVID-19 pandemic had a significant airborne infection transmission component. The level of significance was contested and so much more work was required to determine how to demonstrate and then reduce the risk of airborne transmission.

Reducing airborne infection, with a primary focus on ventilation and the role that ventilation can play, is a key component for generating airborne infection resilience and supporting how buildings should be designed and/or operated. By having a much greater focus on ventilation, many other benefits could be accrued such as better air quality, health, well-being and productivity amongst other things.

The project benefited throughout its duration from the insights, guidance and expertise of a small Advisory Group drawn from the UK and US, which was chaired by Dr Hywel Davies, Chief Technical Officer of CIBSE, the leading professional body covering building services provision in the UK.

ABOUT AIRBODS

The AIRBODS Research Programme was split into four work packages:

- Experiments
- Modelling
- Field studies
- Design guidance and dissemination

WORK PACKAGE 1: EXPERIMENTS:
Class 2 environmentally controlled chambers were used to provide experimental data on the transport and distribution of aerosols.

WORK PACKAGE 2: MODELLING

TASK 2.1 - UNDERSTANDING THE PHYSICAL PROCESSES:
Analytical methods were used to develop an understanding of the physical processes involved in aerosol transport. Air temperature, relative humidity and the behaviour and evaporation of aerosols were correlated.

TASK 2.2 - COMPUTATIONAL FLUID DYNAMICS (CFD) MODELLING :
Different CFD modelling techniques, were compared and informed the analytical models The work underpinned design and operation guidance for practicing engineers wishing to use CFD for other scenarios and geometries.

TASK 2.3 - RELATIVE RISK INDEX (RRI) PREDICTION TOOLS :
An existing indoor environment Relative Exposure Index model was augmented using the mathematical models generated in Task 2.1.

WORK PACKAGE 3: FIELD STUDIES:
Field studies were undertaken in a wide range of large and small space types. The measurements included temperatures, relative humidity, CO_2 and air flow which were used as inputs to analytical models.

WORK PACKAGE 4: DESIGN GUIDANCE AND DISSEMINATION :
The lessons learnt from Work Packages 1, 2 and 3 were used to inform practical guidance on responses to SARS-CoV-2 for at least the building typologies investigated and provide prediction tools and modelling advice. Focus groups were held to provide additional context and guidance feedback.

KEY PARTNERS

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UCL

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EST 1892 LSBU

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University of Cambridge

WR wirth research COMPLETE PERFORMANCE ENGINEERING

Department for Business, Energy & Industrial Strategy

Department for Digital, Culture, Media & Sport

Department of Health & Social Care

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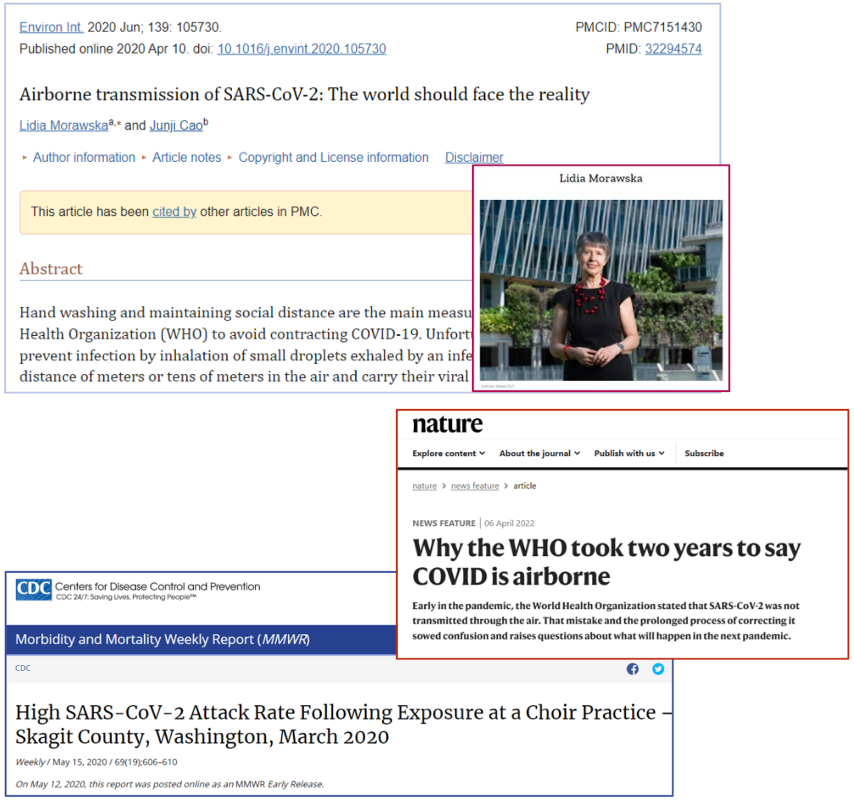

Environ Int. 2020 Jun; 139: 105730. PMCID: PMC7151430
Published online 2020 Apr 10. doi: 10.1016/j.envint.2020.105730 PMID: 32294574

Airborne transmission of SARS-CoV-2: The world should face the reality

Lidia Morawska[a,*] and Junji Cao[b]

Author information ▸ Article notes ▸ Copyright and License information Disclaimer

This article has been cited by other articles in PMC.

Abstract

Hand washing and maintaining social distance are the main measu… Health Organization (WHO) to avoid contracting COVID-19. Unfort… prevent infection by inhalation of small droplets exhaled by an infe… distance of meters or tens of meters in the air and carry their viral…

Lidia Morawska

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NEWS FEATURE | 06 April 2022

Why the WHO took two years to say COVID is airborne

Early in the pandemic, the World Health Organization stated that SARS-CoV-2 was not transmitted through the air. That mistake and the prolonged process of correcting it sowed confusion and raises questions about what will happen in the next pandemic.

CDC Centers for Disease Control and Prevention
CDC 24/7: Saving Lives, Protecting People™

Morbidity and Mortality Weekly Report (MMWR)

CDC

High SARS-CoV-2 Attack Rate Following Exposure at a Choir Practice — Skagit County, Washington, March 2020

Weekly / May 15, 2020 / 69(19);606–610

On May 12, 2020, this report was posted online as an MMWR Early Release.

AIRBORNE TRANSMISSION IS ESTABLISHED

- Super-spreading events were seen as evidence of airborne transmission of SARS-CoV-2, especially in very poorly ventilated spaces.
- 2020: After several months of debate: WHO, PHE and the CDC recognised that inhalation is likely the dominant transmission route in most settings.
- Aerosols in exhaled breath, laden with virus particles, are important at close range and at longer distance.

Risk factors for airborne transmission include:

- Duration of time spent in a space
- Activities that may generate more viral aerosols (singing, loud talking, aerobic exercise)
- Low ventilation rates
- Large number of people present

...All these factors may be present at live mass gathering events

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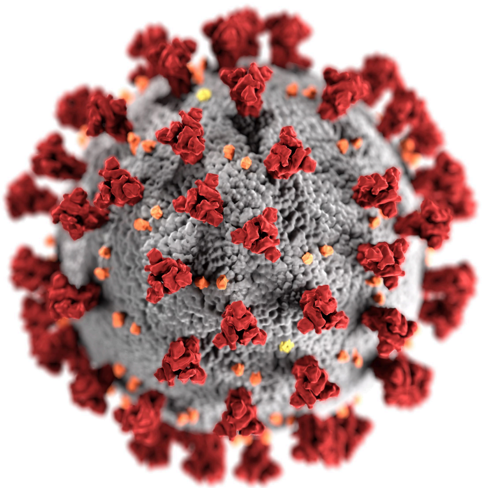
AEROSOLS AND SARS-CoV-2



(CDC/Unsplash)

KEY FACTS ABOUT SARS-COV-2

SARS-COV-2 AND COVID-19

Severe Acute Respiratory Syndrome Coronavirus 2:
- Coronavirus that causes COVID-19 disease.
- Believed to have first appeared in Wuhan, China in 2019.
- Spread across globe becoming a pandemic.

COVID-19:
- Infectious respiratory disease caused by SARS-CoV-2 virus.
- Range of symptoms from none to severe (majority mild to moderate).
- Cost the lives of millions of people worldwide with global economic impacts.
- Long COVID is a substantial ongoing challenge even post vaccine.

WHAT ARE ITS CHARACTERISTICS?

- SARS-CoV-2 has a spherical shape with spikes.
- Even though 0.1um is the theoretical minimum size of a virus particle, it is very likely to be in much larger aerosols most of the time.
- Impacts probability that a particle of a given size contains at least one virion (a complete infectious viral particle).
- Also impacted by the viral load in the respiratory fluid as well as the point of origin of the particle within the respiratory tract.

(Bar-On, 2020) (Cortellessa, 2021) (Zhang, 2020) (WHO, 2021) (WHO, 2022) (Iddon, 2022b) (Morawska, 2022)

KEY FACTS ABOUT SARS-COV-2

HOW DOES IT SPREAD?

- Through droplets emitted into the air while an infected person exhales, talks, coughs etc.
- Smaller droplets, or aerosols, can stay suspended in the air for long periods, e.g hours.
- Larger droplets fall onto surfaces due to gravity (fomites) forming a surface transmission route along with contaminated hands. It is difficult to demonstrate this route (low levels of evidence).

SHORT-RANGE TRANSMISSION
- Via inhalation of exhaled breath containing virus-laden droplets of all sizes from at distances of less than 2m.
- Most likely transmission route due to high concentration of virus airborne in local vicinity.

LONG-RANGE TRANSMISSION
- Via inhalation of virus particles at greater distances.
- Fully evaporated particle or still contained in droplet (much smaller than when exhaled due to evaporation).
- Can lead to super-spreading events although it is a rarer phenomenon.

AIRBORNE TRANSMISSION
- Includes short-range and long-range transmission.

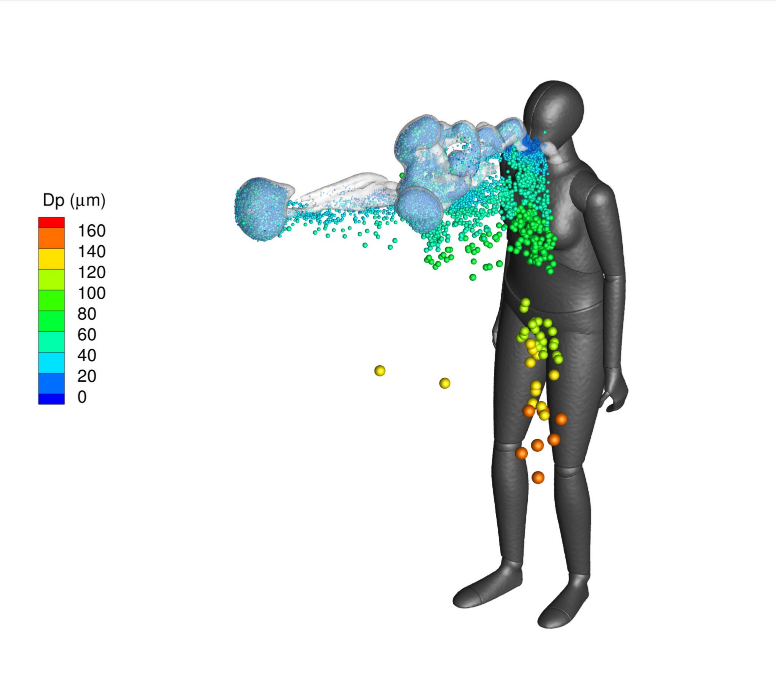
VIRAL CONCENTRATIONS
- Short-range values are much higher than long-range due to dispersion with distance from source.

The COVID-19 pandemic, climate crisis, humanitarian emergencies and other shocks reinforce the fragility of health and human security. Life expectancy - our gold standard measurement of global health - has declined for two years running in the wake of COVID-19.

Achim Steiner, United Nations Development Programme

(Bar-On, 2020) (Cortellessa, 2021) (Zhang, 2020) (WHO, 2021) (WHO, 2022) (Iddon, 2022b) (Morawska, 2022)

AEROSOLS



AIRBODS CFD model of exhaled breath or 'aerosol cloud' containing droplets and various gases – the larger droplets fall more quickly due to gravity.

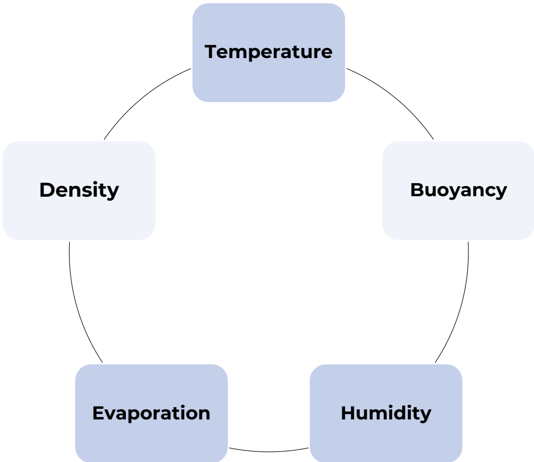
DEFINITION

- Aerosols are small droplets emitted during different activities such as breathing, talking and coughing.
- Contained in jet of air from lungs exhaled through mouth or nose within cloud of gas and droplets
- Formation via picking up respiratory fluid from lungs, throat and mouth.
- Big debate on threshold diameter definition during COVID-19 pandemic:
  - World Health Organisation (WHO) 'historic' position less than 5µm.
  - More recent definition favoured by many aerosol scientists based on their ability to remain airborne for minutes or hours travelling long distances due to their small size and mass before they evaporate or disperse – *less than 100µm.*

IMPORTANCE

- Scientific community has demonstrated through accumulated evidence and analysis of reported super-spreading outbreaks that one of the modes of transmission of SARS-CoV-2 is the airborne route.
- It is considered that airborne transmission occurs through the inhalation of aerosols that contain viruses which can deposit in the lungs due to their smaller size.

(Shen 2021) (Escandón, 2021) (Malki-Epshtein, 2022) (Jones and Iddon, 2021a)



Many environmental factors change composition of a droplet in a gas cloud. Impact of acidity, UV radiation and salinity on a virus particle are not discussed in this guide. A typical exhaled droplet consists of:

- Saliva
- Protein
- Salts

EFFECT OF ENVIRONMENTAL CONDITIONS ON DROPLETS WITHIN AN AEROSOL CLOUD

DROPLET AND CLOUD HUMIDITY

- High humidity reduces the droplet evaporation rate
- Low humidity increases the droplet evaporation rate
- Droplet evaporation increases local relative humidity

DROPLET AND CLOUD DENSITY

- Composition of droplet affects its evaporation rate
- If considered pure water, it will fully evaporate
- If considered saline, e.g. saliva, the components of salt and water directly affect the evaporation rate and some 'solids' remain
- Size and number of droplets influence the mixed density of exhaled cloud

DROPLET AND CLOUD TEMPERATURE

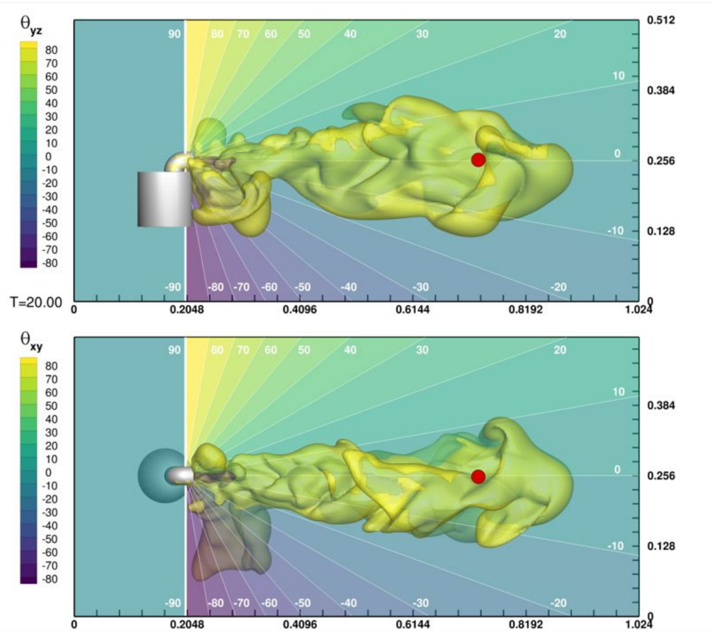
- High cloud temperature increases droplet evaporation rate
- Low cloud temperature reduces droplet evaporation rate
- Droplet evaporation influences the cloud temperature locally
- Droplet temperature at its surface different to cloud temperature – the heat from the evaporating volume of the droplet reduces the temperature of the aerosol cloud

EFFECT OF ENVIRONMENTAL CONDITIONS ON DROPLETS WITHIN A CLOUD

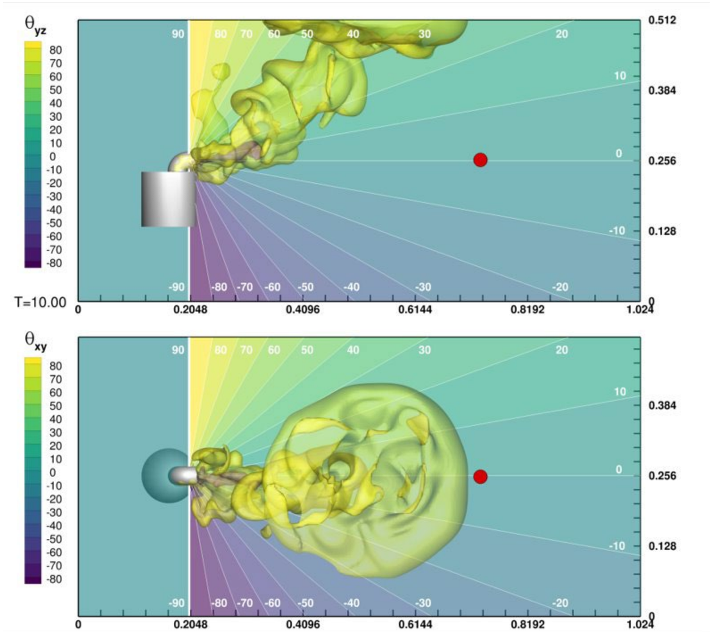
CLOUD BUOYANCY, DENSITY AND TEMPERATURE

- As cloud density increases, cloud buoyancy reduces
- Higher cloud temperature, compared to ambient, increases buoyancy
- Lower cloud temperature, compared to ambient, reduces buoyancy

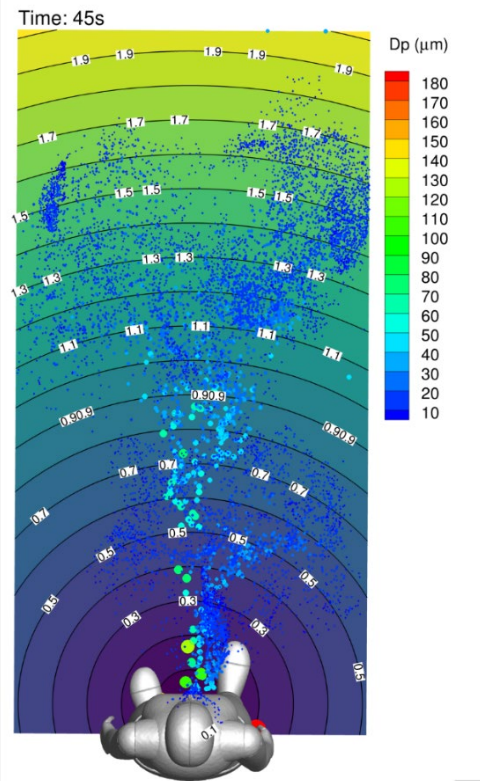
These CFD models show an aerosol cloud emitted from the nebuliser used in the AIRBODS test chamber. The thermally neutral cloud scenario (bottom left) shows a very different distribution to the positively buoyant one (bottom right).



CFD model of nebuliser with neutral buoyancy



CFD model of nebuliser with positive buoyancy



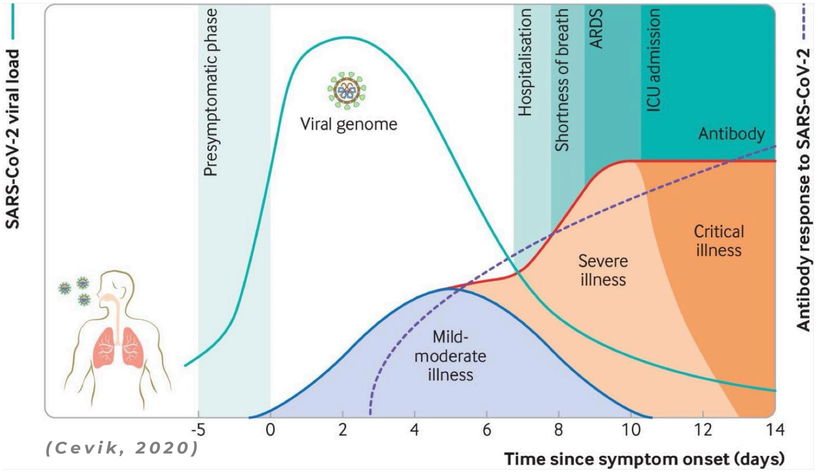
AIRBODS CFD model of exhaled breath at one point in time showing particle suspension in air viewed from above. The movement of different diameter (Dp) droplets in air and their deposition at ground level are indicated.

DROPLETS AND THEIR MOVEMENT IN AIR

- Warm, humid cloud of exhaled breath has thousands to millions of droplets from very small aerosols to large droplets.
- Droplet fluid evaporates at a greater rate in drier ambient air.
- Larger droplets become smaller (aerosols) by evaporating.
- When emitted, larger hydrated droplets (over 100μm) make up less than 5% of the total number yet represent more than 60% of the exhaled volume of respiratory fluid.
- Larger droplets tend to fall quickly to the ground due to their mass and the force of gravity. Smaller droplets and aerosols stay suspended in air for much longer, even hours.
- An infected person can pose an airborne infection risk if they produce droplets carrying virus particles. Virus particles are contained within droplets.
- We don't yet know how the virus is distributed in droplets. Infectious dose received is, therefore, dependent on the number and size or volume of droplets inhaled.
- Some activities (e.g. singing and coughing) produce more droplets and aerosols than others.

Some advanced CFD modelling techniques looking into the detail of modelling droplets are described in Section 8.

(Iddon, 2022c) (Jones and Iddon, 2021a)



(Cevik, 2020)

VIRAL LOAD

The viral load is dependent on many factors:

- Symptomatic and asymptomatic infectors.
- Approx. scale: 10^3-10^{12} SARS-CoV-2 RNA copies per ml of saliva.
- Increases over time from moment of infection.
- Peaks on average three days from the onset of symptoms - evidence from nasopharyngeal (NP) swabs.
- Over time, viral load reduces, usually within a week or more after the onset of symptoms.
- Knowing the viral load in saliva, it is possible to estimate the viral emission rate and therefore the number of viral particles a susceptible individual may be exposed to in a space and whether this may be enough for them to become infected.
- 'Virion' is a term used for viral particles.

Viral load (breathed out)	= Number of virus particles found in respiratory fluid of infected people

(Lai, 2022) (Cevik, 2020) (Cevik, 2021) (Hakki , 2022) (Ciric, 2020)

Viral load ≠ Infectious dose

INFECTIOUS DOSE

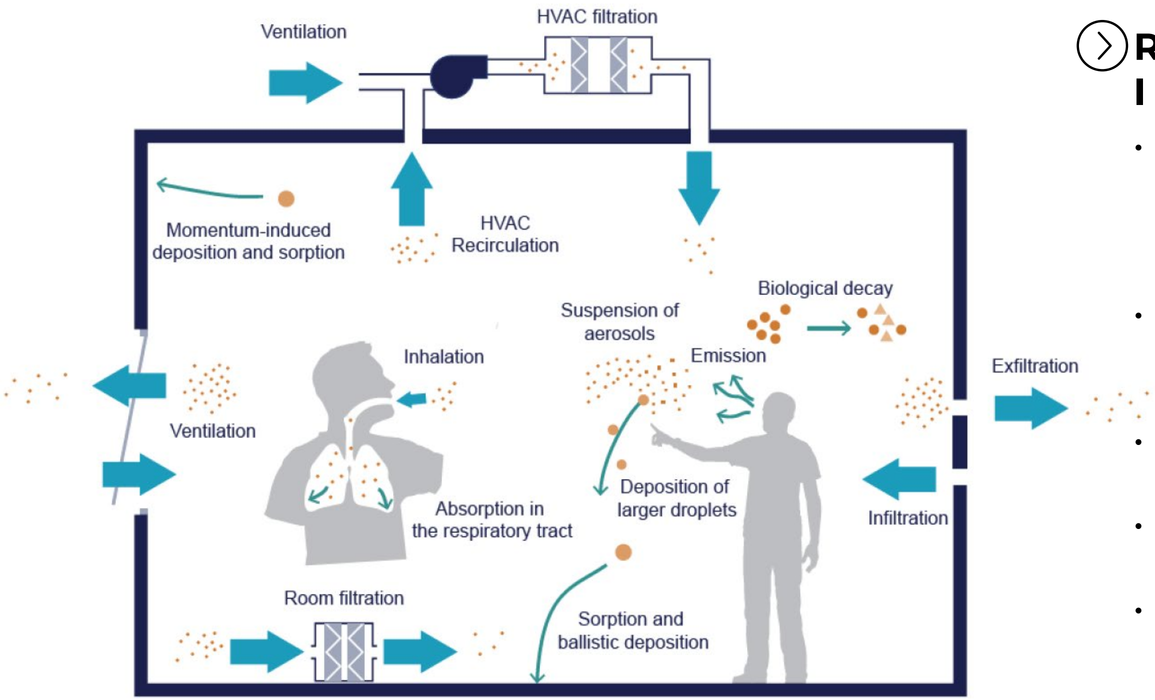
- Infectious dose still unknown for SARS-CoV-2.
- Varies significantly from person to person which is captured statistically in dose-response models.
- Large uncertainty in exposure time required for infection and how this is impacted by ventilation.
- High complexity and uncertainty around received dose, its impact on susceptible individuals and how the dose received by fomite route relates to aerosols.

Infectious dose (breathed in)	= Number of virus particles to which a susceptible person needs to be exposed to for the disease to develop

(Ciric, 2020)

3

AIRBODS AIRBORNE INFECTION RISK METRICS



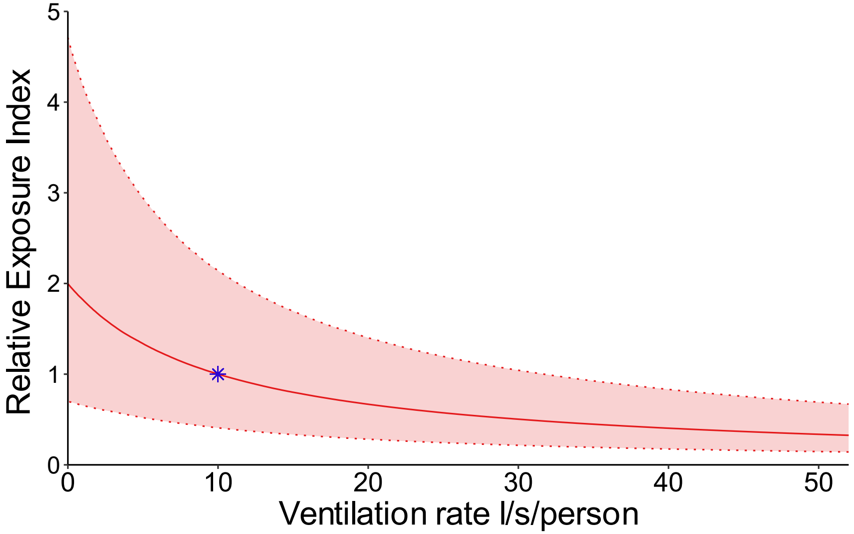
Gains:
- Emission from a person
- Entry from outside via ventilation
- Entry from outside via infiltration
- Virus already present in the space

Losses:
- Dilution via ventilation
- Surface deposition
- Biological decay and UVC denaturing
- Respiratory tract absorption
- Filtration

RELATIVE EXPOSURE INDEX (REI)- INDIVIDUAL RISK

- Relative Exposure Index (REI) metric is a measure of personal exposure risk to long range airborne viruses. It uses a mass balance approach to model the concentration of virus in the air and therefore estimate the inhaled dose (see left).
- REI is used to estimate the relative exposure to an expected inhaled dose of virus from the air in a given scenario in a space against a reference scenario.
- Method assumes a single infector with the same viral load is present in each scenario.
- It compares the calculated inhaled dose by susceptible occupants.
- Benefits are that the very large uncertainty in the viral load of an infector (and the subsequent emission rate of virus into the air) cancels out in the equations.
- It therefore provides an index of comparative *not* absolute risk.
- The comparative risk is of sharing a scenario with a given infector relative to the reference scenario.

(Iddon, 2022c) (Jones, 2021)



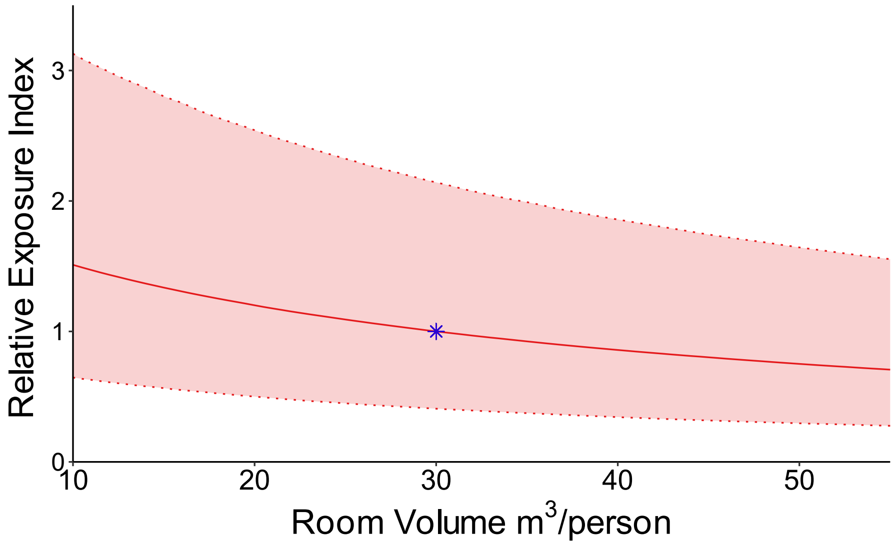
Graph showing how REI changes in a 20-person office as ventilation rate increases. Red line is the median REI and extents show the 95% confidence interval. Asterisk ventilation rate is 10l/s/person.

REI – EFFECT OF VENTILATION RATE

Reference 20-person office (see left):

- Increasing ventilation rate reduces the REI.
- Increasing the ventilation rate in poorly-ventilated spaces reduces the REI by more than if a well-ventilated space had the ventilation increased by the same amount. For example, compare REI at 0l/s/p with 10l/s/p and 20l/s/p.
- Doubling the ventilation rate does not necessarily halve the REI because there are other removal mechanisms.
- Uncertainty in viral emission rate, biological decay and deposition are also modelled.

(Iddon, 2022c) (Jones, 2021)



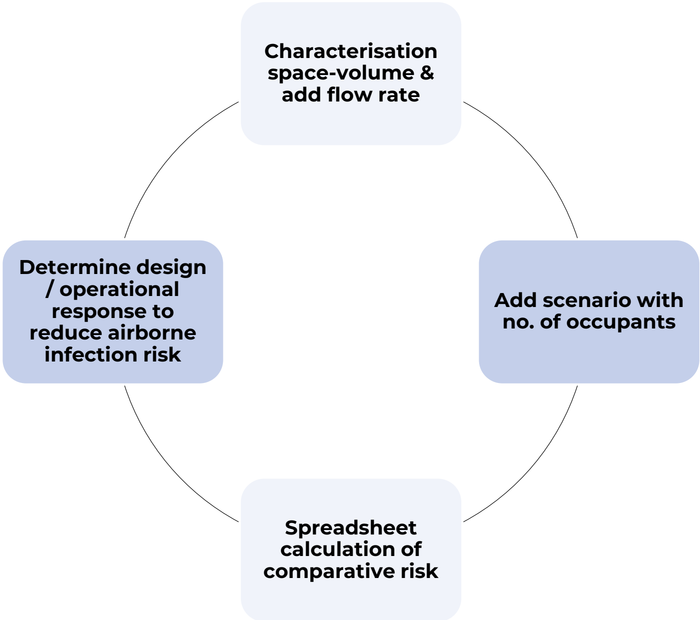
Graph showing how REI changes in a 20-person office as per person space-volume increases. Red line is the median REI and extents show the 95% confidence interval. Asterisk space-volume is 30m³/person

REI – EFFECT OF ROOM VOLUME

Reference 20-person office (see left):

- Increasing per person space-volume reduces the REI.
- Reduction is due to other removal mechanisms that are space-volume dependent (e.g. biological decay and deposition).
- Doubling the per person space-volume does not necessarily halve the REI because, in this case, the ventilation rate remains constant at 10l/s/person.
- Uncertainty in viral emission rate, biological decay and deposition are also modelled.

(Iddon, 2022c) (Jones, 2021)

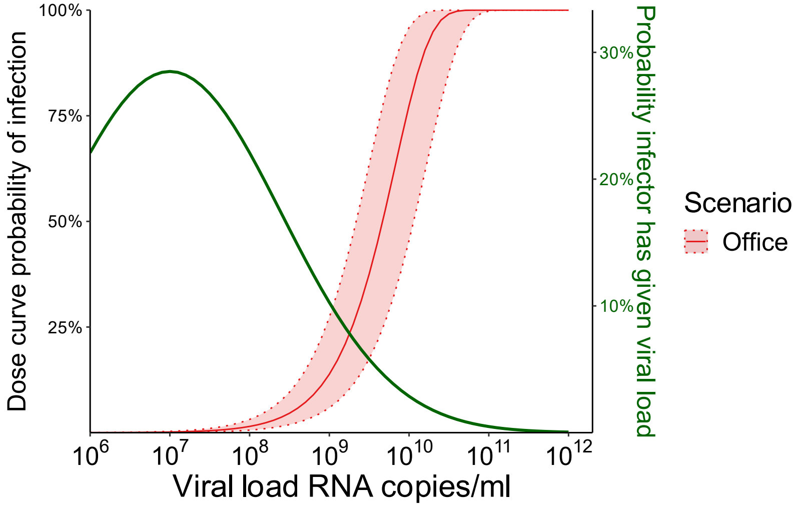


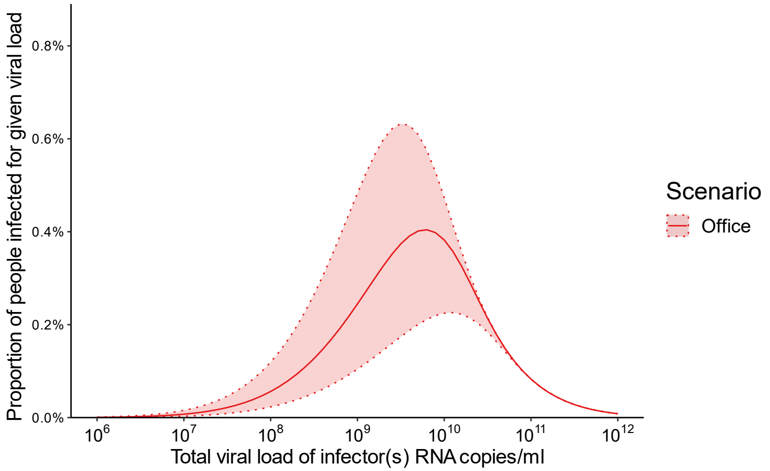
REI process

LIMITATIONS OF REI

- Assumes only one infector in the given scenario and not a measure of absolute risk.
- Assumes well-mixed spaces so doesn't account for spatial variation in aerosol concentration due to ventilation or aerosol sizes.
- Risk of infection is dependent on the inhaled dose and the dose response characteristics and transmission is known to be over-dispersed.
- If the infector viral emission rate is not sufficiently high it will result in very small inhaled doses and low risk of infection, even if the scenario has a high REI.

(Iddon, 2022c) (Jones, 2021)





PROPORTION OF POPULATION INFECTED (PPI)- POPULATION RISK

- Proportion of Population Infected (PPI) metric was developed to consider the probability of an infector being present in any given scenario.
- It includes the number of the susceptible people inhaling a dose and the probability of that dose giving rise to infection.
- Absolute values are still indicative due to assumptions related to current large range of uncertainty in:
  - Viral loads of infectors
  - Virion emission rate for a given viral load
  - Dose response curve.
- Impact of variables on the magnitudes of outputs provides a useful insight into the airborne infection risk at the population scale.
- The model assumes all non-infectors are susceptible and immune naïve.

This methodology with some modifications for application to buildings forms the basis for the BODS tool assessment described in Section 10 of this guide.

PPI values given in figures in this document are indicative only due to uncertainties in viral emission rate and dose response. The observed trends are useful for determining effect of various interventions but the absolute magnitude of PPI are indicative only.

(Iddon, 2022a, b & c)

	Units	20 Person Office Reference	comments and references for data
Number of occupants, *N*		20	
Space Volume, *V*	m^3	600	
Exposure time, *T*	h	8	
Air change rate, *ψ*	h^{-1}	1.2	
Air flow rate, *ψV*	ls^{-1}	200	10l/s/person
Biological decay, λ	h^{-1}	LN(0.63, 0.43)	Removal of viable virus due to biological inactivation, see van Doremalen et al 2020
Surface deposition rate, *γ*	h^{-1}	U(0.61, 2.48)	Removal of aerosols by deposition onto surfaces, see Thatcher et al 2002
Removal rate, *φ*	h^{-1}		calculated, Jones et al 2021
Equivalent ventilation rate, *φV*	ls^{-1}		calculated, Jones et al 2021
Respiratory tract absorption fraction, *K*	%	U(0.43,0.65)	Not all inhaled aerosols deposit onto respiratory tract, only a proportion, see Darquenne et al 2012
Respiratory rate, q_{resp}	m^3h^{-1}	N(0.56,0.056)	Breathing rate for sedantry adult males, other rates can be found in Adams et al 1996
Respiratory activity, *breathing:talking*	%	75:25:00	Respiratory activity effects average aerosol diameter and number of aerosols generated per unit volume of exhaled air, derived from data in Morawska et al 2009, see Jones et al 2021
Concentration of aerosols in exhaled air, C_{drop}	droplets/m^3	N($1.5x10^4$,$1.5x10^5$)	calculated, Jones et al 2021
Droplet diameter geometric mean, D_{drop}	µm	N(1.84,0.18)	calculated, Jones et al 2021
Evaporation constant, E_{const}		125	Aerosol hydrated diameter can be up to 5 fold greater than measured in experiments like Morawska 2009, here we assume that the hydrated volume is 125 greater, ie 5 fold greater diameter. See Nicas et al 2005
Dose constant, *k*		410	The number of viable viruses required to give a 63% chance of infection, here a value for SARS-CoV-1 is used, see Iddon et al 2022b for limitations
Viable fraction, *v*	%	100	Only a proportion of measured viral genome is viable virus, see Iddon et al 2022b for more information
Community infection rate *(CIR)*		1:100	The number of covid positive individuals within a community, see Iddon et al 2022b for more information
Viral load, *L*	log_{10} RNA copies ml^{-1}	N(7,1.4)	The amount of viral genomic material per ml of respiratory fluid, derived from Chen et al 2021, see Iddon et al 2022b for limitations

Example of some of the spreadsheet data inputs and outputs

EXAMPLE CASE: OFFICE

The following example is for a 20-person office space with the following key inputs:

- Ventilation rate – 10 l/s/person
- Space -volume – 30 m^3/person
- Exposure time – 8 hours
- Community infection rate – 1:100

- The results from the reference space can then be compared to other spaces or adjustments to model inputs can be analysed.
- This first set of results is an example of a good environment which is quite spacious and well ventilated.

- Outdoors
- Outdoors, sheltered
- Indoors, naturally ventilated, high ventilation
- Indoors, naturally ventilated, low ventilation
- Indoors, mechanically ventilated

Ventilation classification

- Arrival and Departure Areas
- Dwelling Areas
- Concessions / Bars-Standing
- Bars / Restaurant-Seated
- Main Activity Areas (Structured)
- Main Activity Areas (Unstructured)
- Private Boxes / Meeting Rooms
- Toilets, Corridors, Lifts, Stairwells (small, enclosed, short occupancy)

Usage classification of spaces at event venues

SPACE CLASSIFICATION

To aid with the analysis of the measurements, the different space types across the building need to be identified and grouped according to their usage, as well as their ventilation strategy. In certain cases:

- Identify spaces that will be used for 'structured' activities, for example, in performance venues where there is allocated seating.
- Consider spaces where there is 'unstructured' usage where occupants can freely move around, for example in a music festival.
- Even primarily outdoor events will typically have indoor concession stands, bars and toilets.
- Tents can become indoor spaces if they are unventilated.

(BSI, 2017) (CIBSE, 2015a) (Building Regulations, 2010) (HSE, 2022) (Adzic, 2022a)(SAGE, 2021) (Malki-Epshtein, 2022) (Malki-Epshtein, 2023)

GROUPING OF SPACES




- A building may have a large variety of spaces in terms of space utilisation, access to outdoor air and ventilation strategies.
- When developing a ventilation strategy, it is recommended to group spaces according to their ventilation characteristics and space classification as well as activity, dwell time and structure of occupants, for example:
    - Open plan office - structured seating, desk-based activity, long occupancy.
    - Social space - unstructured occupancy, higher activity, variable dwell time (building type dependent).
    - Circulation – unstructured occupancy, walking/standing, short occupancy (transient zone).
    - Concession in large venue – unstructured occupancy, higher activity, variable dwell time (transient zone).

(Malki-Epshtein, 2022)

Air Quality Bands	Classif-ication	Range of CO_2 concentrat-ions: Absolute values (ppm)	Range of excess CO_2 concentrat-ions: Above outdoor (ppm)
At or marginally above outdoor levels	A	400 - 600	0 - 200
Target for enhanced aerosol generation (singing, aerobic activity)	B	600 - 800	200 - 400
High air quality design standards for offices	C	800 - 1000	400 - 600
Medium air quality	D	1000 - 1200	600 - 800
Design standards for most schools pre-Covid	E	1200 - 1500	800 - 1100
Priority for improvement (SAGE EMG)	F	1500 - 2000	1100 - 1600
Low ventilation/dense occupancy. Must be improved	G	>2000	>1600

AIRBODS have developed an indoor air quality (IAQ) classification system based on SAGE, BSI and CIBSE guidelines which allows for detailed analysis of different types of spaces used for different purposes.

IAQ CLASSIFICATION SYSTEM

- When concentration < 800ppm (absolute value) - space likely to be well-ventilated albeit this does not mean that it does not bear a risk of indoor airborne transmission of viruses.
- When concentration > 1500ppm - space likely to be poorly ventilated or overcrowded and actions should be taken to improve the quality of ventilation.
- To achieve 800-1000ppm, supply outside air around 10 l/s per person in typical indoor spaces (current Building Regulations).
- Risk > 1500ppm when supplying outside air less than 5 l/s per person.
- Target < 800ppm in high aerosol spaces (e.g. exercising or, singing) or where there is a high chance of infectors being present.

(BSI, 2017) (CIBSE, 2015a) (Building Regulations, 2010) (HSE, 2022) (Adzic, 2022a)(SAGE, 2021) (Malki-Epshtein, 2022) (Malki-Epshtein, 2023)

4

CHALLENGES TO INCREASING AIRBORNE INFECTION RESILIENCE

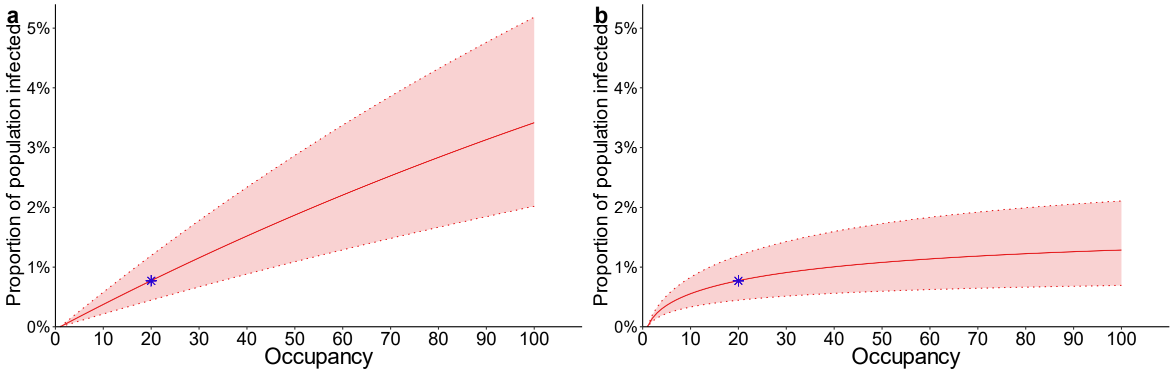
AIRBORNE INFECTION RISK (↓) = **AIRBORNE INFECTION RESILIENCE** (↑)

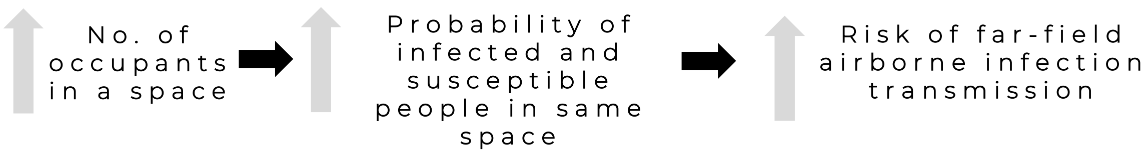
CONTEXT

- In a pandemic there are limitations to "designing out" airborne infection risk.
- There are some highly sensitive parameters that are not within the control of building operation and design decision-making but influence resilience:
    - Community infection rate
    - Infectious dose required to cause infection
    - Shedding of viral load in a shared indoor space.
- It is prudent to consider feasibility, affordability and operational efficiency when considering airborne infection resilience.
- It is important to consider regular operation of space and systems, prepare for operation in a pandemic mode *and* think about 'rare' extreme scenarios but do not over design for them.
- All influencing factors that can be controlled (managed through building operation and design) as well as those that are uncontrolled, such as behaviour, should be considered.

The following *controllable* parameters impact airborne infection risk:

- Occupancy levels
- Activity levels
- Exposure time





Equivalent ventilation rate is the sum of all the removal mechanisms that remove the virus from the air, i.e., biological decay, filtration, deposition.

CHANGE OCCUPANCY LEVELS

- Reducing the number of occupants is the most effective way of increasing airborne infection resilience when compared with increasing the space-volume per person or increasing the ventilation rate per person.
- [Image on left] When the volume (600m^3) and ventilation rate (200l/s) are kept constant and the occupancy increases, PPI risk (at population level) increases as occupancy increases. The ventilation rate per infector increases.
- [Image on right] For same space-volume (15m^3/person) and ventilation rate per person (10l/s/person), PPI risk (at population level) increases at a diminishing rate when increasing occupancy levels. This is because the equivalent ventilation rate increases at a higher rate than the probability of the mean number of infected people.
- The asterisk denotes the reference scenario as described in earlier 20-person office case.

(Iddon, 2022b)

CHANGE ACTIVITY

- Respiratory activity determines the total volume of aerosols emitted per unit volume of exhaled breath. It varies significantly between people, depending also on their respiratory capacity.
- When a person is infected, viable viral genomic material is emitted through the droplets they exhale. Singing and talking generally produce more genomic material than breathing, albeit with high variability.

	Estimated RNA copies h^{-1}
Breathing	203
Voiced counting (talking)	967
Vocalisation (singing)	6198
Breathing:talking 25:75	394

Example estimates of virus emission rates for different activities. Assumes 10^7 RNA copies ml^{-1} viral load. There are many references that provide alternative values.

CHANGE EXPOSURE TIME

- Exposure time is typically related to when a steady state concentration of virus in the air of an enclosed space has been reached.
- It enables the number of viral copies (dose) to which a susceptible person inhales (at a steady rate) to be calculated.
- As the exposure time increases, the probability of infection increases.

(Coleman, 2021) (Morawska, 2009) (Iddon, 2022b)

The following *uncontrollable* parameters impact airborne infection risk:

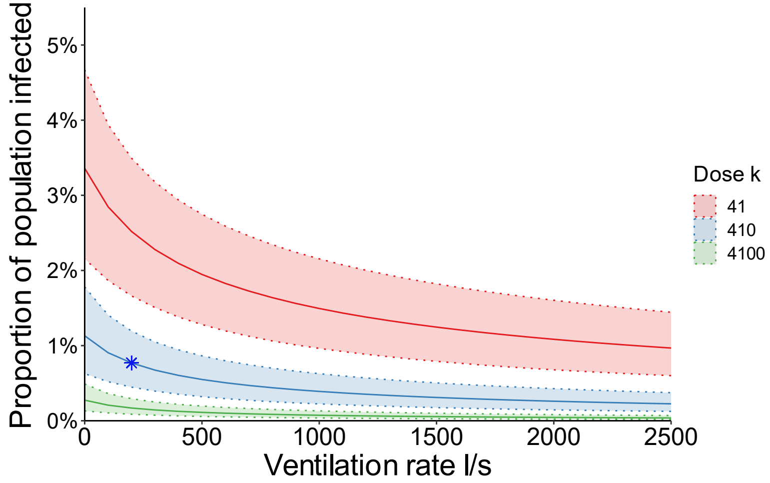
- Viral load
- Infectious dose
- Community infection rate

Viral emission rate is the amount of virus released from an infected person into the air which does not immediately deposit under gravity. The emission rate is dependent on the viral load of the infector, the exhalation rate and the respiratory activity undertaken, e.g., singing and loud talking can increase aerosol volume by 30-fold compared to breathing alone.

VIRAL LOAD

- Viral load (introduced in Section 2) is one of the most important parameters impacting risk of transmission as it influences the viral emission rate (see left).
- When the total viral load in a space is very high, building design measures, e.g. space geometry, are unlikely to significantly reduce risk of infection.
- When the total viral load is very low, it is unlikely to cause any infections in a space, irrespective of its geometry.
- As a result, extreme scenarios are not applicable when considering design measures to increase airborne infection resilience in a space.

(Iddon, 2022b)



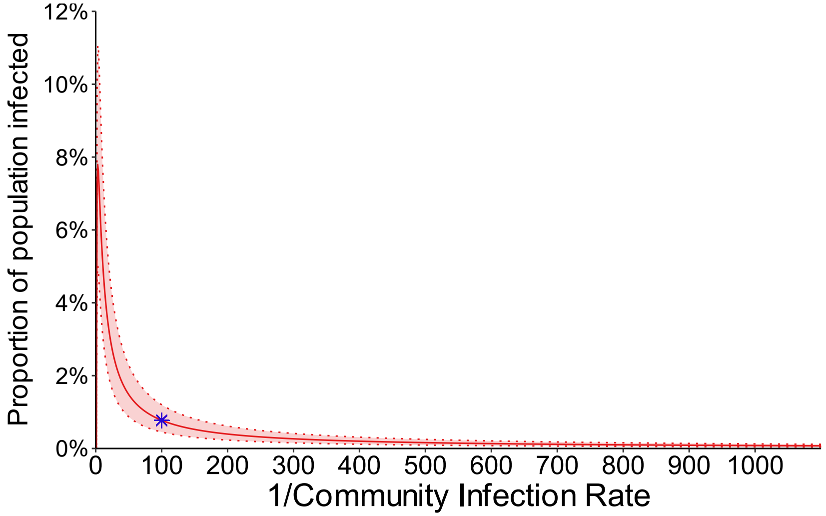
Example showing the effect of increasing ventilation rate for different dose constant, k. The solid lines are the median PPI curves. In summary:

1) Sensitivity test of dose on PPI risk assuming two equally sized populations distributed in a two-room scenario.
2) 10-fold higher and a 10-fold lower k are considered for increasing ventilation rates.
3) A lower k value represents a higher infectivity, i.e. a lower dose is required to cause infection.
4) For k = 410 and 500 L/s ventilation rate, the median PPI is 3.1%.
5) For k = 41 (10 times higher infectivity), increasing the ventilation rate even to 10 times higher (5000 L/s), would still give a higher PPI (4.7%).
6) In fact, for the given assumptions of the tested scenario, approximately 11000 L/s would be required to reduce PPI back to 3.1% (22 times more).
7) If k value remains constant, differences in viral variants results in increased or decreased viral loads and therefore infector viral emission rate.

INFECTIOUS DOSE

- Infectious dose was introduced in Section 2.
- The viral emission rates from infected people and the dose response of susceptible people for SARS-CoV-2 (also noting different variants) are:
  - Highly sensitivity parameters within any assessment.
  - Impact the effectiveness of ventilation options when exploring airborne infection resilience.
  - Values remain unknown.
- A number of studies have used a dose constant, k, of 410, based on the dose curve of SARS-CoV-1 as an assumption.
- This constant is also used in the AIRBODS REI & PPI models and is a key limitation in our knowledge of SARS-CoV-2 and our ability to estimate infection risk in absolute terms.
- Using this base assumption, the example in the box to the left shows that, for viral variants with increased transmissibility, maintaining the absolute levels of airborne transmission risk through ventilation may be unachievable. This is due to unrealistically high ventilation flow rates that may be required.

(DeDiego, 2008) (Zhang, 2020) (Parhizkar, 2021), (Watanabe, 2010) (Iddon, 2022b & c)



Example showing how PPI of the reference 20-person office (as described earlier) changes with different modelled and monitored community infection rates. The asterisk denotes the 20-person office with a CIR of 1:100.

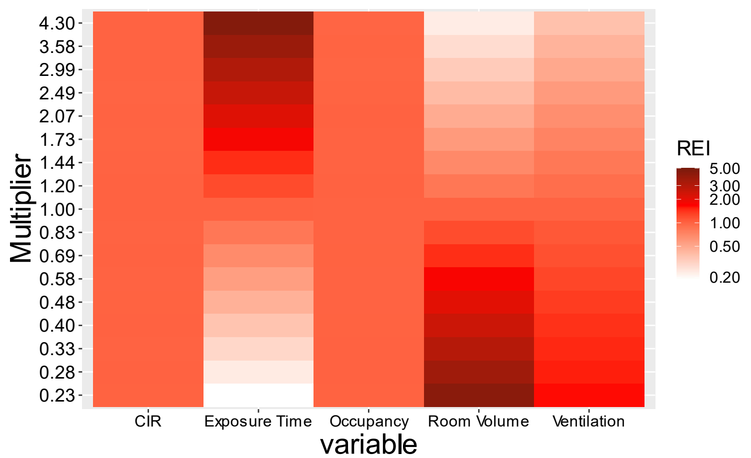
COMMUNITY INFECTION RATE

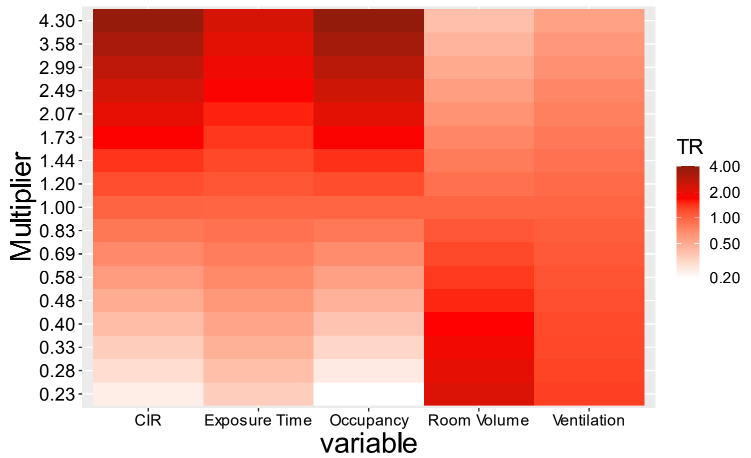
- Community infection rate (CIR) is a measure of the prevalence of infectors in the wider population (or subset population of interest).
- CIR may vary by region or by a particular population demographic.
- As CIR increases, the probability of an infector and susceptible person being present in the space increases.
- As a result, the viral load, dose received and probability of infection in the modelled scenario increases.

Key findings:

- When CIR is low (less than 1:300 infected), the proportion of population infected is very low thus any mitigations that reduce the PPI further are only operating on already low values.
- When the CIR is higher (e.g. 1:100), increasing the ventilation rate to reduce the PPI to the levels predicted when CIR is 1:300 would need to be unrealistically large.

(Iddon, 2022c)





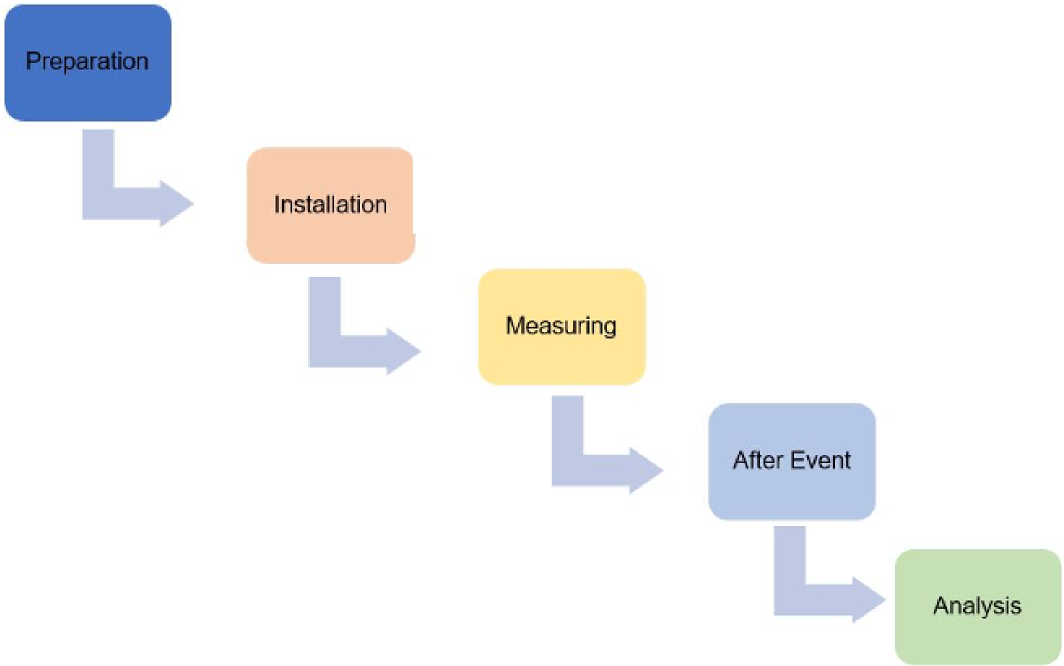
UNDERSTANDING COMPARATIVE SENSITIVITY

- Using the 20-person office example, the multiplier is used to multiply the tabulated variable shown earlier. Using the ventilation variable, for example, 1.2*200l/s is 240l/s and 0.83*200l/s is 166l/s.
- The multiplier steps increase by 1.2-fold compared to the previous step. Coloured results are presented on a log scale – see left.
- The transmission ratio (TR) is the PPI for the comparator divided by the PPI for the reference office scenario (described earlier).
- CIR and occupancy do not affect REI as the method assumes that one infector is present.
- Reducing the CIR reduces the TR because there are less interactions of index cases with susceptibles within the population of 20-person offices.
- Reducing the exposure time reduces the PPI, whilst reducing the REI by more than any other variable. Reduced exposure to an index case reduces the inhaled dose.
- Reducing the occupancy reduces the TR because there are less interactions of index cases with susceptibles within the population of 20-person offices.
- Increasing room volume per person reduces the REI and TR, by increasing the effective ventilation of biological decay and deposition (which are space-volume dependent).
- Increasing the ventilation reduces the REI and TR, but at a slower rate compared to changes in occupancy and exposure time.

(Iddon, 2022c)

5

ENVIRONMENTAL SURVEYS



THE MONITORING PROCESS

1) Preparation:
- Survey the building and plan for sensor installation.
- Collect details on the operation, e.g. occupancy times and usage of the various spaces.
- Meet building managers and request building drawings, seating plans and discuss ventilation strategies.

2) Installation:
- Install CO_2 sensors in the monitoring zones.

3) Measuring:
- Measure and record the CO_2 during the operational time of the building.
- In unstructured events, important actions, such as occupants entering or leaving the space, interval duration, opening or closing of windows in naturally ventilated spaces, should be recorded.

4) After eventing survey:
- Confirm operational details as occurred during monitoring, e.g., occupancy numbers and locations, BMS data on ventilation operation (if available)

5) Analysis:
- Process and analyse CO_2 data.
- Identify areas for improvement and propose possible mitigation measures.

(Malki-Epshtein, 2022)

CO_2 monitoring is inexpensive, can be deployed rapidly and quickly identifies areas where exhaled breath is accumulating.

WHY CO_2 MONITORING?

- Strong relationship between occupancy levels, airborne infection risk, and outdoor air provision.
- In most indoor spaces the only source of CO_2 above outdoor levels is human breath.
- CO_2 concentration can be used as a proxy for exhaled breath relative to outdoor air provision.
- High CO_2 concentration is indicative of poor or insufficient ventilation levels.
- CO_2 concentration depends on number of occupants, their respiratory activity / body mass and the removal rate depends on the ventilation rate.
- CO_2 monitoring is inexpensive, can be deployed rapidly and quickly identify areas where exhaled breath is building up in indoor spaces.
- CO_2 monitoring can help building owners and managers identify poorly-ventilated or overcrowded spaces and suggest mitigation options.
- CO_2 monitoring can help occupants manage existing ventilation with the aim of balancing the need for good indoor air quality alongside thermal comfort, moisture, energy use and noise control. This is useful in the heating season, when overventilation can cause thermal discomfort and have a significant energy cost, but also in the cooling season, when the need to keep heat out of the space prevents occupants from letting outdoor air in.

(SAGE, 2021) (Malki-Epshtein, 2022)

ADDITIONAL THOUGHTS WHEN CONSIDERING CO_2 MONITORING

- CO_2 is not a direct expression of the risk of airborne transmission as there are other factors that influence the fate of virus-laden aerosols.
- CO_2 measurements should be used as a general guide to the ventilation and indoor air quality (IAQ) within a space.
- A rapid, temporary installation of CO_2 monitoring can give valuable insights about current ventilation provision for in use occupancy, highlighting where improvements may be necessary. For some buildings it may be a better solution than long-term monitoring, which can be more expensive and requires a certain level of expertise that the occupants may not have.
- More elaborate analyses can be undertaken to include more environmental factors, such as temperature and humidity, however a speedier analysis using only CO_2 can give meaningful insight to building professionals with respect to managing the airborne transmission risk in their space.

(SAGE, 2021) (Malki-Epshtein, 2022)

Characteristics of space	Examples	Suitability of CO_2
Small spaces up to 125m^3/ 50m^2 Occupied by a consistent number of people for >1 hour	Domestic settings where there is more than one person, small offices and meeting rooms, hospital patient rooms	Can be used, but results should be treated carefully as concentrations may be influenced by occupant variability
Small spaces up to 125m^3/ 50m^2 Occupancy is transient and varies over short periods	Changing rooms, small retail, circulation spaces	Unlikely to give reliable readings so data should be treated with care
Mid-sized spaces 125 – 800m^3/ 50-320m^2 Occupied by a consistent number of people for >1 hour	Larger office and meeting rooms, classrooms, restaurants/bars, some retail spaces, some indoor sports (low aerobic activity)	Often well suited to monitoring as the higher numbers of occupants provides more reliable values. May need to adjust for activity in some settings
Mid-sized spaces 125 – 800m^3/ 50-320m^2 Occupancy is transient and varies over short periods and/or occupant density <1 person/20m^2	Some retail spaces, larger circulation spaces	Can be used, but results should be treated carefully as concentrations may be influenced by occupant variability
Large spaces over 800m^3/ 320m^2 Occupied by a consistent number of people for a well-defined period of time	Large retail spaces, concert venues, large places of worship, airport concourse, larger sports halls	May be appropriate for monitoring in the occupied zone, but less likely to be well mixed and hence may require multiple sensors to provide meaningful information
Large spaces over800m^3/ 320m^2 Occupancy is transient and varies over short time periods	Large atria, rail concourse, shopping malls	Unlikely to give reliable readings so data should be treated with care

Suitability of CO_2 monitoring in different types of space

CO_2 MONITORING: WHAT'S MY STRATEGIC PLAN?

- In larger spaces and spaces with higher ceilings it cannot be assumed that the air is fully mixed and CO_2 monitors may be less representative of the average CO_2 levels within the breathing zone of the room.
- High-resolution monitoring, as carried out within the AIRBODS programme, can show details of CO_2 concentrations in different parts of a space and an understanding of how well mixed the space is, which cannot be done with a lower number of sensors.
- High-resolution monitoring allows for monitoring the entire building and not just selected spaces within the building.
- The table to the left provides guidance on the suitability of CO_2 monitoring for different types of space. It can be used to determine whether a high-resolution monitoring approach should be adopted.

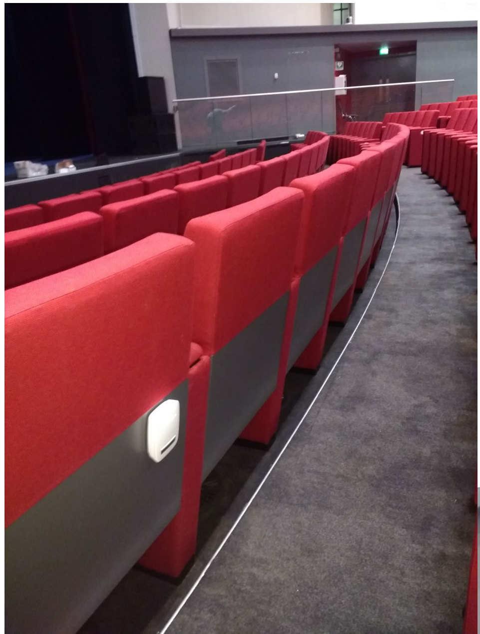
(SAGE, 2021) (Malki-Epshtein, 2022)

AIRBODS team member setting up CO_2 sensors

SELECTING AND SETTING SENSORS

- CO_2 sensors should be non-dispersive infrared (NDIR), as they have been shown to give more reliable readings. An accuracy of +/-3% of reading and a range of 400-5000 ppm is reasonable.
- CO_2 monitors with visual displays are more likely to lead to improved ventilation where CO_2 concentrations in spaces are continually monitored.
- In spaces with frequent changes and people movement (for example, a transport station), it is advisable to set a sampling interval at 2 minutes to allow for measurements to capture these changes. In spaces of more stable occupancy, e.g. in an office space, a 10-minute sampling interval may be sufficient.
- A method for storing and accessing the data should be established early on, based on the available options. For example, it may be that the data of each sensor are sent to a database, from which they can be downloaded, or it might be possible to connect them to an online dashboard for real-time monitoring. Sensors that log data continuously and which can be accessed remotely via a dashboard are particularly useful. Doing so would allow instant notification when the CO_2 levels exceeds threshold values.
- To ensure reliable calibration and quality of measurements, it is advisable to do some testing, once sensors are installed. This can include checking the measured values outside occupancy hours to see if they match outdoor CO_2 levels and sanity-checking them during the monitored occupancy period.
- When CO_2 readings are particularly low (<500ppm) or high (>1500ppm) they can be checked by moving the position of the monitor before taking action.
- It is often more appropriate to measure CO_2 relative to the background concentration, rather than in absolute values in order to manage differences in sensor calibration offset.

(V-KEMS, 2021) (SAGE, 2021) (Malki-Epshtein, 2022)



PLACEMENT OF SENSORS

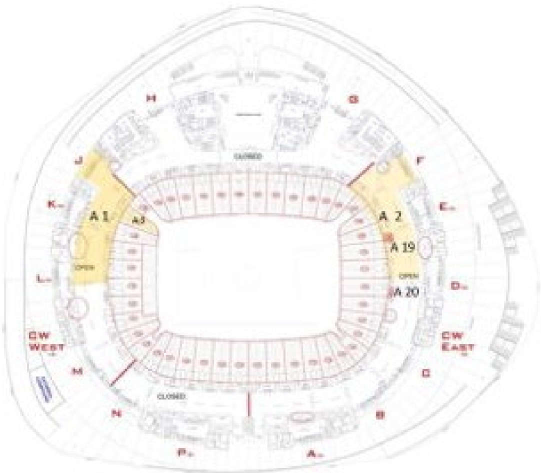
- A registry of where the sensors are installed around the building is important to enable data processing.
- The placement of sensors should be away from airflow inlets or natural ventilation openings. When occupants are expected to be standing, appropriate heights to place sensors, e.g. on walls, would be within 1.6-2.3m, to be within the breathing zone or higher to prevent tampering. In some cases, it may be useful to place sensors higher in order to understand if stratification of airflow occurs and to measure CO_2 outside the breathing zone.
- IAQM and CIBSE have recommended sensors being placed within the breathing zone at heights of 1.1-1.7m, and BSI at 1.5m above the floor.
- BSI suggests placing sensors 1-2m from walls, although this was found not to be possible in some settings . In theatre auditoria that were monitored, most sensors were placed on the back of seats or under them, except for the cases where there were under-seat ventilation components or inlets.
- It is noted that CO_2 monitoring in extract ducts only can underestimate CO_2 levels in the breathing zone in large spaces (see Case Studies in Section 9).
- Spaces with high occupancy over longer periods of time (one hour or more) should be prioritised for CO_2 monitoring.

(BSI, 2012) (Adzic, 2022a) (V-KEMS, 2021) (IAQM, 2021)

ADDITIONAL PLACEMENT CONSIDERATIONS

- It is important to understand how the different areas around the building are used to support separating them into monitoring zones. The zones are spaces within the buildings, usually defined by geometry (e.g. w.c., restaurant, corridor).
- The number of sensors per building will depend on its geometry and layout. It is recommended to use more than one monitor in each space so that varying conditions can be represented more accurately and give more understanding of what concentrations prevail in the occupied zones.
- The resolution of CO_2 monitoring should aim to capture varying conditions in a space where there is occupancy and should consider the following parameters:
  - Different occupancy densities
  - Different activity level (for example, audience versus performers in a theatre auditorium)
  - Proximity to inlet or outlet of ventilation system
  - Proximity to natural ventilation openings
  - Changing conditions at different heights of occupancy, in spaces like auditoria or atria with mezzanine levels

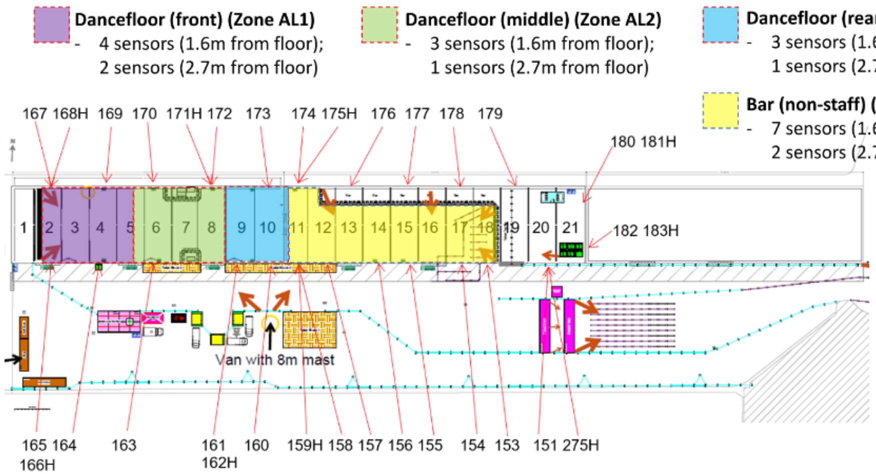
(BSI, 2012) (Adzic, 2022a) (V-KEMS, 2021) (IAQM, 2021)



ADDITIONAL CONSIDERATIONS

- Consider other potential sources of CO_2 beyond just occupants. Where there are high levels of combustion, for instance in kitchens, measurements are unlikely to represent ventilation per person. Other sources could include, for example, candles, propellants for confetti cannons, dry ice effects for serving high end cocktails and theatrical smoke, although water-based systems are more common in the latter nowadays.
- During the preparation period, details about the building should be collected:
  - Drawings to allow estimating room volumes and to log sensor locations
  - Seating plans
  - Description of the ventilation strategy
  - A plan of activity or event if available
- It is recommended to keep a record of important details, such as significant change in occupancy/activity or change in the ventilation operation, that occur during the monitoring times. This may require the presence of an engineer in the monitored spaces or other means of recording activities.
- If Building Management System (BMS) data can be provided along with occupancy numbers, these can be particularly useful. The air temperature, outside air flow rates for each zone, information on air re-circulation (on or off), heat recovery (on or off), and air conditioning information would be particularly relevant.
- If additional sources of CO_2 are likely in the space monitor when these are not in use (if only sporadically). Where possible removing these from the space during the monitoring period is preferred.

(V-KEMS, 2021)



Divide large spaces into areas for analysis according to the different activities and their position in relation to the ventilation system. This helps identification of problematic zones and underlying issues. In the Circus Nightclub study, the space was split into four zones with the proximity of each zone to the openings noted.

PROCESSING DATA

- CO_2 data can be presented in time-series format during operation in a zone of interest. The high-resolution CO_2 monitoring methodology generates large volumes of data from which temporal and/or spatial averages or maxima can be used to quickly identify areas with poor ventilation rates.
- In large spaces, referring to individual sensor readings, average and maximum standard deviation values can be estimated and compared to the spatial average and maximum CO_2 concentrations, respectively. This can support the understanding of how well mixed the air is in the space and significantly differences between readings.
- Appropriate averaging CO_2 periods (e.g. hourly or daily) preferred over instantaneous readings depending upon objectives. For example, a shorter duration needed to understanding purging benefit from opening a window or short occupancy periods.
- In spaces with variable occupancy, average performance can be estimated from mean CO_2 values from the different occupancy events, where monitored CO_2 values are only considered during occupancy times.
- Average performance over the period of occupancy should include periods pre- and post-occupancy including people transition and interval times, depending on type of space and activity being monitored, e.g. live performances can drive rapid changes.
- The average and maximum CO_2 values estimated for each space can be classified into average and maximum air quality bands (see earlier).

(Adzic, 2022a) (SAGE, 2021)

CO_2 Decay Method

ln(Ct - CR) = - QΔt + ln(C0 - CR)

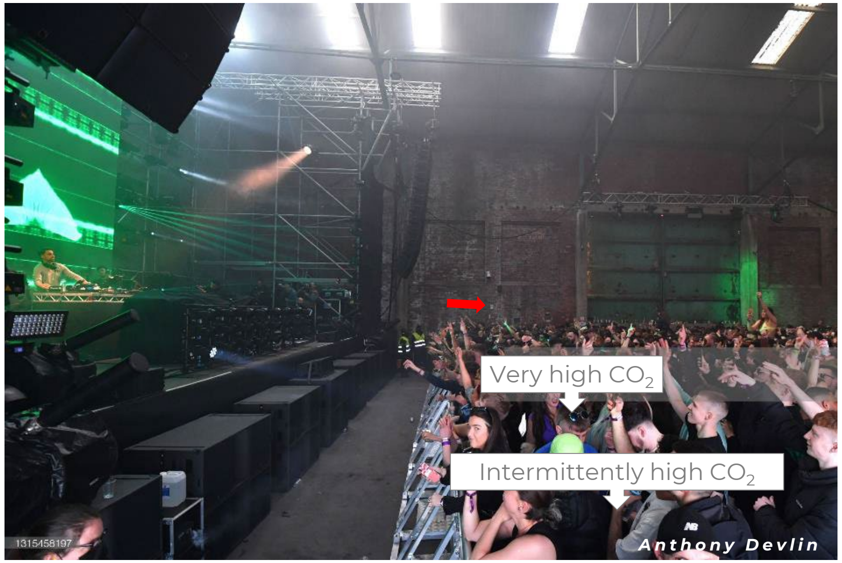
Where:
- Ct - CO_2 concentration at time t
- CR - CO_2 concentration in outside air or the steady state CO_2 of the lower occupancy
- C0 - CO_2 concentration at t=0
- Q - air change rate

- Plotting ln(Ct −CR) for each timepoint during the CO_2 concentration decay after a change in space occupancy enables the air change rate to be derived by regression analysis.
- C0 can be taken at a point right before occupancy starts to reduce, if the room CO_2 concentration is approximately at steady state.
- Uncertainty within the decay curve should be modelled to calculate a range of outside air flow rates, as well as CO_2 decays from measurements of various occupancy events for the space.
- The range of airflow rates calculated can be used to assess the ventilation performance in the space and the differences between different occupancy events.

ESTIMATING VENTILATION RATES FROM CO_2 MEASUREMENTS

- Knowing or having an estimate of the ventilation flow rate in a space is useful when interpreting results, assessing ventilation performance and supporting later detailed modelling exercises to identify if the system works as intended.
- If the ventilation flow rate in a room is not known, it is possible to calculate it using the CO_2 measurements.
- One calculation route uses the method of Roulet & Foradini (2002) and spatial CO_2 averages assuming, for instance, a uniform distribution of CO_2 in the space. This can be unrealistic, especially in the case of large spaces.
- Another route is through CO_2 decay using the method of Liddament - see a brief explanation of the method in the box to the left. This methodology can be applied when there is a significant change in occupancy, which can be confirmed through observations, for example, at the end of the occupancy period. The method may require assumptions about occupancy changes and steady state CO_2 concentrations. When using this method, it is important to ensure the ventilation is continuing to operate through the period of decay.

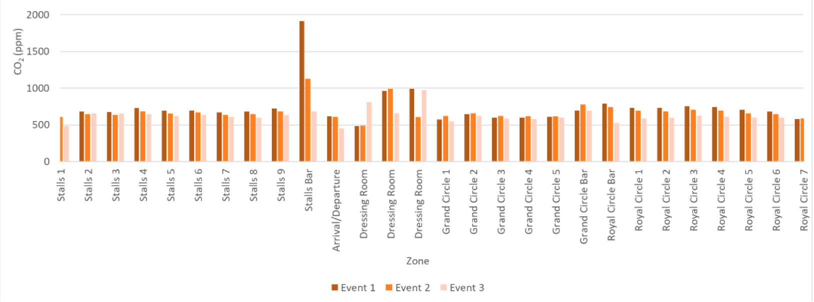
(Iddon, 2022b) (Liddament, 1996) (Roulet and Foradini, 2002) (Adzic, 2022a)



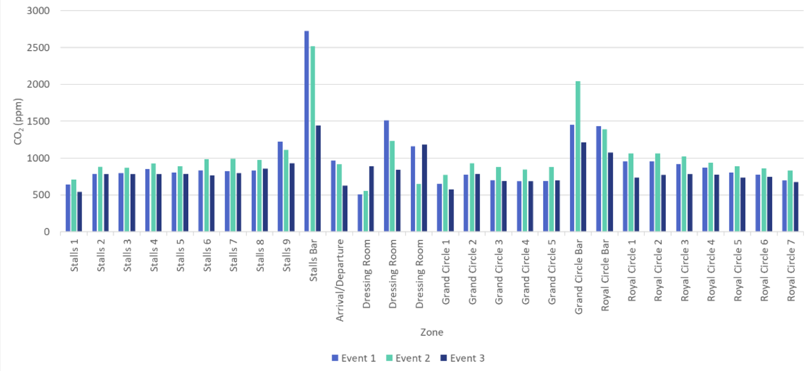
INTERPRETING DATA

The analysis of high-resolution CO_2 measurements can assist with answering the following questions:

- What indoor air quality class is achieved in the space?
- Are there indications of insufficient ventilation or overcrowding?
- Are there spaces that should be prioritised for improvements?
- Is there high variability between CO_2 measurements within the space? Could this be due to:
  - Varying occupancy density?
  - Poor mixing of air?
- Are there periods of time with particularly high occupancy?
- Do the ventilation controls work as expected?
- Is there a need to introduce or extend intervals in occupancy?



Average CO_2 levels in a variety of spaces in a theatre. The stalls bar zone has considerably higher average CO_2 compared to the auditorium zones due to overcrowding during intervals and insufficient provision of ventilation.

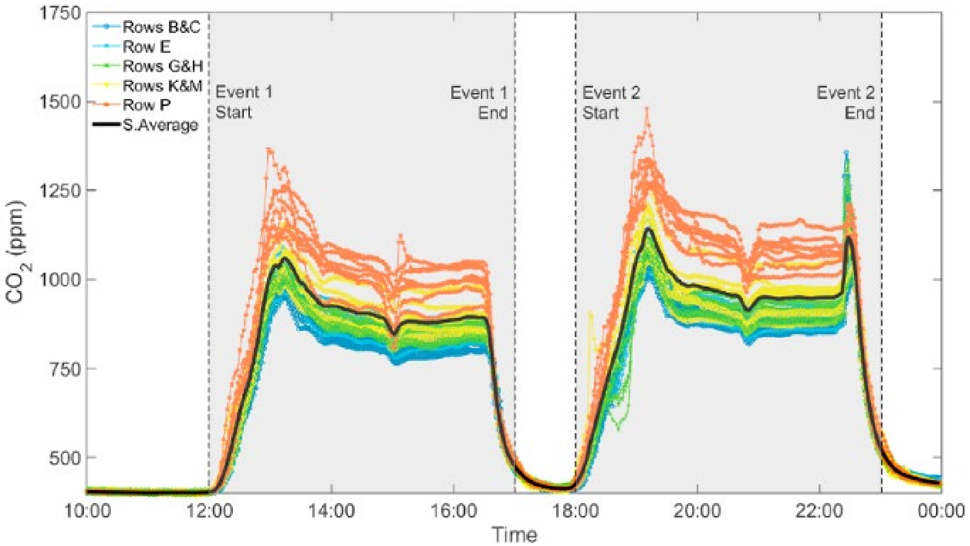


CO_2 maxima from the same theatre venue highlight much greater CO_2 readings in two of the three bar zones when compared to the rest of the theatre areas.

IDENTIFYING AREAS FOR IMPROVEMENT

High CO_2 values can indicate:

- High occupancy levels
- Poor ventilation due to:
  - Ventilation strategy not being adequate to preserve high air quality for the peak occupancy scenarios in the measured space
  - Poor maintenance or faults in the system

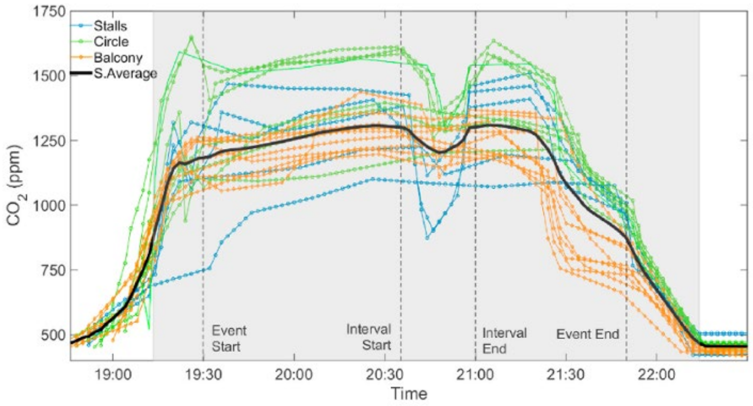


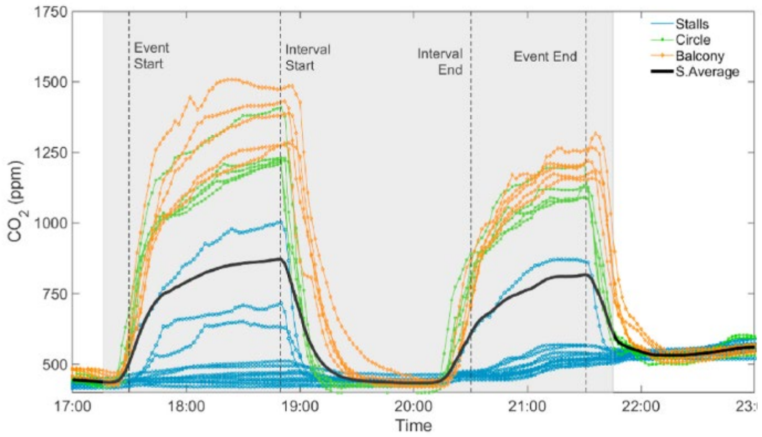
Time series of CO_2 measurements in a theatre on one day showed a difference of 400ppm between the back row and the front of the auditorium with the two areas having similar occupancy density. This demonstrates poor mixing of the air volume of the space. The effect of demand-controlled ventilation can be seen through the slow decrease in measured CO_2 levels after the set-point is reached. This implies that ventilation flow rates ramped up to maintain the target concentration. The activation of the demand control is also supported by the average CO_2 concentration in the space which was 1069ppm - close to the control threshold.

UNDERSTANDING VARIABILITY AND TRENDS IN MEASUREMENTS

- Large variations between average and maximum CO_2 values in a space can indicate increased occupancy for specific times across the occupancy duration (see Grand Circle Bar on previous page).
- A large standard deviation means high variability in measured values. This may be because the air in the space is not mixed well or because there is variable occupancy density in different parts of the room.
- In large spaces that are served by lots of air supply and extract grilles, it is also likely that CO_2 measurements will vary a lot, i.e. there is a high standard deviation. More details on occupancy and ventilation are needed in these circumstances in order to support interpretations.·
- Measurements showed a good correlation between CO_2 concentration and occupancy density, with CO_2 levels following event management patterns in many settings.
- A trend was found between decreasing volume of air per person and increasing average CO_2 levels which was more prominent in high occupancy spaces.
- In cases where the ventilation systems were not demand-driven, a rise in maximum CO_2 values with increasing occupancy in a space was observed.

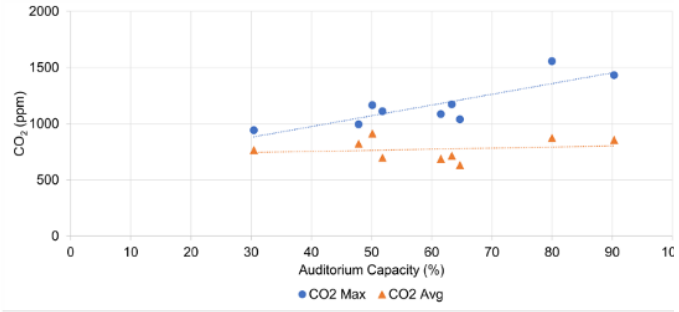
(Adzic, 2022a) (V-KEMS, 2021)

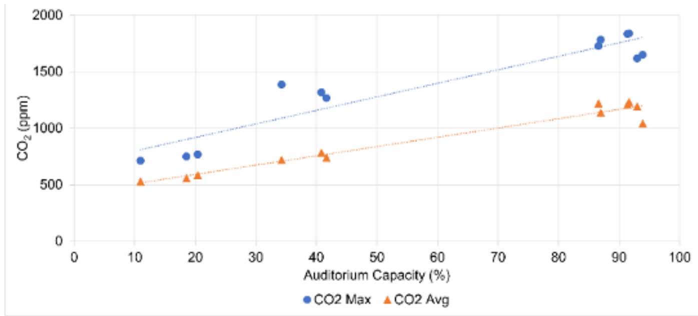




OCCUPANT DYNAMICS

- During one theatre event (upper left), there is an obvious decrease in CO_2 levels when many people left the auditorium during the interval.
- Another theatre event (lower left) was at 90% capacity which allow an assumption of uniform distribution of occupants to be made. The mean CO_2 concentration during the event was 574 ppm and maximum was 1410 ppm. This is explained by the 100-minute interval taking place in the middle of performances when the auditorium was mostly vacated.
- Within this theatre (below left) with a 100-min interval, when observing different occupancy levels, the average CO_2 concentration throughout the event remaining constant regardless of the level of occupancy. That said, higher occupancy levels resulted in higher maximum CO_2 concentrations.
- In a different theatre (below right) which had a 30-minute interval, the average and maximum CO_2 concentrations were higher with higher occupancy levels.





(Adzic, 2022a)

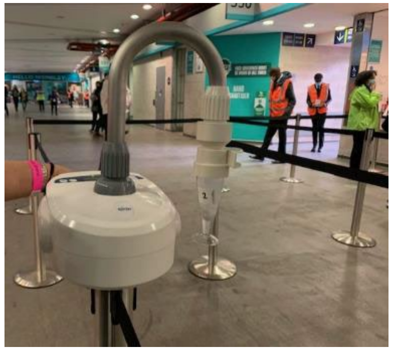
KEY OBSERVATIONS AND RECOMMENDATIONS

- Energy-saving has dominated the agenda for years, resulting in increasingly airtight indoor spaces where leakage from outdoors is minimised. Ventilation and air conditioning systems are normally set to recirculate stale air to improve thermal comfort and reduce energy costs, at the expense of fresh air.
- We recommend new approaches to CO_2 monitoring for post-occupancy surveys and risk assessment relating to ventilation and IAQ. CO_2 monitoring is now inexpensive, and can be deployed rapidly at high resolution to identify areas where exhaled breath builds up in indoor spaces.
- Our research shows that useful lessons can be learned from a fast, temporary installation in real world conditions with high occupancy levels. This can include high resolution monitoring, survey and understanding of the ventilation systems and in-person site surveys

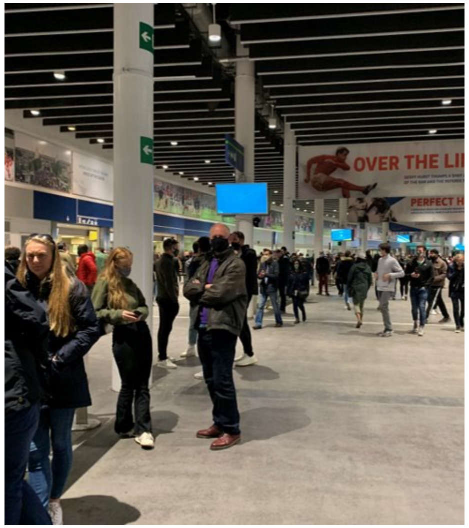
The BRIT Awards 2021: Microbiology data was collected and analysed in the O2 Arena, a large, multi-purpose indoor arena of 20,000-spectator capacity in London that is used for events.

MICROBIOLOGICAL SAMPLING

- Microbiological sampling can support building design and operational decisions by providing information on the types of areas and surfaces in which it is most likely to encounter bacterial contamination under specific conditions and scenarios.
- Microbiological sampling can directly detect specific pathogens, such as SARS-CoV-2, in air or surface samples and help evaluate possible routes of transmission and level of risk in a space.



(Adzic, 2022a)



Key focus areas:

- The gate areas, spectator seating blocks & terraces, and private and enclosed lounge and suite areas serving food and drinks.
- Air samples collected at times of maximum occupancy.
- High-touch surfaces including handles (e.g. door handles, bannisters, escalator handrails), service counters where food and drinks are served.
- Tables where food and drinks are consumed.

UNDERTAKING MICROBIOLOGICAL STUDIES

- Microbiological sampling requires specialist expertise and should be carried out by UKAS-accredited microbiology laboratories.
- There is currently no standard or guidance that outlines specific criteria for evaluating bacterial counts for surfaces or air in public spaces, however there are standards for healthcare and pharmaceutical production premises.
- Bacterial numbers on surfaces in low-to-medium-risk healthcare areas are considered acceptable when in the range of 5–10 bacterial colony counts (units of CFU per cm^2) with similar levels given for pharmaceutical production.
- There are also lack of standards or guidance for public spaces regarding bacterial counts in the air. The following specific references are relatable:
    - < 180 CFUs per m^3 - operating theatres
    - < 200 CFUs per m^3 - packing areas in pharmaceutical production premises
    - < 500 CFUs per m^3 - air quality of office spaces.

To carry out a microbiological assessment the following is recommended:

- Sample collection should be carried out with a frequency and resolution to account for natural variability.
- Sample areas and surfaces mostly used by the occupants.

(NHS, 2021) (Kemp, 2020) (IEE, 1996) (PHE, 2020) (Adzic, 2022a)

...RNA copy numbers were too low to be deemed likely to cause a risk of transmission.

INTERPRETING MICROBIOLOGICAL DATA

- In the O2 Arena, low levels of SARS-CoV-2 N gene RNA were detected on surfaces in three specific spectator areas.
- Although the RNA copy numbers were too low to be deemed likely to cause a risk of transmission, they did reveal that infectors were present in the event despite the requirement for a negative lateral flow test result from all staff and spectators, i.e., some of the tests may have shown a false-negative result or that in some cases there was incorrect reporting.
- It was found that seating blocks had lower bacterial counts than lounges, terraces and suites, due to better ventilation.
- Bacterial colony counts were an order of magnitude higher than those prescribed in the aforementioned guidance which is expected for a heavily occupied event in an indoor venue. However, it also indicates that when transmissible diseases are present amongst the spectators, these may be transmitted in such settings and this requires further investigation.
- It also highlights the importance of testing when managing mass gathering events during a pandemic as, during this event, the risk of COVID-19 infection was found to be low.

(Adzic, 2022a)

6

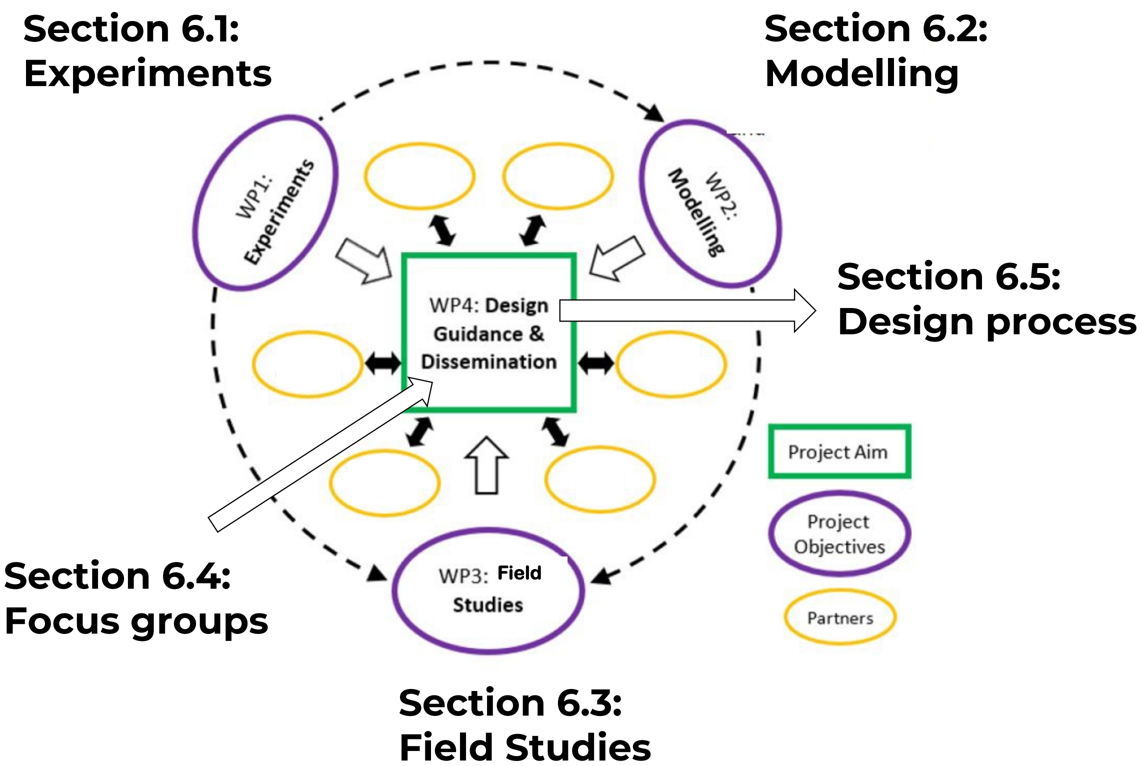
DESIGNING FOR VENTILATION

Graduation event held in marquee with large openings around the sides and audience wearing compulsory masks.

WHY VENTILATION?

- Section 2 introduced aerosols as a transport medium for short- and long-range airborne infection. This has been a primary focus of the AIRBODS research programme.
- The ventilation system in a building can effectively reduce long-range inhaled dose reducing airborne infection risk.
- Although the ventilation system in a building is less effective in reducing short-range inhaled dose and other transmission routes, such as off surfaces or fomites, it can still have an impact.

Good practice for engineering design in consideration of airborne infection risk incorporates health resilience in combination with wider considerations for indoor air quality, energy efficiency and thermal comfort. Many of these aspects will be incorporated into future research.



OVERVIEW

The AIRBODS Research Programme was split into four work packages:

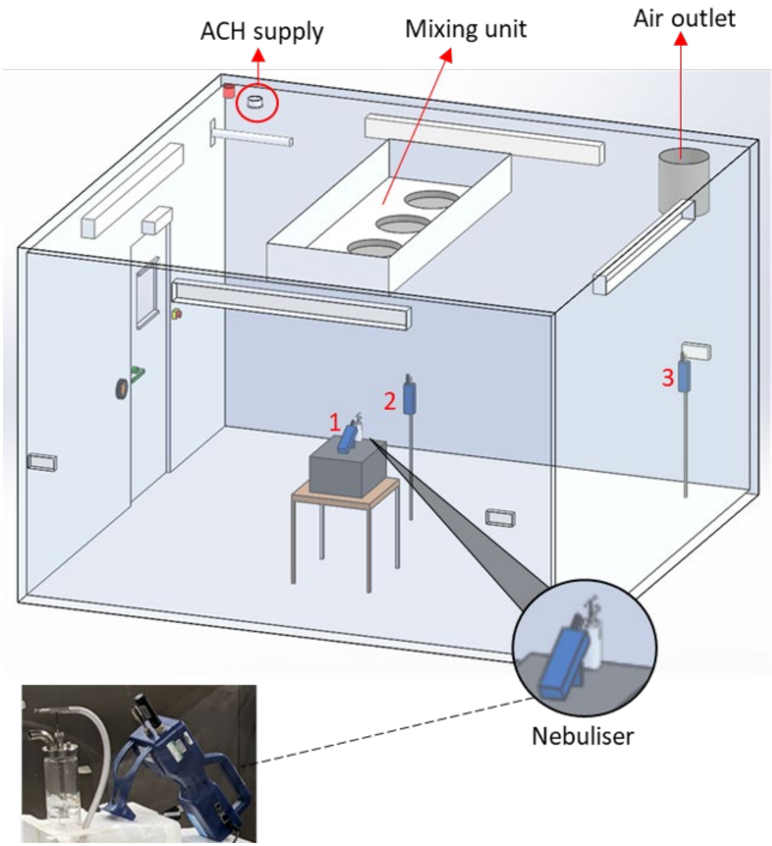
- Experiments
- Modelling
- Field studies
- Design guidance and dissemination

This section:

- Does not cover areas or issues not within the AIRBODS programme, such as air cleaning devices. Some of the AIRBODS team have been authoring separate CIBSE guidance on this.
- Shares some of the experiments, modelling and focus group findings.
- Explores how to design for ventilation whilst considering airborne infection risk.
- Looks at use of key parameters to consider when influencing this risk, e.g., through ventilation strategy.
- Makes recommendations on how to limit this risk.

6.1

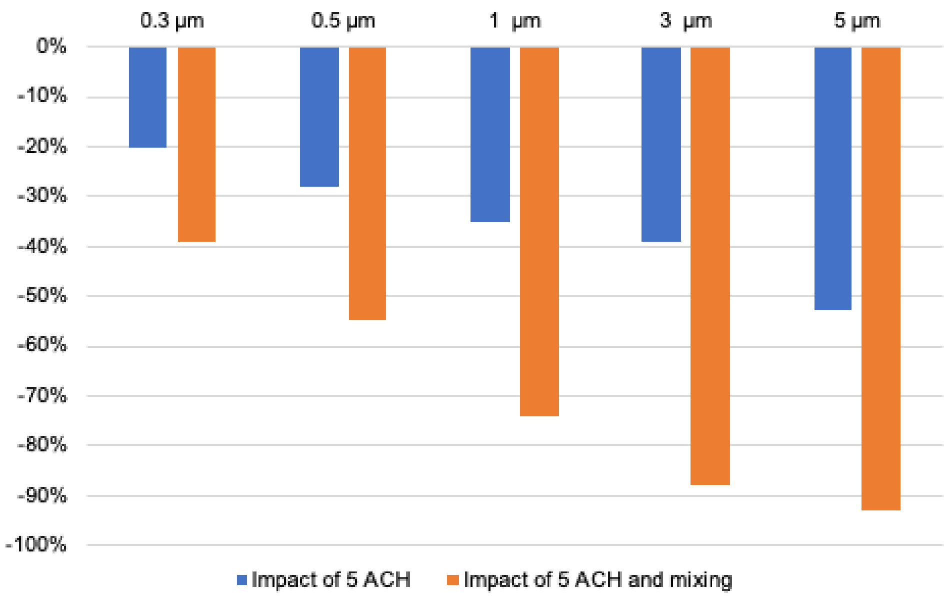
DESIGNING FOR VENTILATION: EXPERIMENTS



EXPERIMENTS

- Key drivers for the experiments were:
    - Aerosols produced by an infected person can carry virus particles long distances.
    - Reducing the number of aerosols decreases the risk of infection.
- The effect on aerosol movement of different ventilation strategies combined with different sizes of screens was investigated.
- The effect of settings and how they contribute to the reduction in number of aerosols in the air was also investigated.
- Five size ranges were detected using particle counters, diameters as follows:
    - 0.3-0.5 μm - shown as 0.3 μm
    - 0.5-1.0 μm - shown as 0.5 μm
    - 1.0-3.0 μm - shown as 1.0 μm
    - 3.0-5.0 μm - shown as 3.0 μm
    - 5.0-10.0 μm - shown as 5.0 μm.

(Hoch, 2022)



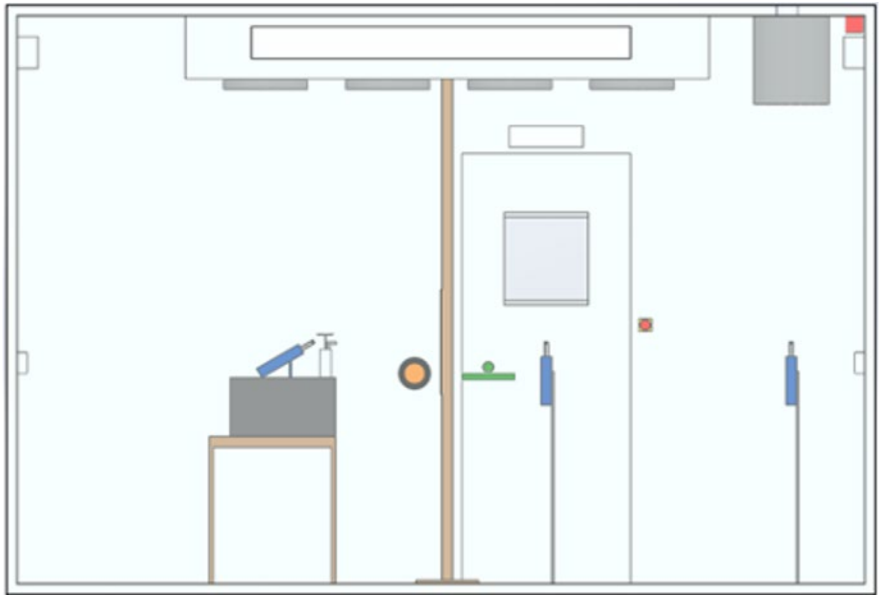
Percentage reduction in numbers of aerosols of different sizes due to ventilation

EXPERIMENTS

IMPACT OF VENTILATION AND AIR MIXING

- The first set of experiments conducted (control scenario) compared the impact of the different ventilation strategies on the aerosol counts without the use of screens.
- The results showed that particle counts significantly drop as ventilation is introduced and they drop even further when mixing is introduced.
- The experiment highlighted the importance of introducing ventilation and mixing of air in reducing the aerosol counts, which in turn means that ventilation and air mixing contribute significantly to minimising airborne infection risk.

(Hoch, 2022)



Screen shown in the centre of the space and placed between nebuliser (droplet generator) and particle counter

EXPERIMENTS

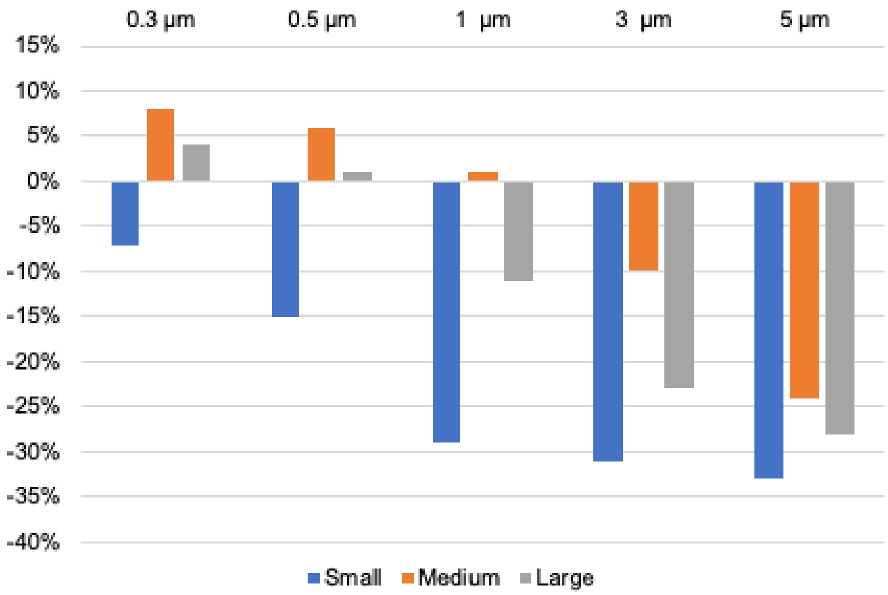
IMPACT OF VENTILATION AND SCREENS

Experiments undertaken with three screen sizes:

- Small - 50cm by 50cm
- Medium - 125cm by 125cm
- Large - 210cm by 210cm

The key conclusions from the detailed results shown on the following two pages are as follows:

- Improving ventilation and mixing is recommended above the use of screens.
- When using screens, it is important to consider the room attributes and the interaction of the screens with significant airflow patterns, which may bring about unintended consequences.



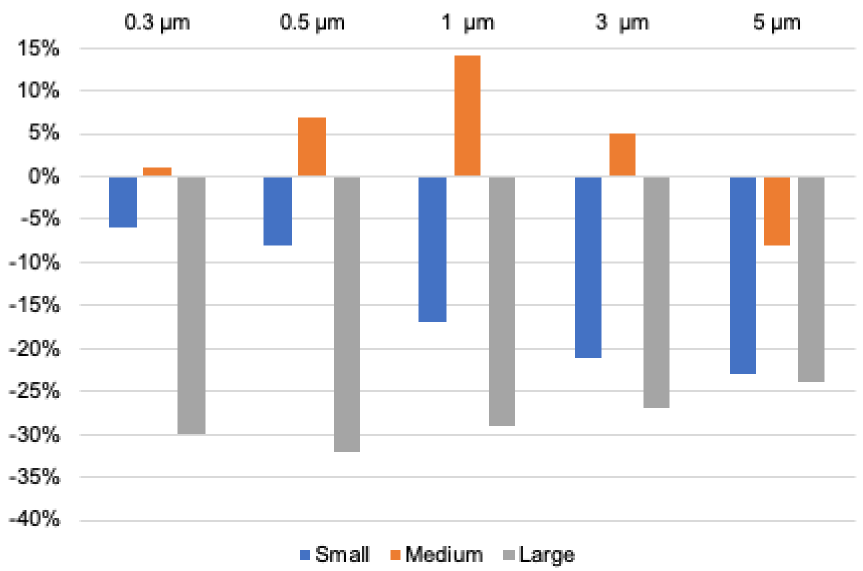
Percentage reduction in numbers of aerosols due to screens of different sizes with ventilation system switched off.

EXPERIMENTS

IMPACT OF VENTILATION AND SCREENS – *VENTILATION OFF*

The results showed that:

- Screens can reduce the number of aerosols that reach a susceptible person.
- Screens are more effective at reducing the numbers of larger aerosols and less effective at reducing the numbers of smaller aerosols.
- In this test chamber configuration, the small screen was most effective at reducing the numbers of all aerosol sizes, followed by the large size, and finally the medium size.



Percentage reduction in numbers of aerosols due to screens of different sizes with ventilation system switched on.

EXPERIMENTS

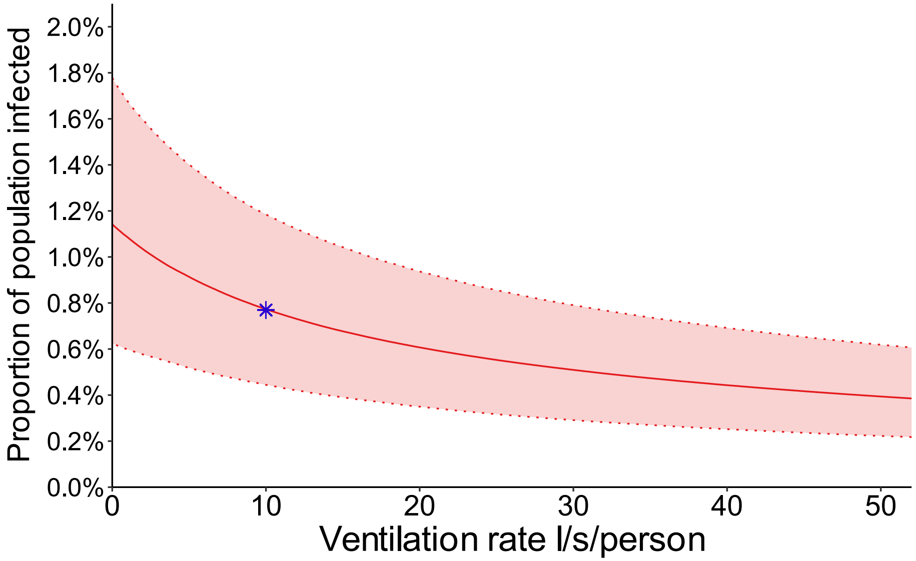
IMPACT OF VENTILATION AND SCREENS – *VENTILATION ON*

The results showed that:

- Ventilation is more effective at reducing the numbers of aerosols reaching a susceptible person than the use of screens.
- At 5 ACH, the large screen reduces aerosol numbers the most, followed by the small screen.
- The medium screen can *increase* the numbers of aerosols that reach a susceptible person.
- It is very important to consider the room geometry and ventilation inlets and outlets when making decisions on screen location and size.

6.2

DESIGNING FOR VENTILATION: MODELLING



Proportion of population infected (PPI) at 'population level' as a function of ventilation flow rate per person in a 20-person office. The impact of increasing the ventilation rate per person in a poorly-ventilated space is much greater than in a well-ventilated space. The asterisk denotes a 20-person office space ventilated at 10 l/s/person.

MODELLING

HOW GOOD IS YOUR VENTILATION?

- AIRBODS-developed metrics (REI & PPI), introduced in Section 3, were used throughout the research programme to model airborne infection risk under a well-mixed assumption for different setting scenarios.
- Here, PPI is used to show the effect of ventilation flow rate on the population level risk, aiming to help with the following questions:
    - What is a 'poorly-ventilated space'?
    - What is a 'sufficiently-ventilated space'?
- A limitation of analytical models is that a well-mixed or single zone condition is calculated. Not all spaces can be characterised by well-mixed conditions. Different types of ventilation systems have different ventilation efficiencies, i.e., their ability to remove pollutants (or virus-laden aerosols) differs.
- Aerosol distributions in various sub-zones of a space can be an important factor in long-range airborne transmission risk.

Section 8 explores, using CFD, how some additional spatial detail can support designing for increased airborne infection resilience.

MODELLING

IMPACT OF FLOW RATES

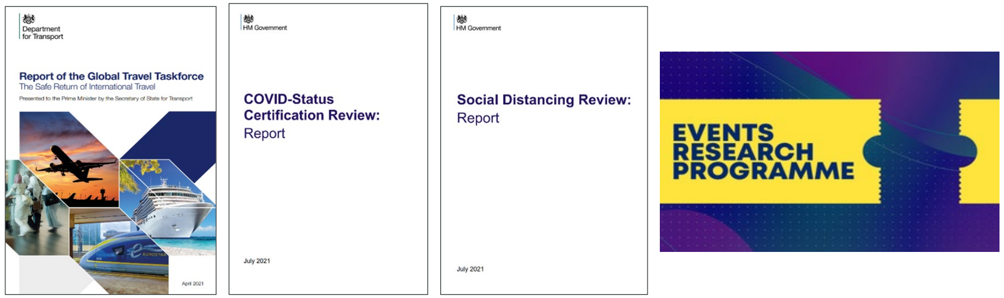
- Increasing the ventilation rate per person reduces the risk of infection, as the virus in the air is diluted. - the dose that a susceptible person inhales, assuming a well-mixed volume space, is reduced.
- Risk reduction rate diminishes as ventilation rate *per person* increases.
- Ventilating flow rates higher than building standards or guidelines brings limited benefits.
- Increased flow rates lead to:
  - Higher energy costs and carbon footprint
  - Increased maintenance and wear-and-tear costs
  - Possible reduced thermal comfort
  - Possible increased susceptibility of occupants to pathogens due to reduced relative humidity - dried out mucosal membranes.
- Increasing ventilation to provide ventilative cooling during the warm season will have some impact on the reduction of airborne transmission risk, although this will be at a lesser effect.

(Iddon, 2022c)

6.3

DESIGNING FOR VENTILATION: FIELD STUDIES

The Events Research Programme was one of the four UK government's Roadmap Reviews for moving out of the pandemic



Where are the risks? – **environmental studies**

Understanding **risks** relating to transmission at live mass gathering events, especially airborne transmission and its relation to ventilation strategies

FIELD STUDIES: POST-OCCUPANCY DATA

BACKGROUND CONTEXT

- The UK Government's Scientific Advisory Group for Emergencies (SAGE) found that public and business understanding of how ventilation could mitigate against COVID-19 transmission is lower than other measures, such as cleaning. This was despite a growing consensus within the scientific community that inhalation is more important than fomite transmission.
- The quality of ventilation across the UK building stock is unknown, but evidence suggests that a wide range of building types are not adequately ventilated, including:
  - Older buildings, which may have been built prior to current standards.
  - Some buildings that may have been repurposed.
  - Poor ventilation performance may be due to operation, maintenance and/or design.

(SAGE, 2021)

Phase I, 18/4/21
FA cup semi-final
2,000 spectators

Phase II, 13/6/21, EUROs:
England vs Croatia,
22,500 spectators

Phase III, 7/7/21, EUROs
semi final: England vs
Denmark, ~70,000 spectators

FIELD STUDIES: POST-OCCUPANCY DATA

DEVELOPMENT OF EVENTS RESEARCH PROGRAMME (ERP)

- A need for data on the ventilation performance of existing buildings used to host events was a key driver that led to the Events Research Programme in 2021.
- AIRBODS assessed the exposure of occupants to exhaled breath in a large variety of venues and events across the UK through the use of high-resolution CO_2 monitoring (methods detailed in Section 5).
- This research provided a wealth of data on the performance of ventilation in a multitude of building types and events with a large variety of ventilation strategies, whilst they were occupied at live events.
- Key findings that relate to the factors that comprise an effective ventilation strategy are summarised in this section.

(SAGE, 2021)

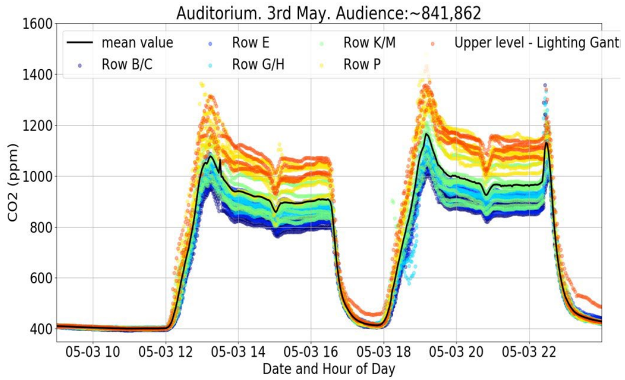
FIELD STUDIES: POST-OCCUPANCY DATA

VENTILATION EFFECTIVENESS

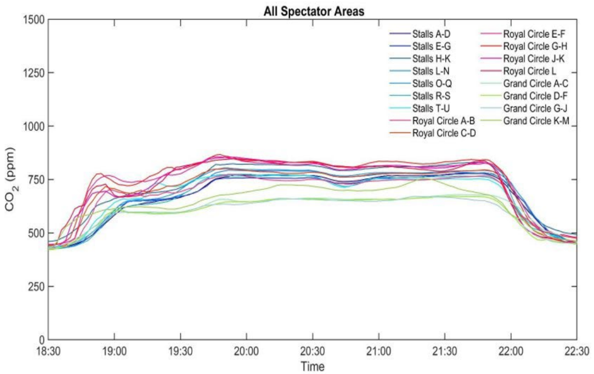
- Ventilation effectiveness - the *ability* for incoming air to be homogeneously distributed within a space – is as important as its associated flow rate to control pollutants (and virus-laden aerosols).
- Overcrowding, due to the nature of some events or the design of some public spaces, can restrict the flow of air resulting in parts of the occupied zone being poorly ventilated.
- The Circus Nightclub field studies (see left) highlighted that ventilation effectiveness was found to be poor for the venue. There were higher CO_2 concentrations generally identified away from the door openings and stage due to uneven supply air distribution and local occupancy levels.
- The airflow characteristics for a space and how outdoor air might enter it needs to be considered as part of an effective ventilation strategy. An additional focus on how air enters an occupied area with minimal energy losses, possibly supported by advanced computer models, could further support operational decisions associated with airborne infection resilience.

Circus Nightclub in Liverpool – a naturally-ventilated warehouse licensed for 10,000 people. 30% capacity during ERP field studies. 6 large warehouse door openings (49m^2) were distributed along one side of the building at regular intervals.

(Malki-Epshtein, 2023)



Ventilation distribution at the Crucible Sheffield, a small theatre, as observed from 44 CO_2 monitors around the space



CO_2 data from 17 monitors distributed around The Piccadilly theatre, a large theatre with a high ceiling, on three different levels

FIELD STUDIES: POST-OCCUPANCY DATA

VENTILATION STRATEGY

- One example of the impact of ventilation strategy on the resulting ventilation effectiveness showed (graph top left):
  - The space is not well mixed, with CO_2 values varying by nearly 400ppm from the back row to the front of the auditorium.
  - The back row of the theatre peaks at nearly 1400ppm and stays above 1000ppm for the entire event.
  - This variation in the space demonstrates the limitations of using CO_2 sensors only at the extract to control ventilation in a large space that may not be well mixed.
- Another example showed better air quality due to an improved ventilation strategy (bottom left):
  - Attendance was at ~50% of full capacity but the CO_2 data indicate a good ventilation strategy and a well-mixed space.
  - The Grand Circle shows lower values than the other two auditorium levels.
  - The values recorded never exceeded 800 ppm in all three spectator areas.
  - The data shows constant levels of CO_2 indicating a continuous and sufficient fresh air ingress in the auditorium.

(CIBSE, 2022) (Adzic, 2022a) (Malki-Epshtein, 2023)

FIELD STUDIES: POST-OCCUPANCY DATA

AIR MIXING

- In large volume spaces it may be difficult to achieve well-mixed conditions.
- Poor mixing of air in large theatre auditoria indicated through high variances in CO_2 concentrations even when average values were acceptable (see Case Study in Section 9).
- High-resolution CO_2 monitoring provided evidence that challenge the assumption of indoor spaces having well-mixed conditions with homogeneous indoor air quality.
- Variable audience experience depending upon location leading to wide range of air quality and airborne infection exposure risk outcomes within the same event.

(Adzic, 2022a) (Malki-Epshtein, 2023)

FIELD STUDIES: POST-OCCUPANCY DATA

REASONS FOR POOR AIR MIXING

- Ventilation system configuration.
- Inefficient supply air delivery.
- Ineffective mixing and buoyancy effects.
- Crowding and placement of furniture restricting air movement.
- Disconnect between design intent, actual usage and occupant needs.
- Fit-out of space not aligning with the ventilation strategy of original design.
- Change in use of building.
- Ineffective retrofitting and/or design leading to inadequate provision of ventilation.
- Lack of awareness of the impact of important parameters to ventilation performance.

Ventilation is invisible; people find it difficult to determine what is good ventilation and to know or agree when to take action such as open/close the windows. CO_2 monitoring allows the indoor environment to be "seen".

Case studies:
In one theatre auditorium with a low-level supply and high-level extract system, higher CO_2 concentrations resulted in the upper seats with a similar likely outcome for virus-laden aerosols. In another, some areas were bypassed with air extracted before reaching all occupied zones. This was an outcome from repurposing a ventilation system and switching some of the original extract to supply air grilles.

(Adzic, 2022a) (Malki-Epshtein, 2023)

FIELD STUDIES: POST-OCCUPANCY DATA

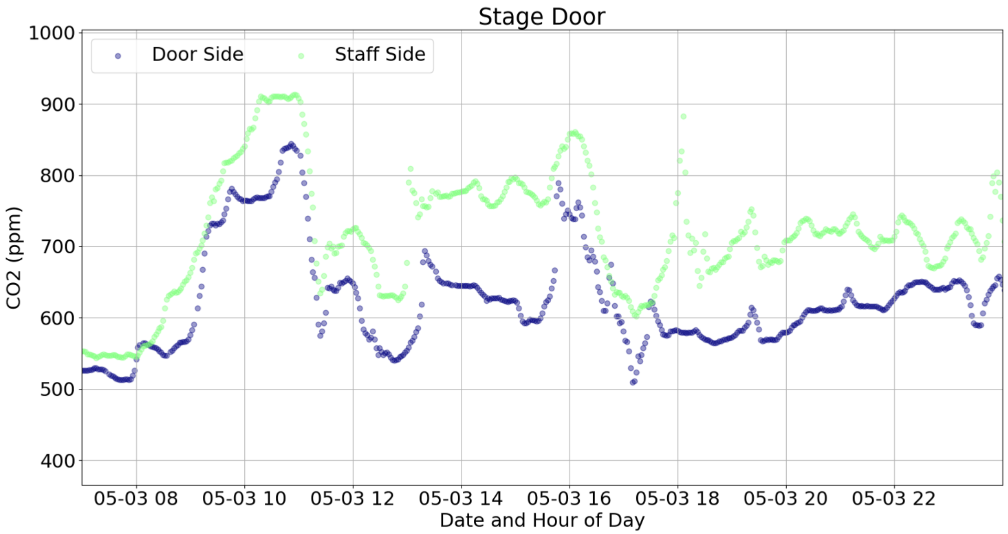
ADDITIONAL CONSIDERATIONS

- Reduced ventilating airflow due to temporary blinds or noise control measures.
- Application for a particular type of ventilation system, e.g. single-sided natural ventilation at a nightclub venue. At the dancefloor end of a closed venue, the openings were restricted by partially closed metal shutters with hanging vertical plastic strip curtains or 'butchers screens' reducing local air supply. The dancefloor was the area with highest occupancy density and this was combined with highest aerosol generating activities, e.g. singing and shouting.

RECOMMENDATIONS

- As noise attenuation measures may conflict with the natural ventilation strategy, consider synergy between acoustic and ventilation design early.
- Repurposing of buildings can lead to conflicting requirements so consider possible future uses at design stage, clearly outlining limitations and, where possible, potential flexibility for future usage.
- Explore options for 'enhanced' natural ventilation for managing air quality and thermal comfort when needed and 'purging' under high occupancy.
- Consider use of open sided marquees instead.

(Malki-Epshtein, 2023)

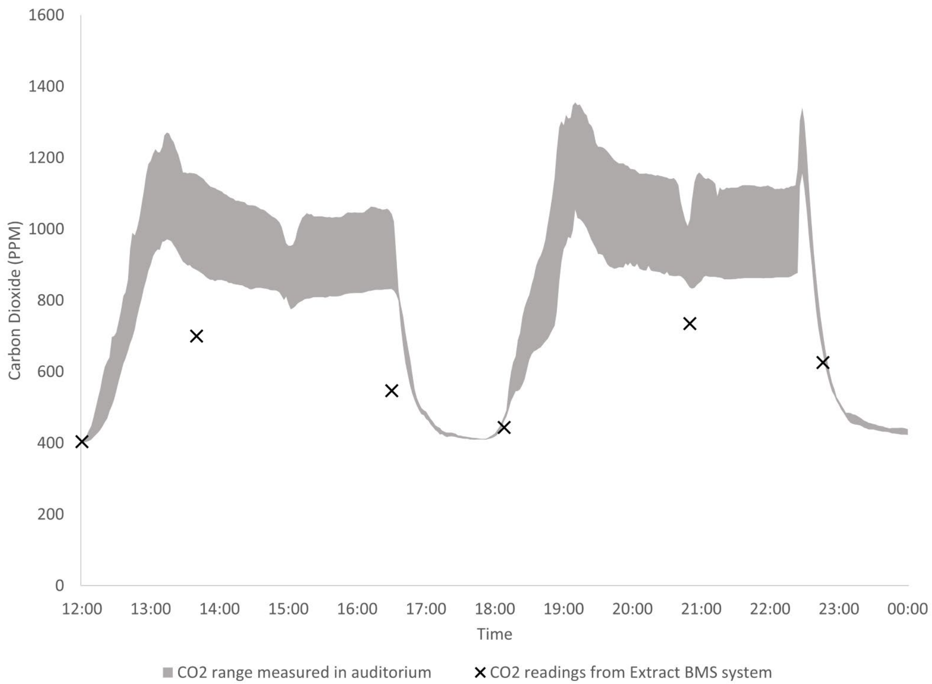


Time series of CO_2 readings either side of screen comparing one side (receptionists – 'staff side') with the other (staff entrance – 'door side')

FIELD STUDIES: POST-OCCUPANCY DATA

SCREENS

- Impact of a perspex separation screen placed either side of the stage door on CO_2 concentrations was examined at the Crucible Theatre - see left.
- The screen:
  - Reduced air mixing in the space.
  - Led to increased CO_2 levels and less air dilution on the staff side.
  - Emphasises need to consider how both sides of a screen will be ventilated when installed.



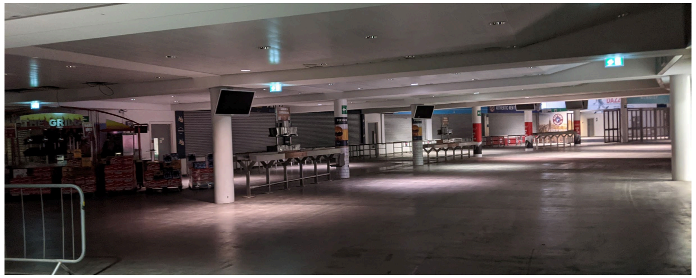
Time series of CO_2 readings within auditorium and at extract duct

FIELD STUDIES: POST-OCCUPANCY DATA

MECHANICAL VENTILATION CONTROLS

- High-resolution CO_2 measurements at the Crucible theatre were compared with CO_2 sensor readings taken from the building management system during two games at the Snooker World Championship – see left.
- It is important to locate ventilation-controlling CO_2 sensors close to the occupied zone as placing it at the extract duct can lead to lower concentrations / poor ventilation control.
- The use of demand-controlled ventilation was shown to lead to lower CO_2 concentrations within the controlled zone of a theatre auditorium, however, in practice, these systems do not always operate as intended.
- Intelligent and demand-driven ventilation controls with the ability to cater for variances in the occupancy and ventilation targets are recommended where possible. They enable the provision of outdoor air rate as required and can provide a balance between airborne infection resilience, thermal comfort and energy usage throughout the year.

(Adzic, 2022a) (Malki-Epshtein, 2023)



FIELD STUDIES: POST-OCCUPANCY DATA

SPACE CONSIDERATIONS

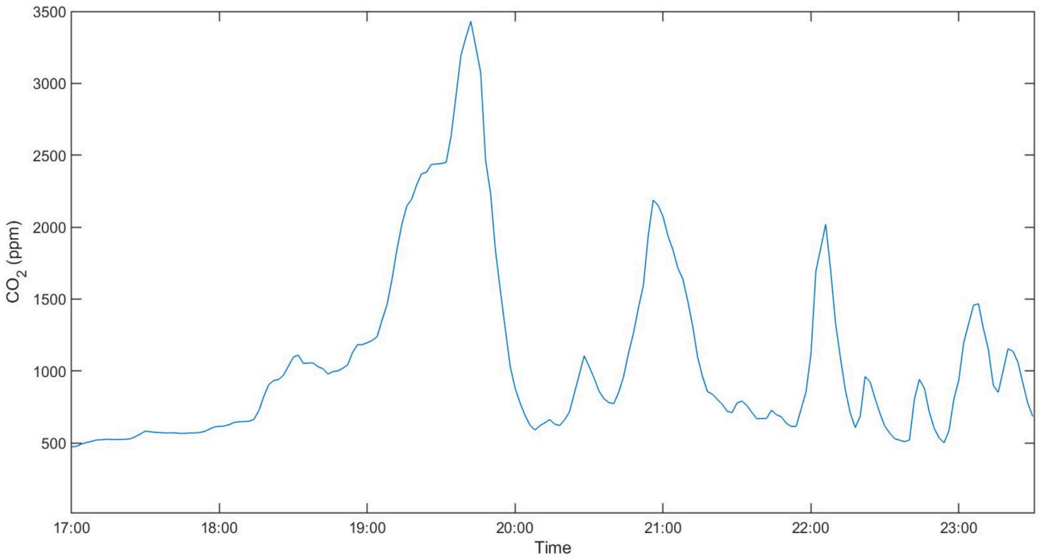
- Design intent - differences were observed between the way spaces are used against their original design intent resulting in a change in their airborne infection resilience.
- Semi-outdoor spaces may also need to be considered in terms of ventilation provision. For example, in outdoor areas such as marquees, with tents surrounding parts of the space, airflows may be restricted in case of overcrowding and therefore distribution of outdoor air to all occupied zones may not be straightforward.
- A stadium may be an outdoor arena but it will typically have indoor concession stands, bars and toilets or may have unstructured stand-only food and drink areas indoors, where visitors may end up spending a substantial amount of time.

(Malki-Epshtein, 2022)

FIELD STUDIES: POST-OCCUPANCY DATA

IDENTIFYING HIGH RISK ZONES

- In a stadium, the unstructured stand-only food and drink areas were often found to become “pinch-points” of high CO_2 concentration and restricted airflows leading to higher risk of both near-field droplet and far-field aerosol inhalation.
- In transient areas, such as toilets, corridors, lifts and stairwells and especially in large buildings hosting lots of people, there was a greater tendency towards poor air quality.
- The ventilation strategy should consider all higher risk areas, e.g., high occupancy for longer periods, at peak-occupancy events:, e.g., queuing, early on in the design process.



CO_2 time series in a single toilet at a high-capacity event at Wembley Stadium, showing values up to 3500 ppm at times. Toilets, corridors, lifts, stairwells (small, enclosed, short occupancy) were found to be poorly ventilated with very high peaks during busy times, at all Event Research Programme events.

(Malki-Epshtein, 2022)

6.4

DESIGNING FOR VENTILATION: FOCUS GROUPS

FOCUS GROUPS

BACKGROUND

A series of focus group sessions were completed to:

- Engage with building practitioners and users
- Learn from their experience operating or designing buildings during the pandemic
- Determine how this might support future design and operational practices to enhance airborne infection resilience in buildings.

The following questions were asked:

- What lessons can be learned from the experience of building designers, operators and users in support of infection-resilient building design?
- What considerations should be accounted for at design stage?
- What could go wrong?
- What other real-life factors can influence the infection-resilience of buildings?

Other considerations:

- High variability in the needs, challenges and solutions of buildings within different sectors and of different sizes.
- Feedback was based on their experiences which may or may not be relevant to any building type or scenario, recognizing that one size may not fit all.

FOCUS GROUPS

GROUP DEFINITIONS

Three sessions comprising 14 participants in total were carried out, as follows:

- Group 1 - *Designers i*ncluding architects, developers and engineers with POE experience
- Group 2 - *Operators* including facilities managers of university estates and of a conference centre
- Group 3 - *Non-technical* building users including cinema, theatre, pub owners or staff

Barriers	Solutions
Lack of awareness about the importance of ventilation	**Provide education on the benefits of ventilation, air quality and airborne infection resilience to building users**
Lack of awareness that ventilation is poor	**Use CO_2 monitoring displaying measured data to put risk into context for proportionate actions to be taken**
Unclear roles and responsibilities related to the operation of CO_2 monitoring system	**Clear assignment of roles and responsibilities for managing system**
Limited understanding, as well as lack of guidance and support on: • **how to operate ventilation system** • **what CO_2 monitoring outputs and indicators mean and actions to trigger**	**Training and instructions that consider:** • **diversity in users including their resources** • **roles and responsibilities** • **social/cultural expectations and norms** • **background technical knowledge and capabilities**
Limited evidence on the effectiveness of CO_2 and other IAQ monitoring systems as an intervention to improve indoor environments	**Further research needed to:** • **understand the side of users** • **develop communication material to suit their needs** • **expand existing knowledge on the long-term cost-effectiveness of interventions, e.g. impact on ventilation** • **improve technology to better understand behavioural response of different users**

AIRBODS focus group findings related to natural ventilation controls

FOCUS GROUPS

NATURAL VENTILATION CONTROLS

- A very large number of buildings rely on natural ventilation controlled by the occupants.
- In shared office spaces, there are complex social determinants that influence window opening and thermal control including social norms, human interactions and degree of separation between occupant and building control.
- Although people are somewhat tolerant to thermal discomfort to maintain relationships with co-workers, excessive use of openings during cold periods may prevent occupants from opening the windows (and increase energy costs).
- Behavioural patterns that influence real-life implementation of natural ventilation strategies, are important – best to integrate behavioural science with building design.
- Complex balance between health and comfort needs of occupants combined with energy usage - beneficial use of automated natural ventilation controls or standalone CO_2 monitors with a visible display to enable occupant-led management of ventilation.

(Snow, 2016) (SAGE, 2021)

FOCUS GROUPS

DESIGNER GROUP: GENERAL FEEDBACK

Airborne infection reduction measures	Considerations
CO_2 along with temperature controls implemented in schools	Increased CO_2 levels observed in the summer, when the external air temperature becomes higher than the internal, due to the temperature control of automatic openings and fans having priority over CO_2 control.
Displacement ventilation system to remove expelled pollutants from breathing zone	CFD study on air movement showed that excessively high air speeds were required to remove expelled particles from the breathing zone. More data and case studies are needed to shed light on the effectiveness of various ventilation strategies.
Air filters becoming common practice in MVHR systems	Increased maintenance requirements
Increased openable windows	Conflicting requirements due to overheating and noise issues. Manual operation may give the feeling of control to the occupants, but possible thermal discomfort may ultimately prevent usage of openings.

FOCUS GROUPS

DESIGNER GROUP: TECHNICAL CHALLENGES

Technical challenges	Recommendations *
Poor maintenance of ventilation systems	Protocol of routine checks and assignment of clear responsibilities in operating ventilation and ensuring good indoor air quality
Ventilation strategies lack the flexibility that is needed when the buildings are going to be used in different ways according to the tenant, who may wish to separate and subdivide spaces. This has an impact on the ventilation effectiveness.	Flexibility to become a design parameter, accounting for different possibilities of usage, when tenants are unknown
Overventilation has a great impact on energy consumption and running costs, as well as thermal comfort, as many systems have not been designed to deliver such high demands.	Current building standards on ventilation should be followed (AIRBODS input)
Natural ventilation is in high demand and becoming a norm in some sectors, e.g. residential. However, there are limitations to consider, such as ground floor security, window restrictors for safety, which limit airflows and whistling effect from trickle vents in tall buildings.	Hybrid ventilation strategies may provide solutions to such limitations. To evaluate whether the desired ventilation rates and ventilation effectiveness are achieved under specific scenarios, airflow modelling can provide an understanding and drive design decisions (refer to Section 8). (AIRBODS input)
Experience with natural ventilation in offices has made some developers reluctant to the option, due to complexity of controls and difficulty in ensuring effective air distribution in all occupied areas.	The input of behavioural science will be valuable in our understanding of how to tackle manual control issues. In the meantime, options such as automatic control of natural ventilation, mechanical ventilation or hybrid ventilation can be explored in such settings. The effectiveness of air distribution of the selected strategy can be assessed at design stage using modelling. (AIRBODS input)

*All inputs are from participants unless stated otherwise

FOCUS GROUPS

DESIGNER GROUP: OTHER CHALLENGES

Other challenges	Recommendations *
Translation gap between what designers understand will happen in the building and what happens at the user's side Lack of knowledge and training of facilities managers and building users on how to use their ventilation controls and how to manage indoor air quality in their buildings.	Need for intuitive buildings – UX (user experience) should become part of design (focus group participants) Training of building operators and building users
Ineffective handover of building data to its users, often with uncoordinated information between provided information and as-built status Information provided in technical language not appropriate for building stakeholders with different levels of technical understanding. O&M manuals and building user guides don't get looked at	Curated transfer of building data from designer to users Operational guidance in appropriate language according to the recipients and relatable to their specific setting Videos can be an effective way of training building users on how to use their building
High demand for new buildings, low demand for older buildings that do not meet the latest good practice specifications.	There is a clear need to give focus to the refurbishment sector. Drivers to upgrade the existing building stock towards infection resilience need to come from building regulations (Royal Academy of Engineering reference). Findings from research, industry experience and guidance on refurbishments (CIBSE TM53, CIBSE, BSRIA KS12, BSRIA TN8/98) and POE data are needed to enhance the know-how of engineers. (AIRBODS input)
Value engineering and financial pressures make ventilation systems deviate from original design intent and impact ventilation effectiveness. Ambiguity in design guidance gives space to value engineering to have this effect.	Clarity is needed in the criteria and requirements of building regulations and industry guidance. Strong case for improved ventilation backed-up by science to engage interest in delivering effective systems (AIRBODS input)

*All inputs are from participants unless stated otherwise

FOCUS GROUPS

OPERATOR GROUP: GENERAL FEEDBACK

Airborne infection reduction measures	Considerations
Extended operation time of ventilation system	Increased maintenance requirements and wear-and-tear of equipment combined with financial restrictions on maintenance budgets
Natural ventilation was encouraged and has been the building operation policy for years	Often not used due to cold discomfort Particularly difficult to understand how occupants manage it in shared spaces like open plan offices
CO_2 monitoring in performance space	Difficult to interpret readings in order to inform operation, due to additional sources of CO_2 other than humans (in special effects)
CO_2 monitoring installed in meeting rooms with an instruction panel next to it explaining its purpose	People sometimes play with it Empirically shown to be effective, as people tend to open the windows
Utilised purge mode of ventilation system controlled with CO_2 sensors in a new building	
Awareness campaign of need to open windows Spatial awareness informing on maximum occupancies in each room through a notice on the wall	
Installed local reversible supply and extract fans in windows in naturally ventilated spaces with limited airflows	Solar and thermal performance of the window, as well as view out and aesthetics of such a solution could be an issue, if not integrated from the start. However, in pandemic mode operation it can help increase airflow in the space (AIRBODS input)

FOCUS GROUPS

OPERATOR GROUP: TECHNICAL CHALLENGES

Technical challenges	AIRBODS recommendations
Difficult to understand where outdoor air comes from in some mechanical ventilation systems	Relates to transfer of building data from designers to operators
Automatic natural ventilation openings fitted only with temperature control	In installed systems, standalone CO_2 monitors and manual override could help control opening based on IAQ
Performance stage ventilation system not appropriate for activities taking place on stage, e.g. takes away smoke, blows drapes and projector screen, so historically has not been used, as performance teams complain.	This is a design stage issue, which highlights the importance of considering particular needs of specific space types and activities taking place in them

FOCUS GROUPS

OPERATOR GROUP: OTHER CHALLENGES

Other challenges	AIRBODS recommendations
Challenging to find new ways of operating, along with the day-to-day job tasks of managing the building	**This possibly underlines the need to have a dedicated person managing IAQ and required changes**
Not easy to get the whole FM team onboard in changing operational routines or doing further investigations on performance	**Behavioural science input and awareness of the importance of ventilation may support this issue**
In multi-building premises, design specifications and commissioning may come in different formats and it can be complicated to find the right information	**Need for improved commissioning and transfer of building data from design stage to in-use**
Not knowing what the criteria should be to do a detailed risk assessment during the pandemic	**Need for easy-access guidance with clear criteria**

FOCUS GROUPS

NON-TECHNICAL BUILDING USERS GROUP: GENERAL FEEDBACK (1 OF 2)

Airborne infection reduction measures	Building type	Challenges and considerations	AIRBODS input
Mixing fans	Music venues	Used for production effects, e.g. smoke machines, but also to support air movement and mixing	Improved mixing is encouraged
Natural ventilation through opening of doors (no other means of ventilation in place)	Music venues	Not possible to provide outdoor air during production time Limited purging time due to event programme	Example of 'pandemic mode operation' measure
Natural ventilation through shafts – kept open in winter during the pandemic	Cinema	Cold discomfort High energy costs Not fully operational due to poor maintenance and birds entering	Need for maintenance and possible re-consideration of ventilation-heating strategy
Natural ventilation through opening windows in office areas	Cinema	Manually controlled by occupants Venue staff: "We can advise, but we cannot enforce in these areas"	Refer to Section 5
Mechanical ventilation that provides heating and cooling controlled via temperature and CO_2 sensors (demand-driven)	Cinema	-	-
Opening of fire doors between performances to purge the air was the only option	Cinema	Cold discomfort and complaints from customers in the winter	Fire doors should be kept closed unless fitted with approved automatic closers High priority area for improvement
Introduced intervals to purge the air between performances and increased interval time. Challenged performers to reduce performance times to allow for more frequent air changes.	Music venues Cinema	Background recorded music typically played at intervals had to be reduced in volume or not played at all to prevent noise issues. Shorter turnaround time for performances.	Example of 'pandemic mode operation' measure

FOCUS GROUPS

NON-TECHNICAL BUILDING USERS GROUP: GENERAL FEEDBACK (2 OF 2)

Airborne infection reduction measures	Building type	Challenges and considerations	AIRBODS input
CO_2 monitoring implemented prior to making any operational changes	Music venues Cinema	-	Encouraged approach
Switched system to 100% fresh air	Cinema	Thermal discomfort and high energy costs Noise issues due to increased fan activity	Although this may be a short-term solution during 'pandemic mode operation', Section 5 describes how overventilation has diminishing effects in reducing airborne infection risk and therefore ventilating to current building standards is advised.
Reduced and spread occupancy during pandemic mode.	Cinema	Non-viable financially in the long term	Example of 'pandemic mode operation' measure
Introduced two operational modes: one with 50% occupancy at daytime and 90% occupancy in the evenings for audiences with different level of concern.	Cinema		Example of 'pandemic mode operation' measure
HEPA filter cleaner machines and 50% occupancy in space without ventilation	Theatre (had not reopened at the time of the focus groups)		High priority area for improvement
Controlled entrance (one in-one out) during pandemic mode	Library		Example of 'pandemic mode operation' measure
Click and collect	Library		Example of 'pandemic mode operation' measure
Moved box office outdoors to avoid long queues indoors	Music venue		Example of 'pandemic mode operation' measure
Encouraged the use of masks through venue policy, when masks not enforced	Cinema		Example of 'pandemic mode operation' measure

FOCUS GROUPS

NON-TECHNICAL BUILDING USERS GROUP: TECHNICAL CHALLENGES

Technical challenges	AIRBODS recommendations
Music venues are buildings with high respiratory activity and high occupancy density with performances often having a long duration. Noise versus ventilation is a historic challenge for music venues.	CO_2 monitoring to identify issues Support in refurbishing high priority spaces, exploring hybrid or mechanical ventilation, if natural ventilation is not an option.
There are a lot of heritage spaces that have been converted to venues producing high volumes of sound and have not been designed for that. These spaces have often undergone interventions to keep noise in, that have blocked natural ventilation openings. E.g. windows have been permanently shut, two doors are kept closed separating performance space from outdoors during performance time.	Refer to Section 5 - Considerations for natural ventilation
Sometimes it may be difficult to integrate a mechanical ventilation system in existing buildings, due to limitations in their design	Alternative options, such as increased natural ventilation, air cleaning, change of use of space for reduced occupancy and dwell time, partitioning or a combination of them, may need to be explored.

FOCUS GROUPS

NON-TECHNICAL BUILDING USERS GROUP: OTHER CHALLENGES

Other challenges	AIRBODS recommendations
Lack of capital to invest in the level of refurbishment required to provide good indoor air quality	**Government driven change required**
Limited routes for public funding and limiting eligibility criteria, e.g. from local councils, to refurbish ventilation system	**Government driven change required**
Facilities management team not on site **Tenant/landlord responsibilities of different building aspects**	**Redesign of internal processes, roles and responsibilities to allow easy access to maintenance and effective implementation of solutions**
Lack of clear assignment of responsibilities on building operation amongst different teams or departments increases complexity and time of decision making	**As above**

Additional observations for this group:

- Uncertainty related to how their ventilation system operates and how it is controlled
- Uncertainty related to what flow rates it delivers or how to find out in older buildings
- Lack of clarity on what is the right approach against infection transmission
- Concern about customers not feeling safe to return to their venues, with ventilation believed to be a primary reason
- Having an intuitive understanding of factors impacting airborne transmission (high ceiling and large space mentioned, as an example)
- Participation in networks and actively engaging in educating and informing themselves according to emerging needs, such as ventilation during the pandemic
- Interest and motivation to support research and education through their own experiences

FOCUS GROUPS

GENERAL RECOMMENDATIONS

- AIRBODS engaged with designers, technical and non-technical staff of buildings in a series of focus groups,. One of the issues that have emerged through the research is a lack of understanding as follows:
    - Building users on how to use their building
    - Designers on how occupants are likely to use the building.
    - As a result of their experiences, participants shared that building users need support in understanding how to operate their buildings and building designers need to consider how to make buildings more intuitive.
- Based on these findings, the provision of easy-access operational guidance on how to operate critical aspects of the building, including ventilation is encouraged as part of the handover to the building users.
- Some guidance may already exist in the form of operation and maintenance manuals and/or building user guides, however, it is often the case that this material does not get used as expected. Possible reasons are:
    - Use of language that is not targeted to its audience
    - Length of the documents
    - Lack of visuals
    - Complex format
    - Absence of content relevant to the users.

(SAGE, 2021)

Quote from post-occupancy evaluation (POE) engineer:

15 years ago, we designed a school to be naturally ventilated and we left instructions on how to use the windows in summertime, in mid-season and in wintertime. We did CFD to support this information and we produced a guide that went up on the wall. I went back years later to find that that had been replaced by information that school kids had produced by making the information that we gave them much simpler. The teachers and the pupils had organized themselves into designated groups to open and close the windows at the end of the day.

FOCUS GROUPS

OPERATIONAL GUIDANCE FOR BUILDING USERS

To operating a building whilst considering airborne infection resilience, guidance should be adjusted for its recipients (e.g. building occupants & facilities managers) with content such as:

- Encouragement of occupants to utilise ventilation all year long with specific operational suggestions for heating, cooling and intermediate seasons.
- Explanation of the designed control strategy in the different spaces.
- How to operate their ventilation system in an energy efficient way.
- How to consider and minimise cross-contamination between different spaces.
- Provision of easy-to-digest material (e.g. infographics) explaining how to use the control features (if in place) including what the different indicators and values mean. For example, generate a guide how to interpret CO_2 levels, what a red-light indicator means and what actions should be taken in different scenarios.

(SAGE, 2021)

At design stage:
- Feeding post-occupancy evaluation data into design
- Referring to behavioural studies
- Engaging with the client or end-user

At operational stage:
- Signage/messaging within the building to encourage behaviours or explain systems and strategies
- Creation of easy-access content, e.g. videos accessed through a QR code describing how to operate a system

FOCUS GROUPS

MAKING BUILDINGS MORE INTUITIVE

- To make a buildings more intuitive, greater synergy is needed between building designers, communication specialists and behavioural scientists. This is an area that requires focused development and research.
- A staged approach may be required – see box to left.
- Intuitive buildings may reduce the need to overdesign in order to meet challenging performance targets, such as infection resilience. Immediate steps to make buildings more user-friendly can still be taken and could include:
    - Provision of advice on how to enhance mixing, e.g., by utilising all openings at a reduced opening angle in the winter in naturally ventilated spaces.
    - Encouragement of intervals and purging of the air during unoccupied times.
    - Advice on when an issue needs the attention of facilities management or an external technical specialist.
    - Proposition of an operational plan with clear responsibilities and routine checks assigned to dedicated persons.

6.5

DESIGNING FOR VENTILATION: DESIGNING, PREPARING AND MITIGATING

RETHINKING VENTILATION DESIGN

Good practice engineering design for ventilation including consideration of airborne infection resilience should adopt a stepped approach along the lines recommended here.

STEP 1

SPACE TYPES

Group spaces according to their usage and ventilation characteristics.

STEP 2

DESIGN LIMITATIONS

Identify limiting factors with an impact on ventilation, e.g., noise, air pollution, financial constraints.

STEP 3

USAGE SCENARIOS

Identify realistic usage scenarios of each space. Engaging with the client/tenant or seeking data from similar buildings can support this step.

STEP 4

HIGH RISK ZONES

Identify areas that may be more prone to poor air quality at peak occupancy. These may be transient zones.

STEP 5

DESIGN SCENARIO

Select a realistic peak-usage scenario and consider the ventilation system efficiency at regular operation and peak operation.

STEP 6

VENTILATION MODES

Evaluate whether there is a need for regular and enhanced ventilation modes.

NEW BUILDINGS

Additional considerations:

- noise and air pollution
- financial constraints

REFURBISHMENTS

Additional considerations:

- asbestos
- listed façade
- structural limitations spaces with no access to outdoor air
- existing fire strategy
- tenant-landlord interaction

RETHINKING VENTILATION DESIGN

Only when the scenarios and associated limitations have been identified and agreed should the more standard design practices be undertaken. The refined principles can then be used to drive the design forward with additional considerations.

STEP 7

POTENTIAL REPURPOSING

Provision for natural ventilation to future-proof the design.

STEP 8

BUILDING STANDARDS / GOOD PRACTICE GUIDES

Use standards and guidance to balance infection risk with IAQ, thermal comfort and energy efficiency etc.

STEP 9

SUB-ZONING

In large spaces with various usages and access to ventilation, sub-zoning may be appropriate to consider in order to effectively ventilate all occupied areas.

STEP 10

CONTROLS

Evaluate different options, giving consideration to demand-driven controls and accounting for behavioural impacts and effective ventilation operation.

STEP 11

MODELLING

Where necessary (e.g. complex spaces) evaluate ventilation design options and verify the performance of the selected option for key scenarios through simulations.

DYNAMIC THERMAL MODELLING

Coarse ventilation assessment on zone level basis. Can include many aspects (e.g. energy use) for compliance checking.

STEP 12

HANDOVER GUIDANCE

Encourage the production of a short, simple and graphic document outlining the ventilation strategy and how it should be used throughout the year.

CFD MODELLING

Detailed ventilation assessment allowing assessment of:

- Ventilation effectiveness
- Air mixing
- High-risk areas.

There are a whole range of measures that could be considered when incorporating airborne infection resilience thinking into the design and operation of buildings. Some of the examples here include having a greater focus on:

- Operating scenarios
- Design scenarios
- Pandemic plans
- Operating plans

RETHINKING VENTILATION DESIGN

SELECT OPERATING SCENARIOS

- When deciding on ventilation strategy, what are realistic occupancy levels at different times and in different locations of the building?
- When hosting high occupancy density events in large spaces, e.g., in a performance venue, which realistic peak-time scenarios dictate provision of higher ventilation rates?
- Engage with client or end users to identify realistic occupancy scenarios.
- Use post occupancy evaluation data or operational data from similar buildings to identify realistic occupancy scenarios. Although at present, such data may be limited, in the coming years this is expected to change.

SELECT DESIGN SCENARIOS

- Base ventilation strategy on the highest-risk occupancy scenario.
- Consider practical and financial considerations and avoid 'over-designing'.
- Consider efficiency of ventilation system during regular operation and at times of peak operation.
- In spaces with highly variable occupancy or activity levels, consider using an adaptable ventilation strategy, e.g., switching to an enhanced ventilation mode.

RETHINKING VENTILATION DESIGN

PREPARING FOR A PANDEMIC

Key considerations:

- You cannot fully 'design your way' out of airborne infection risk. as this would not be practical, affordable or efficient.
- Previous sections have demonstrated how research-backed building design and operation practices are important if you wish to increase airborne infection resilience.
- Recognising differences between new build and refurbishments. In refurbishments, for example, an extreme scenario might include a requirement to change the use of spaces, reduce occupancy or occupy for shorter periods, especially there is little or no opportunity for fresh air ingress.
- A future 'pandemic preparedness plan' for buildings could require:
  - Smart solutions, such as ventilation control
  - A shift in mindset, e.g. related to social and behavioural issues – not explored in AIRBODS
  - ...*as well as* practical changes to systems and processes

RETHINKING VENTILATION DESIGN

PREPARING OPERATING PLANS

- Occupancy management plan - adapting occupancy density, operational hours and intervals. This could be based on:
    - People working from home, where possible
    - Managed shifts with the aim of reducing risk
    - Accepting that people get sick and may have to take time off;
    - Increased intervals.
- A widespread understanding within the community of the importance of ventilation, similar to the efforts placed to communicate an understanding of the benefits of hand hygiene.
- Good ventilation practices established within the daily, regular operation of buildings and, particularly, when manually operated. These could include:
    - Training
    - Clear roles on ventilation operation
    - Standardised protocols on checks and maintenance of systems.
- A combination of the above with provision of medical interventions, such as testing, masking and vaccinations.

7

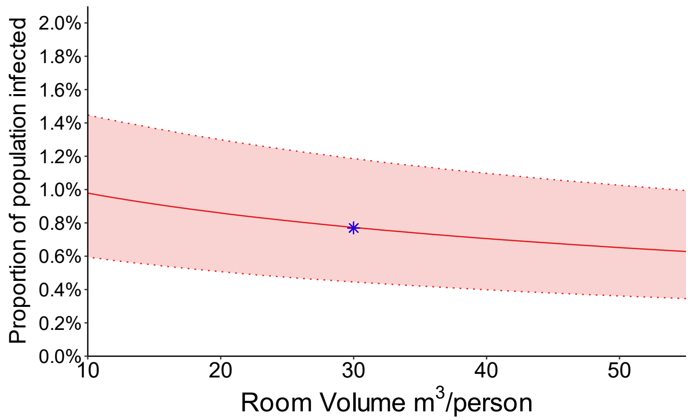
INFECTION-RESILIENT ARCHITECTURAL DESIGN

ARCHITECTURE AND THE PANDEMIC

- Architectural envelopes and internal layouts influence airborne infection risk.
- The pandemic has revealed "flaws" in the way in which we design, manage and operate contemporary buildings.
- Some issues ought to / could be addressed right from the architectural / concept design stage such as:
    - Spatial configuration including internal partitioning. Rules of thumb are important when conceptualizing geometry and layouts. Considerations could include volume of spaces and types of openings, for example.
    - Day-to-day use of spaces including behavioural aspects. Behavioural aspects of occupancy include how infectious users could inadvertently make spaces riskier based on how they move or stay in a particular space – or how susceptible users could expose themselves to more risks.
    - Making buildings more sustainable and resilient to climate change is leading to the adoption of circularity in the building lifecycle. Comprehensive future-proofing consideration for a building could include repurposing (as a potential) so that flexibility / adaptability is built into their design and function at times of higher airborne infection risk.

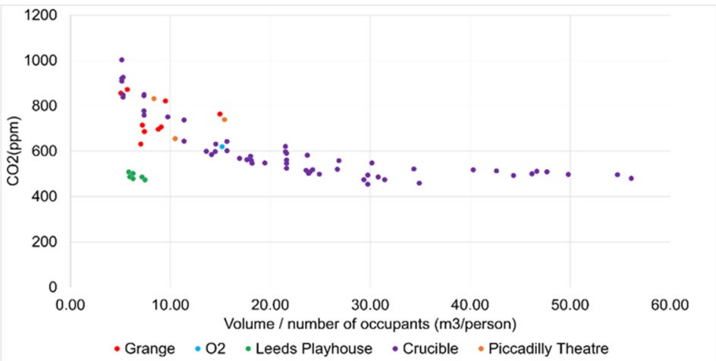
Occupancy capacity at some events were severely restricted at some points within the earlier stages of the pandemic until more confidence was gained on airborne infection risks and how to mitigate against the highest risks.

(Fitzgerald, 2022)



Key considerations are:

- CO_2 levels *are not* dependent on space-volume
- Biological decay and deposition *is* dependent upon space-volume



GEOMETRY & LAYOUT

IMPLICATIONS OF ARCHITECTURAL VOLUMES

- Increasing the volume of space per person can contribute to reducing airborne infection risk (see left). There may be physical limitations to this, so the same effect is achieved by reducing the number of occupants per unit of volume. This is because many aspects of airborne infection risk are volume-dependent.
- In spaces with larger space-volume per person (assuming well-mixed ventilation), the time required to reach a 'steady-state' concentration of virus-laden particle may be significant which impacts the dose received during shorter exposure times. The 'reservoir' capacity of a space, when considered, increases with increased volume.
- During the theatre measurements (bottom left), the volume per person in the auditorium of each event was correlated with the average CO_2 concentration at that event. The average CO_2 increased significantly when the air volume per person was below 10m^3/person.

(Adzic et al, 2022a)

GEOMETRY & LAYOUT

PARTITIONING OF SPACES

- It is advisable to partition large volume spaces intended for a high number of occupants. This reduces the likelihood that an infector is present in the partitioned space.
- It is difficult to propose a maximum number of occupants per space as this depends on occupants' activity and the uncontrollable parameters discussed in Section 4.
- During the design process, decisions related to partitioning should be weighed against the needs of the space, e.g., for collaborative work, the ventilation strategy and the cost of materials and labour.
- The costs and benefits of partitioning should be considered as part of infection-resilient architectural design noting the potential change in ventilation strategy and performance that inclusion may have.

(Iddon, 2022b)

BEHAVIOUR: SHARED SPACES

Note: AIRBODS did not specifically investigate indoor behavioural aspects.

Behaviour of occupants can fundamentally influence effectiveness of ventilation and, therefore, airborne infection risk in indoor spaces. Some key behavioural considerations are as follows:

- Airborne infection is more likely when there's direct contact with an infected person's exhaled air than if the air had time to dilute.
- Such direct contact is more likely when people mix freely in a shared space or are forced to be near other people in a shared space.
- In a shared space, the number of occupants affects the risks of infection by susceptible occupants. Hence, in commercial spaces used by many occupants for instance, it would be reasonable for management decisions such as adopting a hierarchy of controls to be made to avoid putting occupants at unnecessary risk.

(Adzic, 2022a) (Malki-Epshtein, 2022) (SAGE, 2021)

BEHAVIOUR: SMALL VOLUME SPACES

Note: AIRBODS did not specifically investigate indoor behavioural aspects.

- Due to their low (or transient) occupancy, spaces like toilets, stairwells, lifts, corridors are not usually designed for high rates of ventilation, but these spaces could have long queues at large events. However, close contact between such occupants encourages short-range droplet transmission because, unlike outdoors where social distance and dilution may be more effective, far-field indoor airborne transmission at distances > 2m can occur when people congregate in indoor spaces .
- The small volume of toilet spaces (or lobbies) increases risk of short-range transmission and exposure to accumulated exhaled breath when there is a high turnover of people (e.g. at mass-gathering events). The longer people stay or loiter in them, the higher the risk they are exposed to.

(Adzic, 2022a) (Malki-Epshtein, 2022) (SAGE, 2021)

FUTURE-PROOFING: DESIGNING FOR POTENTIAL RE-PURPOSING OF BUILDING

- It is advisable to make (architectural) provisions for natural ventilation from the conceptual and early design stage of buildings as it may be difficult to retrofit.
- Since such future repurposing needs to meet unspecified use cases, a good rule of thumb for new and refurbished buildings is to follow current building regulation requirements.
- Repurposing deep plan buildings for natural ventilation may be challenging with, for example, limitations on access to windows.
- Consider potential changes in outdoor air and noise pollution levels including the future need for windows in spaces less than 12m deep or that exchange air with atria using stack effect.
- It may be challenging to repurpose a commercial buildings in a congested urban area into a residential building and so it would be advisable to employ air quality information available at the planning process to explore the feasibility of mixed-mode ventilation.

8

COMPUTATIONAL FLUID DYNAMICS (CFD) MODELLING

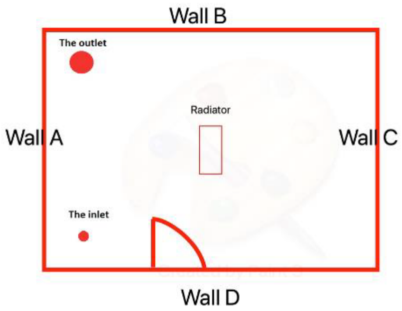
CFD is an extremely powerful tool that allows the user to gain a detailed understanding of ventilation performance at human scale, even in very large spaces. The virtual models can be used to explore many areas of building physics and so it is ideally suited to provide detailed insights into the constituents and movement of droplets and aerosols in air.

PRIMARY CFD CONSIDERATIONS

Before undertaking any CFD modelling it is recommended that the user reviews the CFD and quality assurance related parts of CIBSE AM11 'Building Performance Modelling'. Below are some additional considerations when applying CFD modelling to airborne infection risk investigations:

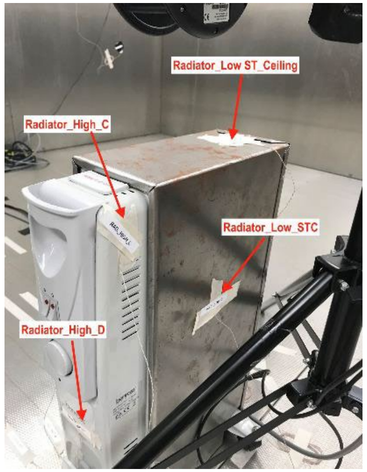
- Level of detail with which body surface geometry
- Breathing through nose and/or mouth
- Approach to occupant breathing
    - Constant volume flow rate equivalent to mean cyclic breathing volume – exhale only
    - Cyclic breathing – exhale only
    - Cyclic breathing – exhale and inhale
- Composition of exhaled breath, e.g. gases, moisture, aerosols and droplets / particles
- Options for body surface thermal model
    - Fixed temperature or heat flux affects thermal plume adjacent to and above body
    - Single value or simple distribution, separate values for skin, hair and clothing
    - Detailed distribution, e.g., one AIRBODS model used values for 59 regions of the body surface obtained from a coupled thermal comfort model

(CIBSE, 2015b)

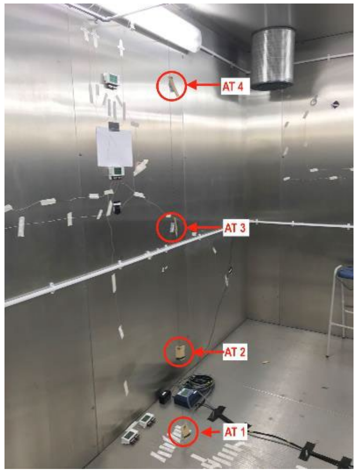


Plan view of test chamber

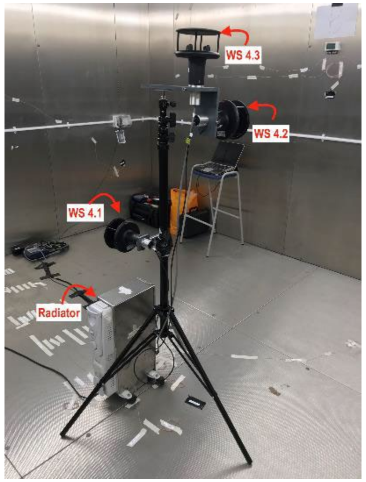
Wall surface temperature sensors



Radiator surface temperature sensors



Air temperature sensors at different heights

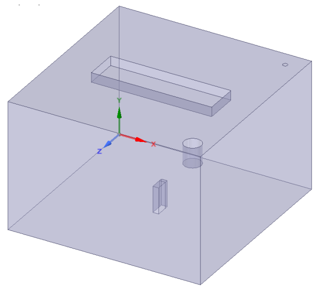


Air velocity sensors at different locations

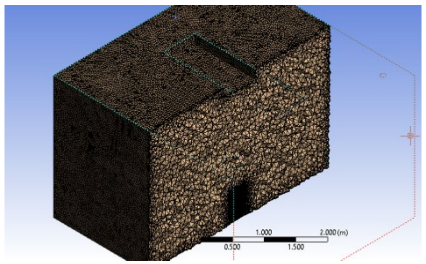
TEST CHAMBER

Measurements from the Human Ecology Research Group (HERG) chamber at UCL were designed to support onward air flow with aerosols experiments. CFD studies were completed on the equivalent experimental configurations. Elements of the measurements side of this validation exercise are described below:

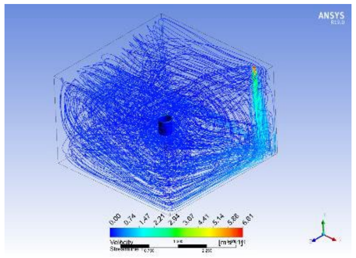
- The radiator was placed in the middle of the room to generate a strong buoyant plume (top left).
- Air was supplied through a single inlet at 0.048 m^3/s and extracted through a single outlet, both at ceiling level.
- The surface temperatures of walls, ceiling, floor and radiator surface were measured by thermocouples (top right & bottom left).
- The air temperatures were measured at three locations at different heights (bottom middle).
- Air velocity was measured around the radiator (bottom right).
- The ceiling mixing fans were modelled as closed box as they were not used in aerosol deposition and distribution experiments conducted in the chamber.



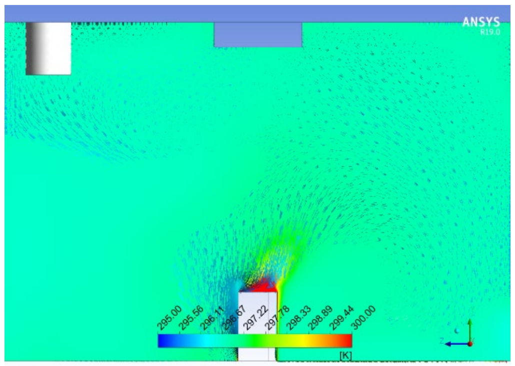
3D geometry



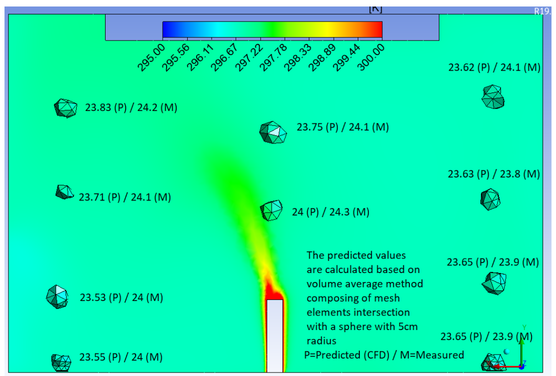
CFD computational mesh



Understanding characteristic air movement



Buoyant plume above radiator



Measurement locations were aligned with CFD data taking locations

CFD VALIDATION

CFD calculations were designed to align with the experimentation as part of an early validation exercise comparing CFD estimates against equivalent measurements with the following characteristics:

- 3D geometry generated equivalent to experimental configuration with a radiator in a central location (top left).
- Unstructured tetrahedral mesh was used along with inflation layers on the surfaces (top middle).
- The air movement is characteristic of a well-mixed environment in this scenario (top right).
- Air velocity vector and temperature contour plots confirms the expected plume above the radiator (bottom left).
- The measured (M) and CFD predicted (P) values shows a good agreement (bottom right). The CFD model is therefore an accurate representation of the tested experiment.

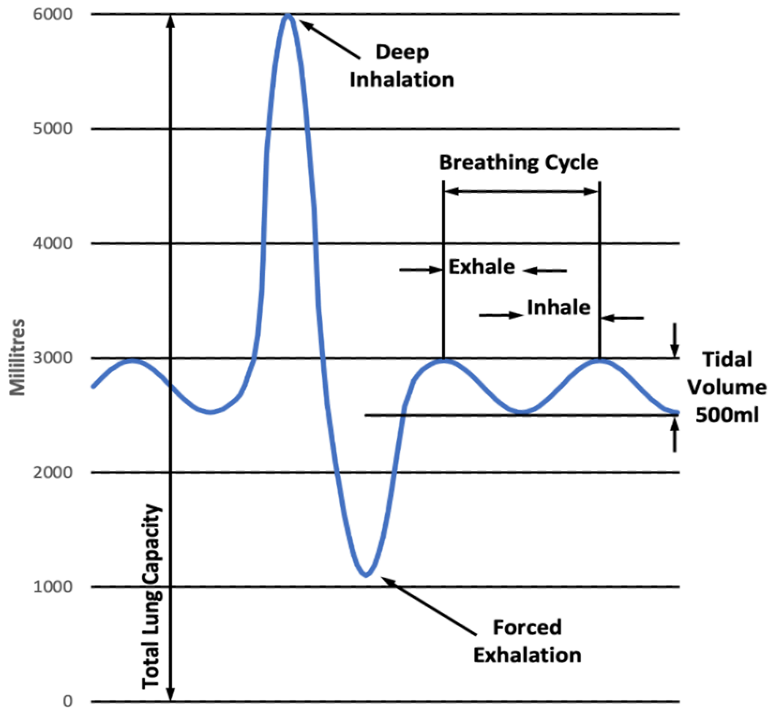
It was noted that the challenges to validate at full scale within a test chamber are different to the challenges in a real space, especially if the space is large. The controlled nature of the test chamber together with the 'design of experiments' approach provided additional confidence in the whole approach as CFD models were applied to real spaces.

	Oxygen (O_2)	Carbon Dioxide (CO_2)	Nitrogen (N_2)	Water Vapour (H_2O)
Ambient Air	20.93%	0.03%	79.04%	0.00729%
Exhaled Air	13.7%	5.3%	79.8%	0.03894%

The composition of ambient and exhaled air

GAS CONTENT AND TEMPERATURE

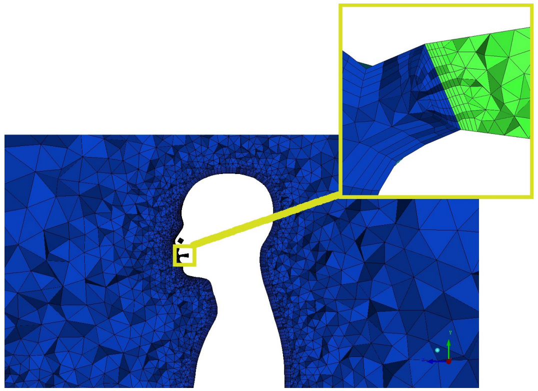
- During inhalation, local ambient air is drawn into the body through the mouth and/or nose.
- During exhalation, the expelled gas mixture has been warmed to body temperature and saturated with water vapour.
- The proportions of the relevant gases that make up ambient air and exhaled air are shown on the left.
- Exhaled air is typically specified using a single fixed values for air temperature, humidity and density, etc.



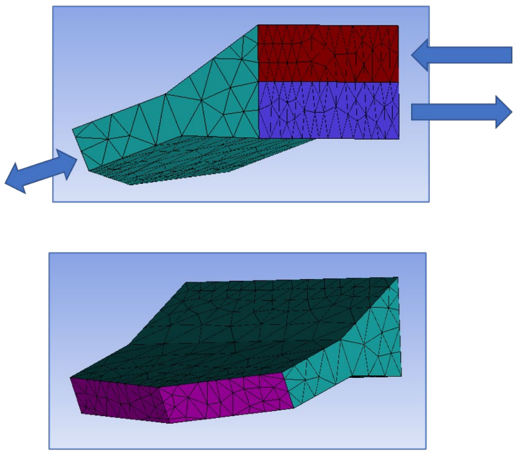
BreathIng volume is dynamic in nature depending upon where a person is on their breathing cycle

THE BREATHING CYCLE

- Breathing, or pulmonary ventilation, is the process by which air is drawn into and expelled from the lungs.
- The breathing rate is determined by:
    - Level of activity or exertion (metabolic rate)
    - Fitness
    - Anxiety etc.
- The total lung capacity for a typical 70kg person, the volume of the lungs when fully inflated, is 6 litres. The remaining volume when a person fully exhales is 1 litre.
- The tidal flow volume is the volume of air inhaled and exhaled when breathing normally at rest. The average resting value is 500ml.
- The variation in flow rate during the breathing cycle is assumed to be sinusoidal. This, together with the flow direction, needs to be precalculated with the equivalent profile (flow rate over time) controlled in the CFD.



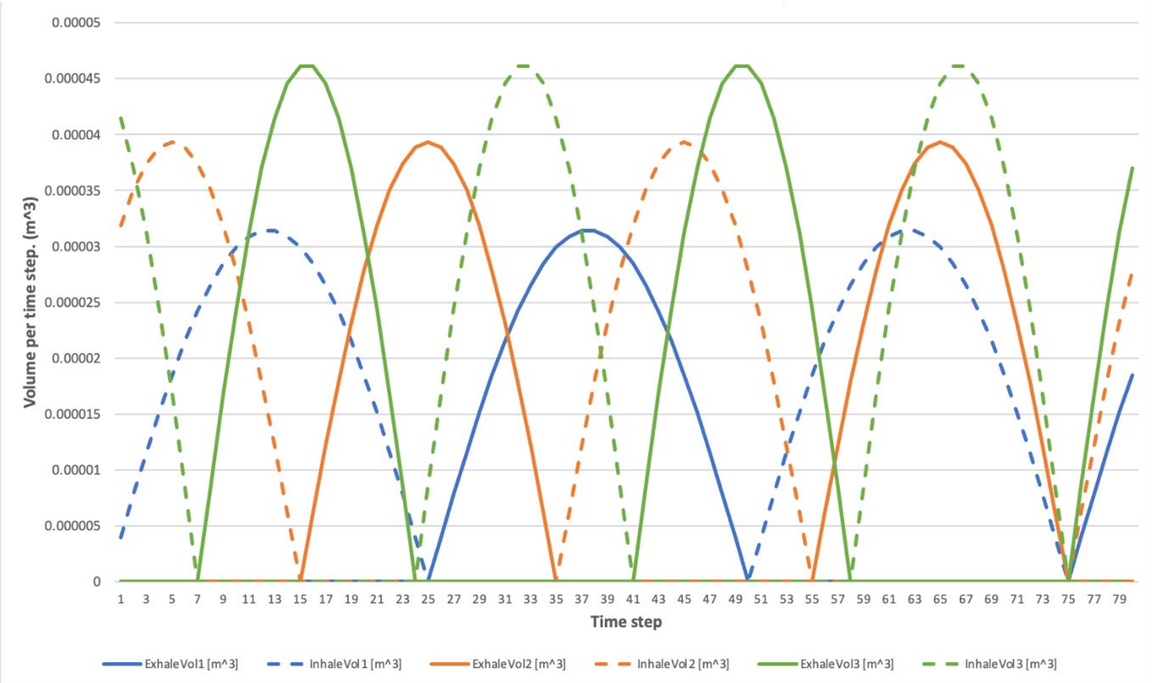
Representing the breathing cycle with increased oral and nasal detailing.



Use of separate CFD boundaries to better represent the breathing cycle

IMPLEMENTATION OF AN ADVANCED BREATHING MODEL

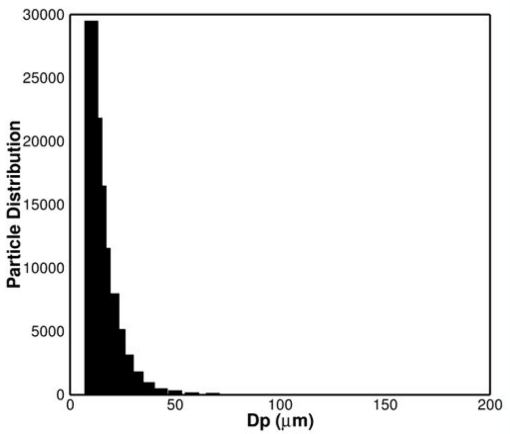
- AIRBODS explored the distribution of exhaled breath detailing the various gaseous components instead of using a single component of air.
- As both inhaled and exhaled air pass through the same openings (nose and/or mouth), the following possible boundary conditions were explored:
    - Inlets - specified gases enter the CFD domain at a designated rate
    - Outlets - unspecified gases leave the CFD domain at a designated rate
    - Openings - gases can enter or leave the domain driven by a pressure difference.
- None of these 3 boundary specifications allows bi-directional flow at a given flow rate at a given time as a single boundary representing a nose or mouth cannot be modelled as both an inlet and an outlet. A 'back of throat' area was therefore defined using both and inlet and outlet to better understand the air mix at the location of the nose and mouth.
- During inhalation only the CFD outlet is active. During exhalation, a gas mixture for exhaled breath is introduced.



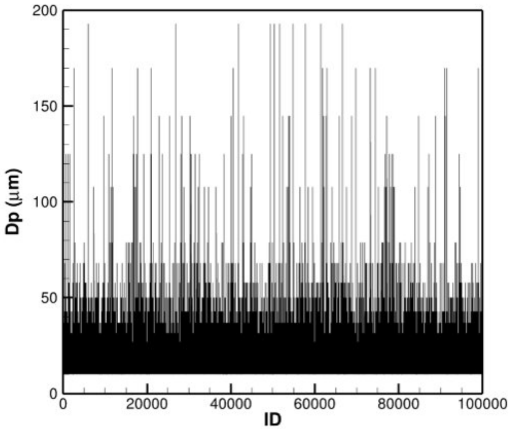
Inhalation and exhalation volume for each CFD time interval (time step)

MULTI-OCCUPANT BREATHING

- Simulations of realistic scenarios are likely to include more than one building occupant requiring multiple-occupant breathing models.
- A wide variation of breathing cycles from multiple persons were aligned within the same simulation to examine the impact of the dynamics of the breathing cycle on exhaled air.
- If multiple occupants are assigned the same breathing rate and begin the breathing cycle at the same time, they will be in-phase and remain in-phase throughout the simulation, possibly leading to unrealistic combined total gaseous emissions.
- Assigning different breathing rates to each occupant will result in different occupant breathing cycle durations which will, in turn, result in a changing phase relationship over a number of breathing cycles.
- The primary control is on the starting points in the individual breathing cycles.



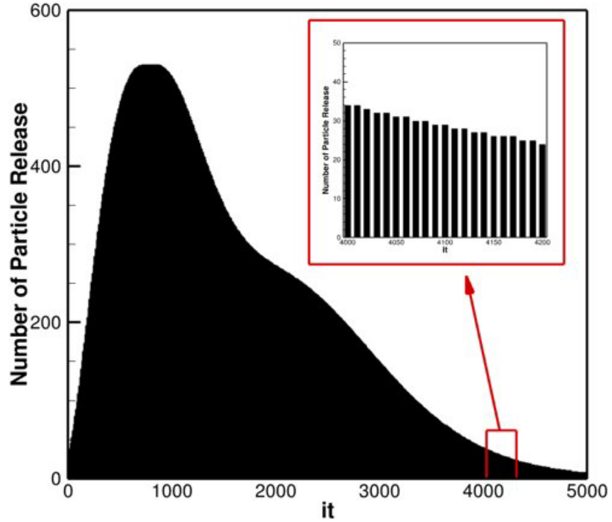
Particle distribution of a cough



Randomisation of the particle distribution

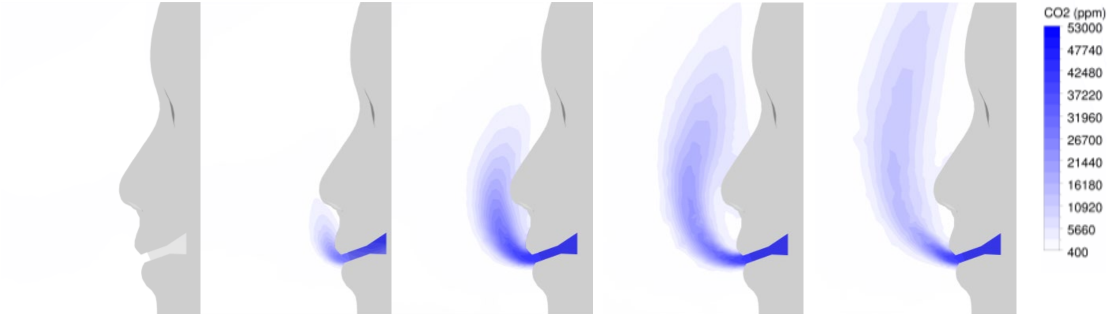
COUGHING MODEL

- A coughing model was developed with an adapted version of the particle distribution curve – the number of particles or droplets versus their diameter (top left).
- This was then randomised (bottom right).
- The quantity of droplet release was correlated onto the mass volume release during a coughing event (below).
- The following conditions were applied:
  - Exhaled droplets - 34°C / 85% RH
  - Ambient air - 22.4°C / 30% RH.

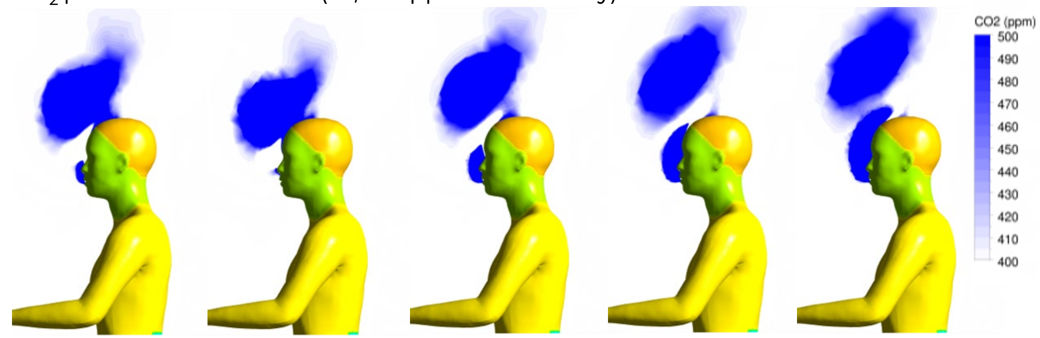


Correlation of the particles released and the mass of air (5000 iteration equates to 0.5s)

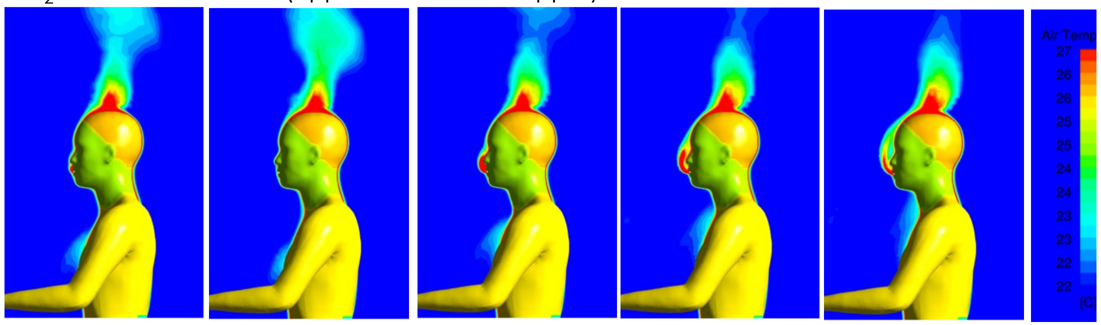
(Lindsley, 2014) (Gupta, 2009)



CO_2 plot of exhaled breath (53,000 ppm at boundary)



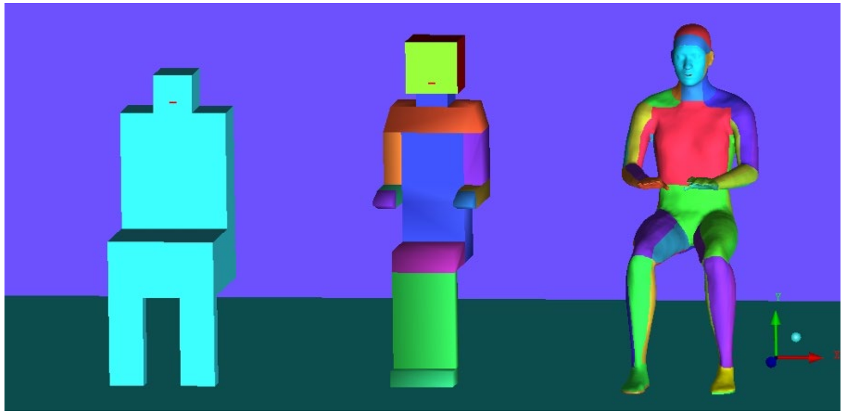
CO_2 in the environment (upper scale now 500 ppm)



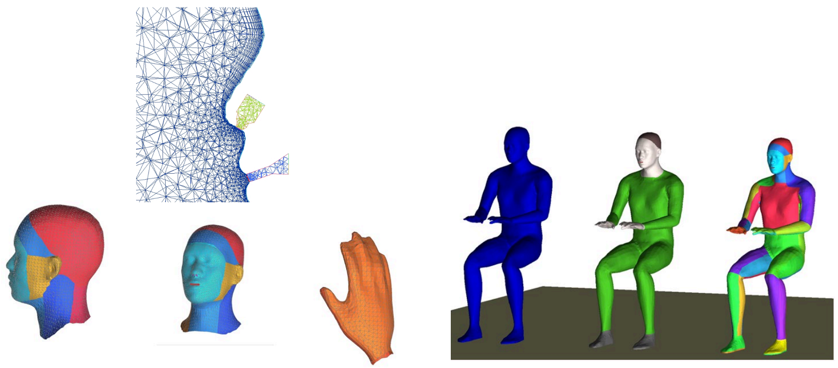
Increased air temperature in the buoyant plume above a person's head

MODEL OF A BREATHING PERSON

- A dynamic breathing model needs to be transient in nature with some parameters, such as flow rate of CO_2, varying over time.
- Key considerations and questions are:
    - Is there sufficient detail in the model to capture, for example, realistic air dilution / mixing and subsequent cross-contamination risk?
    - How do the CFD estimates compare against other approaches that adopt the 'fully-mixed by zone' assumption, e.g., dynamic thermal models?
    - How do the various environmental conditions, e.g., humidity levels effect the distribution of the various gas components and aerosols, if present?
    - What's the effect of averaging, of time in a steady-state CFD case or of space in other tools and methods when equivalent values from the CFD are compared?
- Many questions have been asked as part of the limited AIRBODS programme, some of which form the basis of ongoing research.



Simple, intermediate and complex body CFD representations



Detailing body components

SINGLE-PERSON MODELS

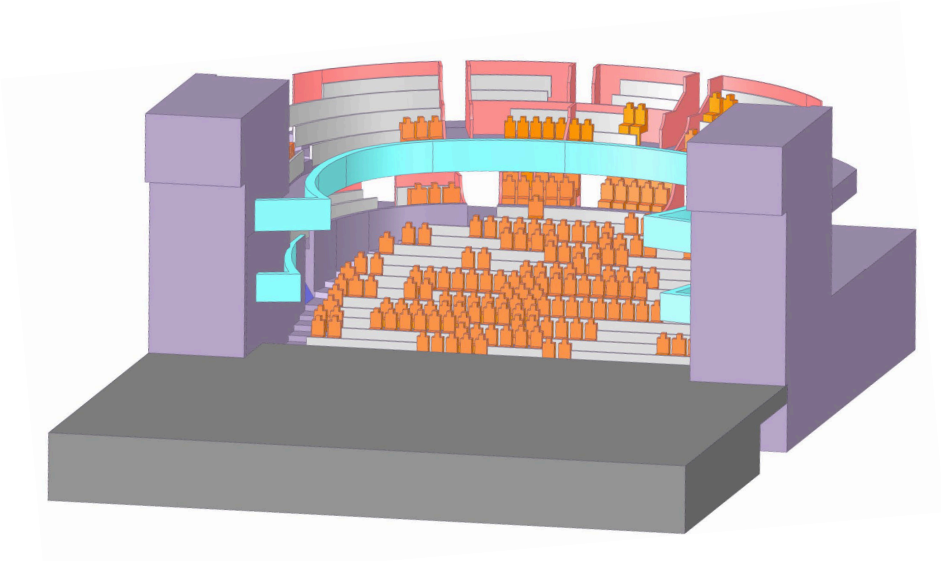
Key decisions when constructing a CFD body model relate to:

- The approach to controlling the convective and radiative heat exchanges. This is especially important when working alongside other software to ensure a consistent approach, e.g., not double-counting the radiative components.
- Geometric complexity of the body from simple 'boxes' to ones with complex curvature (see top left).
- Approach to splitting up the body surface where heat load is applied to each body surface element (see bottom left).

Additional considerations could include:

- Using a simple assumption to apply a third of the body convective heat gain through the head and the rest over the other parts of the body noting how the radiative and convective heat load components may vary in different environmental / room conditions.
- A more advanced approach including a 1-d body surface thermoregulatory model. The CFD in this scenario would also derive the convection-radiation components at each body surface, as a function of the local air movement and temperature across any discrete body surface.
- This latter approach is ongoing research which could better inform how a very detailed modelling approach for a single person might influence the distribution of aerosols in a room when compared to a simplified equivalent model.
- There is added complexity about how the buoyant plume generated by a body interacts with the exhaled breath which has a 'jet-like' momentum associated with it close to source.

(Gao and Niu, 2006) (Cropper, 2010)



Simple CFD body form in one of the AIRBODS auditoria to represent an audience (or crowd in another type of venue)

The strength of a buoyant plume generated by a human body could influence how their exhaled aerosols are distributed within a room. More work is needed on the strength of the buoyant plumes from one or more infected persons in an audience when considering interactions with the other members of the audience.

MULTI-PERSON MODELS AND WORKING WITH DYNAMIC THERMAL MODELS

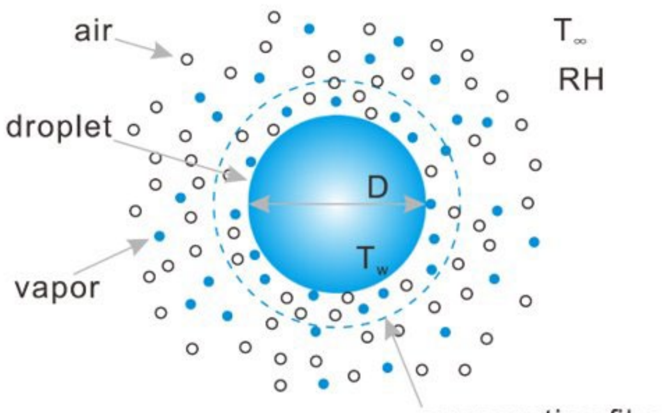
- Due to computational limitations, it may not be possible or practical to apply a single-person model in fine detail throughout an audience or crowd. It may also not provide any additional insights if you could. At one of the AIRBODS theatre venues (see left), the approach to modelling an audience is forming part of ongoing research.
- A dynamic thermal model (DTM with 1D zonal network airflow model) has a standard application throughout industry in many application areas, such as building energy assessments.
- In a DTM, the total heat gain from a person is typically applied to an occupied zone according to the number of people within it at any given hour. The model calculates total body radiant gains applied at the zone 'point' balanced with surrounding surface temperatures in addition to the body convective gains to the same point. Air movement with contamination between each 'fully-mixed' zone is then pressure/ buoyancy driven noting there are no momentum equations as in the CFD.
- Typically, practical CFD models in industry are run in 'convection only' mode at a given hour with the DTM-outputted surrounding surface temperatures applied as fixed values. These have already accounted for body radiant gains which is why only the convective component of the body heat gain is applied in the CFD.
- Although there are other potential approaches including utilising a radiant model in the CFD, in the above approach the body convective heat gain drives the buoyant plume upwards (potentially containing virus-laden aerosols) and therefore influences the effect of mixing with ambient air.

(Vita, 2023)

Working in the sciences at microscale can be extremely challenging. Due to the impracticalities of some measurements, it becomes necessary to employ numerical techniques which are subject to validation including sub-component physics models.

ADVANCED AEROSOL CLOUD AND DROPLET DYNAMICS

- Many aspects of cloud and droplets dynamics are not directly or easily measurable using current physical modelling and visualisation techniques.
- Advanced CFD techniques can capture detailed physics and its associated dynamics at microscale then, once validated to acceptable levels at component and wider scale, used to drive more simplified approaches.
- Key aspects of the AIRBODS advanced models included:
  - Coughing events (see earlier).
  - Developed evaporation physics and evaporation rate models (see later).
  - Coupling discrete particle or 'Lagrangian' models (DPM) with Eulerian or 'gaseous cloud' scalar models.
  - Quantification of outputs, e.g., relating the advanced evaporation model with the dynamics of the DPM droplets.



(Wang)

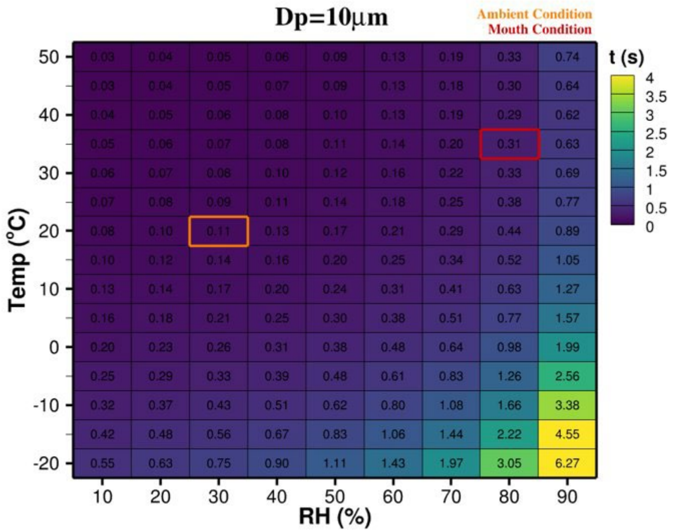
EVAPORATION MODEL

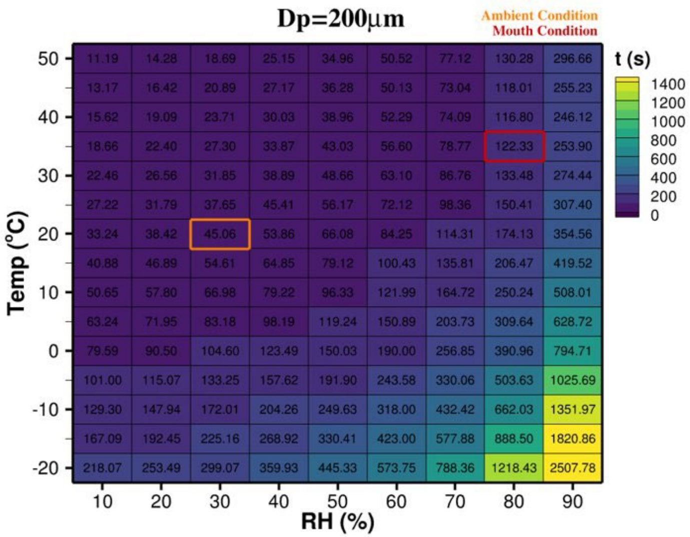
The CFD evaporation model contains the following modelling parameters:

- Relative humidity – This is defined as the ratio of partial vapour pressure and saturated vapour pressure.
- Saturated vapour pressure - Saturated vapour pressure (wet-bulb pressure) is correlated against ambient temperature.
- Partial vapour pressure - Partial vapour pressure (dry-bulb pressure) is correlated against saturated vapour pressure, and dry-bulb/wet-bulb temperatures.

- The three main factors that significantly influence evaporation are the Reynolds Number, humidity levels and surface temperatures.
- Sensitivity studies were undertaken to determine how the approach in the CFD might impact the droplets as they mix with ambient air.
- The first approach uses empirically-derived evaporation rates as fixed relationships in the model (see next page).
- The second approach uses an advanced coupling of the key physical parameters to explore in detail how the droplet dynamics vary from droplets with different initial sizes (see in two pages time).

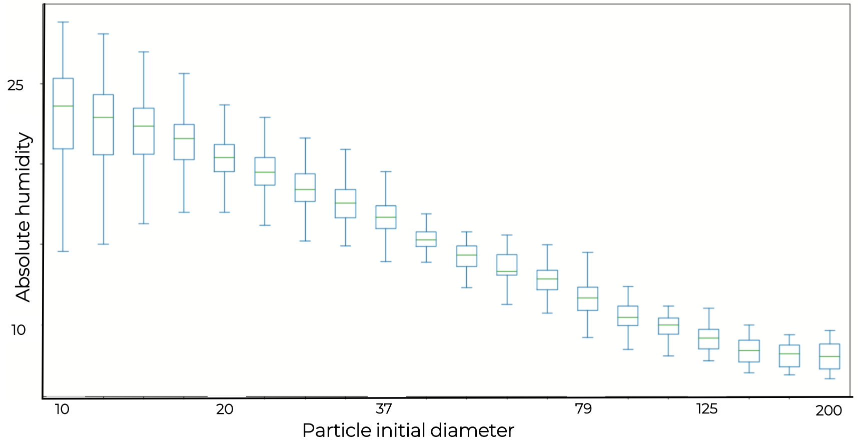
(Foat, 2022) (Wang, 2020) (List, 1958) (Holterman, 2003) (Monteith, 1990)





EVAPORATION RATE (EMPIRICAL MODEL)

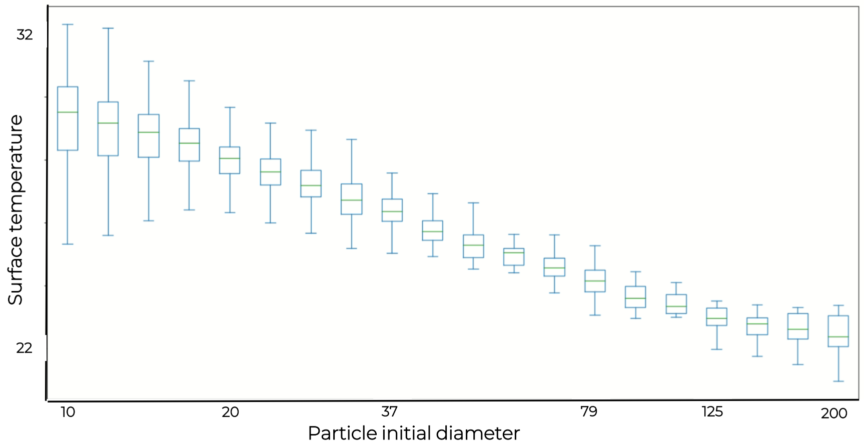
- A sensitivity analysis of the evaporation model was performed on different droplets using tabulated empirical data to inform the time required for the smallest and largest aerosol droplet to evaporate under varying air temperature and relative humidity.
- The data (see left) shows the clear impact of the temperature and relative humidity on the time for the droplet to fully evaporate and reach their solid / nucleate form.
- On the top left, the scale for the small droplet (diameter, Dp, of 10 microns) to evaporate has a maximum value of 4 seconds.
- On the bottom left, the scale for the large droplet (diameter, Dp, of 200 microns) to evaporate has a maximum value of 1,400 seconds.



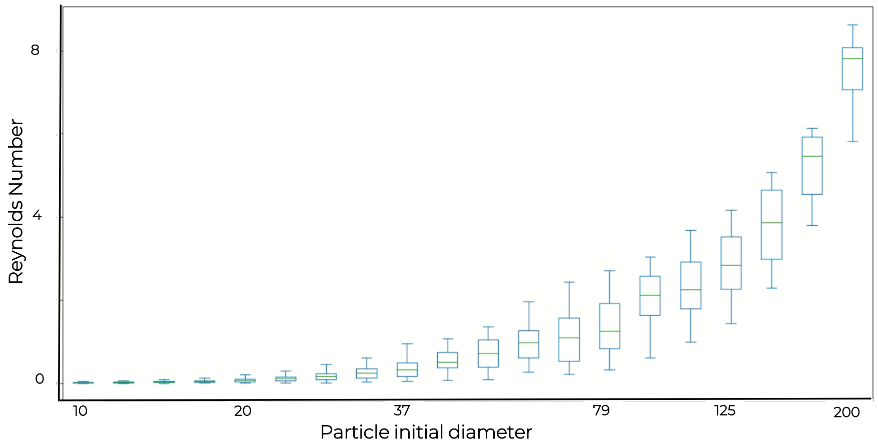
Absolute humidity (g/m³) of different sized droplets (μm)

EVAPORATION RATE (CFD-COUPLED MODEL)

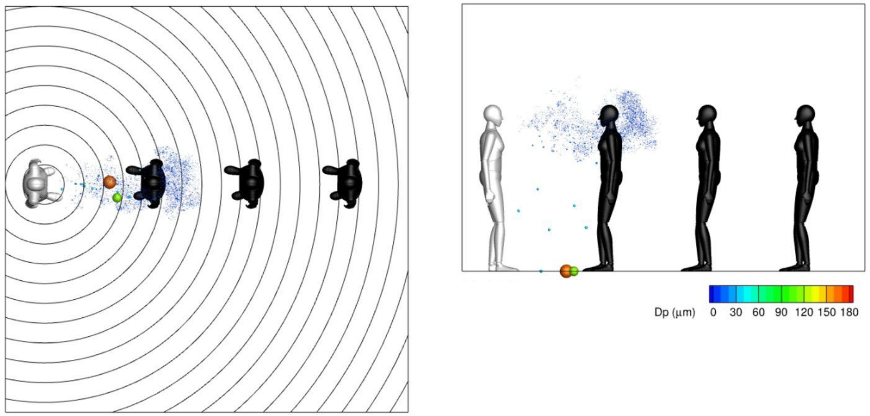
- Ongoing research is focusing upon the dynamics of individual droplets within an aerosol cloud.
- The individual droplets have different humidity levels (top left), surface temperatures (bottom left) and turbulent flow characteristics described by Reynolds Number (bottom right), as a function of their different initial size.
- These graphs outputted by detailed coupled simulations, can inform lower order models through using the described relationships as input, or boundary conditions for their evaporation model.



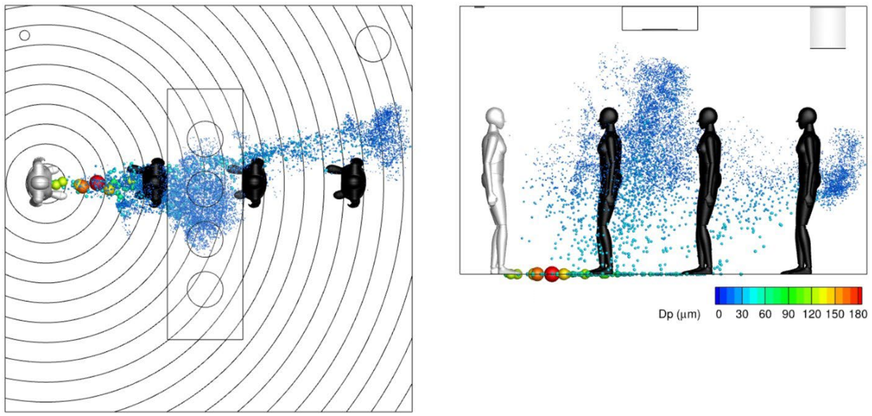
Surface temperature (°C) of different sized droplets (μm)



Reynolds Number (-) of different sized droplets (μm)



Droplet field at 6 seconds



Droplet field at 60 seconds

KEY FINDINGS

- The developed evaporation rate model showed that the change of droplet mass due to evaporation leads to a divergence into the droplet velocity in the discrete particle model (DPM). To correct this, the simulation required a very small time step of about 5.0^{-5}s.
- It also showed that a forward coupling from the aerosol cloud temperature and humidity toward the droplet significantly influenced the rate of evaporation and dynamics of the droplet.
- A backward coupling from droplets toward the cloud had a negligible effect due to the scale difference between the droplet and the cell size. ($V_p/V_{cell}=65*10^{-6}$).
- The difference between the speed of the droplet in the DPM and the gas in the cloud has a significant effect on the cloud-droplet dynamics. This effect was investigated with the following models:
    - Coarse grid/large-field Eulerian simulation without evaporation
    - Coarse grid/large-field DPM-Eulerian simulation without evaporation
    - Coarse grid/large-field DPM-Eulerian simulation with evaporation
    - Medium grid/large-field DPM-Eulerian simulation with evaporation
    - Refine grid/near-field DPM-Eulerian simulation with evaporation
- It was shown that specific guidance is needed on each of these model types to control both the momentum of the droplets and their evaporation rate. This guidance extends to the size of the CFD time step to promote momentum stability, coupling within the cloud-droplet model to reduce spurious oscillations and incorporation of a thermal (active) scalar and humidity field effecting droplet behaviour.

9

CASE STUDIES

As part of the Events Research Programme, the AIRBODS team monitored the indoor air quality in twelve restaurants within several venues during summer 2021. Three of the restaurants at Ascot Racecourse and Wembley Stadium provided a focus for additional REI & PPI calculations (presented earlier) with further thoughts and findings presented in this section

WHAT IS UNIQUE ABOUT RESTAURANTS?

SOCIAL SETTINGS

- ...where people will typically share a table for about two hours. This can vary considerably, depending on the wider setting or occasion.
- Occupants were monitored spending 9 hours in restaurants at day-long horse racing events, where people intermittently leave the restaurant to watch a race.

CLOSE CONTACT

- Near-field transmission is likely to be the dominant route in restaurants.
- People are sat close to each other with 'orders of magnitude' greater viral concentration in the air at distances less than 1m from an infector.

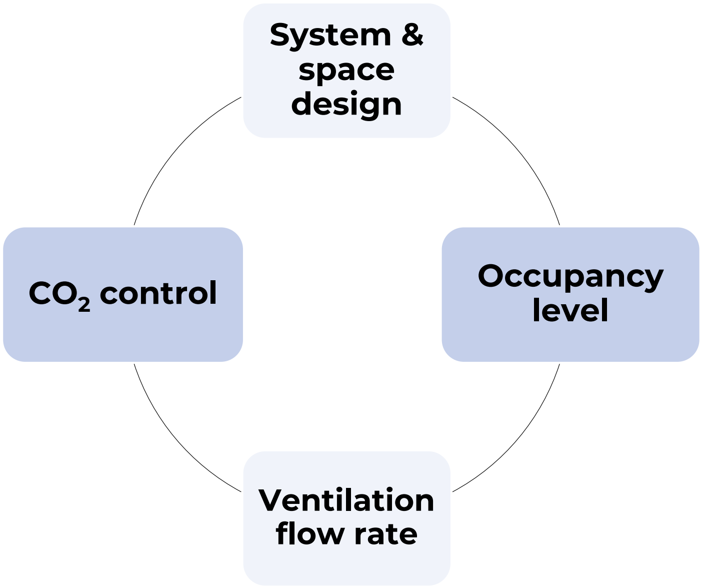
MASKING NOT APPLICABLE

- Masking is not an applicable measure in these settings, as people eat and drink.
- This increases the risk of both near-field and far-field transmission.

LARGE VARIETY OF CONDITIONS

- There is a large variety of space configurations, occupancy density and ventilation strategies in restaurants.

(Iddon, 2022b)



- What are the different restaurant activities and what are their locations?
- What is a reasonable peak usage scenario to design for?
- What is the efficiency of the ventilation system during regular usage?

RESTAURANTS: DESIGN MEASURES INCREASING AIRBORNE INFECTION RESILIENCE

SYSTEM & SPACE DESIGN

- Seat occupants away from 'high concentration' zones, such as near exhaust grilles.
- Consider ventilation efficiency in system design, e.g. displacement systems can remove contaminants with reduced air mixing.
- Localised ventilation reduces cross-flows.

OCCUPANCY LEVEL

- Occupancy density should be in line with good practice guidance, e.g. CIBSE Guide A.
- Control occupancy levels in different areas.
- Identify max occupancy level for different events.

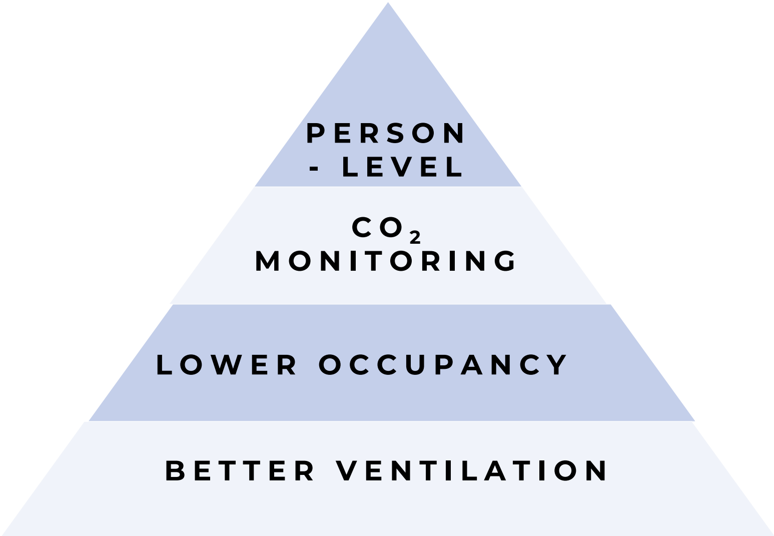
VENTILATION FLOW RATE

- Ventilation flow rate in each occupied area to follow current guidelines with max potential flow rate per person noted.
- Sizing for ventilation strategy should consider the effective dilution or removal of contaminants in each occupied area.

CO_2 CONTROL

- Integrating CO_2 control into ventilation strategy highly recommended to identify poor ventilation and/or overcrowding.
- Demand-controlled ventilation using CO_2 sensors can support maintenance of good indoor air quality using less energy.

(CIBSE, 2015a)



- What capacity is there to 'over-ventilate' specific occupied areas through providing a higher fresh air rate?
- How might over-ventilating impact energy usage and thermal comfort, especially during cold periods?

RESTAURANTS: OPERATIONAL MEASURES INCREASING AIRBORNE INFECTION RESILIENCE

1: BETTER VENTILATION

- Prioritise poorly-ventilated areas.
- Due to increased exposure time and people interactions, increase ventilation rate per person where practicable.

2: LOWER OCCUPANCY

- Reduce occupancy density in overcrowded areas.
- Due to short-range transmission importance, encourage social-distancing.

3: CO_2 MONITORING

- Take short-term measurements to identify high-risk areas.
- Install sensors to monitor indoor air quality and adjust ventilation flow rate accordingly.

4: PERSON-LEVEL

- Avoid crowding up or lingering in lobbies or long queues while waiting to use toilets.

As part of the Events Research Programme, the AIRBODS team monitored the indoor air quality in over 82 events focusing on mechanically-ventilated auditoria. Some venues were more than 100 years old (The Piccadilly, Lyceum and Grange theatres) and others less than 50 years old (The Crucible, the Playhouse, O2 Arena, Liverpool Arena and Conference Centre). Data on occupancy, event management and performance times were collected. Additionally, a microbiological study took place – see Section 5 for more details.

WHAT IS UNIQUE ABOUT THEATRES?

COMPLEX AND QUIET SPACES

Complex spaces to ventilate as

- Air distribution occurs over a large area
- Must be quiet
- High intermittent heat loads (occupancy and stage lighting).

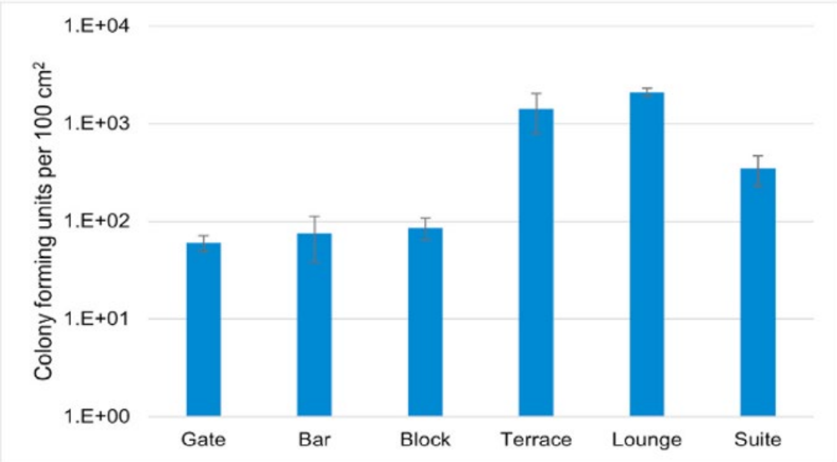
VARIOUS CONFIGURATIONS

- An auditorium, the main seated space, may be tiered rising higher than the level of the stage.
- It may have balcony areas plus many ancillary areas, such as those backstage for performers, for ticketing, bars, restaurants, corridors and toilets.

VARIABLE PROGRAMMES

- Although an average play may last 2 to 3 hours with a 15min intermission, this can vary considerably.
- Different types of events with different schedules may occur, such as in the Crucible Theatre in Sheffield which hosted the World Snooker Championship and was monitored as part of the Events Research Programme.

(Kavgic, 2008) (Adzic, 2022a)



Mean bacterial colony forming unit counts for different arena areas

THEATRES: LESSONS LEARNT FROM MICROBIOLOGICAL SAMPLING

CONSISTENT RANGE

- Microbiological sampling in the O2 Arena auditorium found a consistent range of bacterial counts in the air across different arena area types with lower levels found in the lounge areas and peak levels found in the suites.

HIGHER RISK AREAS

The highest bacterial surface contamination was found in:

- Private and enclosed lounge areas (food and drinks served)
- In the terrace with tables in the main arena
- In the private and enclosed suite areas (private parties , own food & bar)

Note: Both the lounges and suites were open to the auditorium and surfaces at the gate and blocks had much lower levels of contamination.

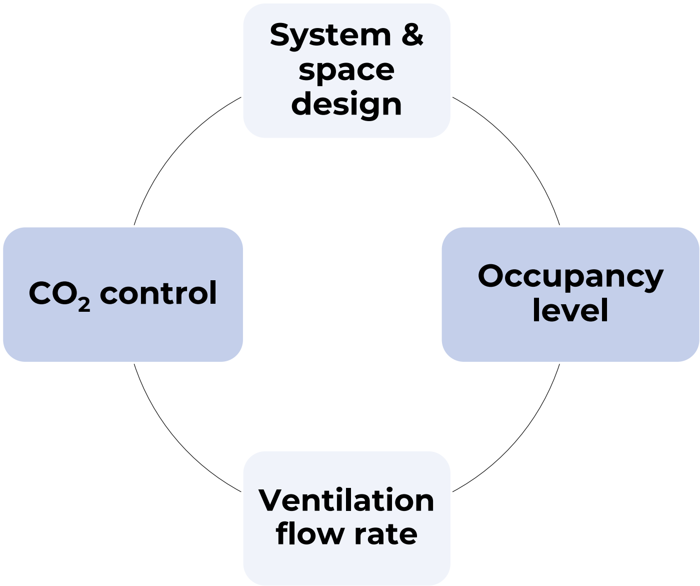
MOST CONTAMINATED SURFACES

- Highest contamination levels found on service counters and table-tops where food was served, whereas handles were less contaminated.

AIR AND SURFACE SAMPLES

- No SARS-CoV-2 was detected in the air samples taken.
- Very low levels of RNA copies detected in 8.5% of the surfaces sampled (3 positive samples found in private suites and one in a lounge.)

(Adzic, 2022a)



- How should the ventilation strategy vary in different areas?
- What is a reasonable peak usage scenario to design for, e.g., a bar area during the interval?

THEATRES: DESIGN MEASURES INCREASING AIRBORNE INFECTION RESILIENCE

SYSTEM & SPACE DESIGN

- For auditoria, the quality of mixing should be considered through increased dilution of re-breathed air where possible, supported by detailed insights of airflow patterns.
- Ancillary spaces (e.g. toilets, circulation and bar areas as well as staircases) are 'pinch point' areas requiring additional considerations.

OCCUPANCY LEVEL

- For auditoria, large space volumes in relation to the number of occupants reduce airborne infection risk.
- Identify max occupancy level for different events.

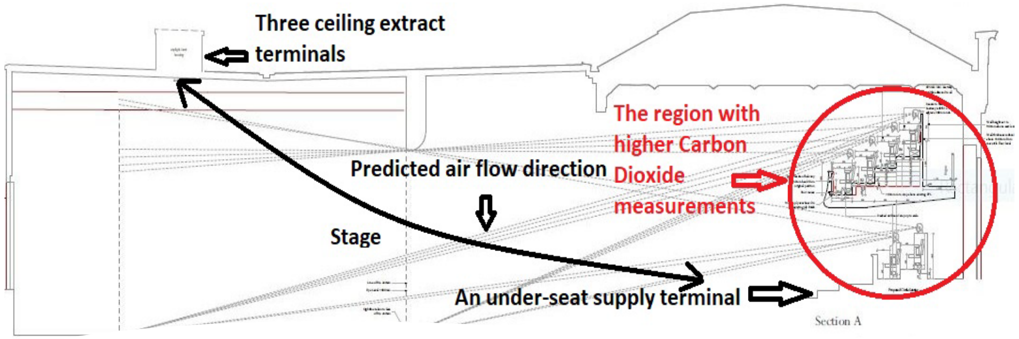
VENTILATION FLOW RATE

- Ventilation flow rate in *each* occupied area to follow current guidelines.
- Limited benefit from 'over-ventilating' already well-ventilated spaces as this could result in thermal discomfort, low humidity levels *and* increased energy costs.

CO_2 CONTROL

- Even when IAQ is excellent or very good, the air may not be well-mixed with some areas exposed to much higher CO_2 levels.
- Demand-driven ventilation systems do not always work as intended, so maintenance and regular checks of the system components are important.

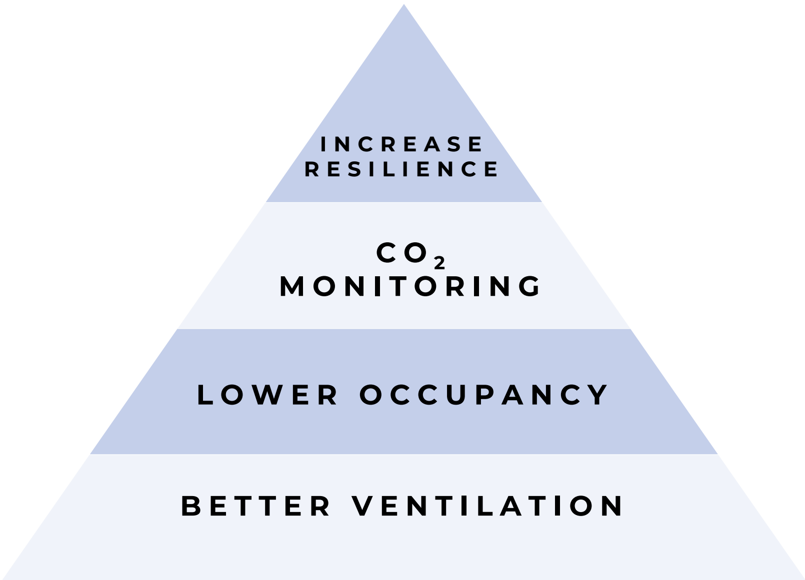
(Malki-Epshtein, 2023) (Adzic, 2022a)



Within this theatre event, even though the ventilation complied with the national guidance at the time of 100% outside air supply and minimum flow rates of 10l/s per person or higher, due to low local ventilation effectiveness within certain regions, the CO_2 levels were higher than expected leading to higher airborne infection transmission risk. This was one observation from one specific venue.

THEATRES: STRATEGIC DESIGN VENTILATION SYSTEM PERFORMANCE

- This example details the output from the measurements at one venue and describes its installed system with some operational parameters. One way to support better ventilation performance is to reconsider the way its strategy is communicated and developed during decision-making stages. Ventilation systems can be quite variable in their geometric and system configurations. Summary for this system and findings for the event are as follows:
  - Displacement ventilation operating 100 % outdoor supply air with flow direction from floor to ceiling.
  - 10.7 l/s per person supply air flow rate (90% occupancy for this event).
  - Underseat supply air terminals located within stalls area only. Extract air grilles located at the back of the stage at high level.
  - The positioning of the air supply and extract grilles and measured CO_2 levels (mostly below 750 ppm) indicated that the indoor air was re-circulated at the stalls and balcony areas.
  - As a result, the circle and the seats at the back of the stall area (shown by the red circle on the left) are lacking air supply and extract ventilation terminals resulting in CO_2 levels above 1000 ppm, sometimes reaching 1500 ppm.
- An improved description, including ventilation aspects of airborne infection resilience, could include various indexes, such as ventilation effectiveness, along with metrics developed in AIRBODS amongst others. Beyond simple visualisations of air paths, ideal sensor locations could be marked up and key risks identified early. There could be a movement away from metrics assuming fully-mixed zones towards more localised ones at person rather than room scale. These metrics could have a well-thought through overlays covering the full multi-objectives of healthier, more productive, efficiently-operated and safer spaces.



- What capacity is there to improve ventilation effectiveness, especially if air mixing is poor, e.g., due to geometry and ventilation system configuration?
- What is the appropriate response with a given ventilation system when large variations in CO_2 concentrations are observed?

THEATRES: OPERATIONAL MEASURES INCREASING AIRBORNE INFECTION RESILIENCE

1: BETTER VENTILATION

- Use ventilation during the intervals to 'purge' auditorium as much as possible.
- Increase interval frequency / duration in poorly-ventilated or overcrowded venues although this can increase risk in ancillary areas and with more people movement.

2: LOWER OCCUPANCY

- Some ancillary areas could be poorly ventilated and should have reduced occupancy during peak periods, such as during intervals.

3: CO_2 MONITORING

- High resolution CO_2 monitoring in large spaces like auditoria facilitates identification of overcrowded or poorly ventilated areas.

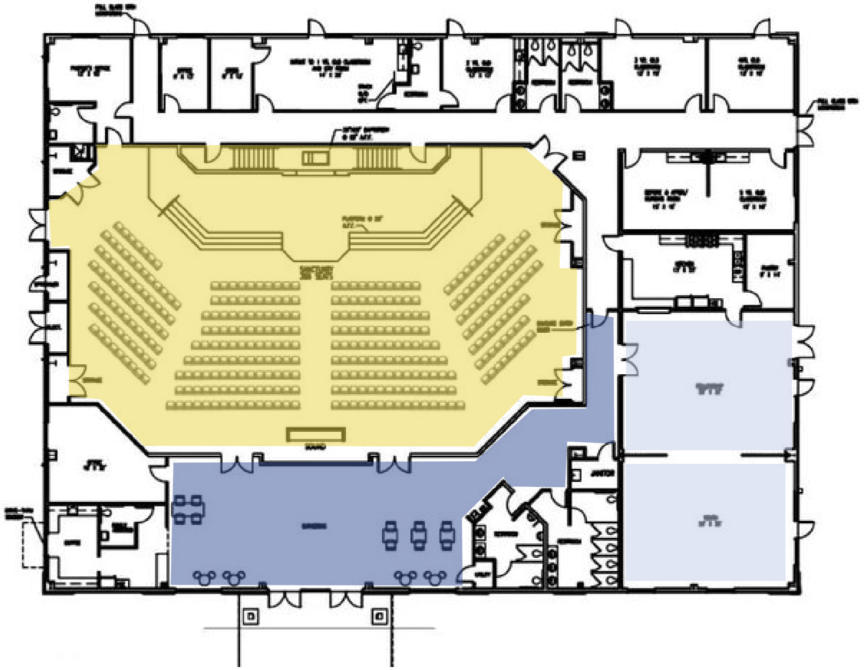
4: INCREASING RESILIENCE

- Increase infection resilience through pharmaceutical and non-pharmaceutical measures (physical distancing, testing and isolation of infected individuals, hand-washing, masking and vaccination).

(Adzic, 2022a)

10

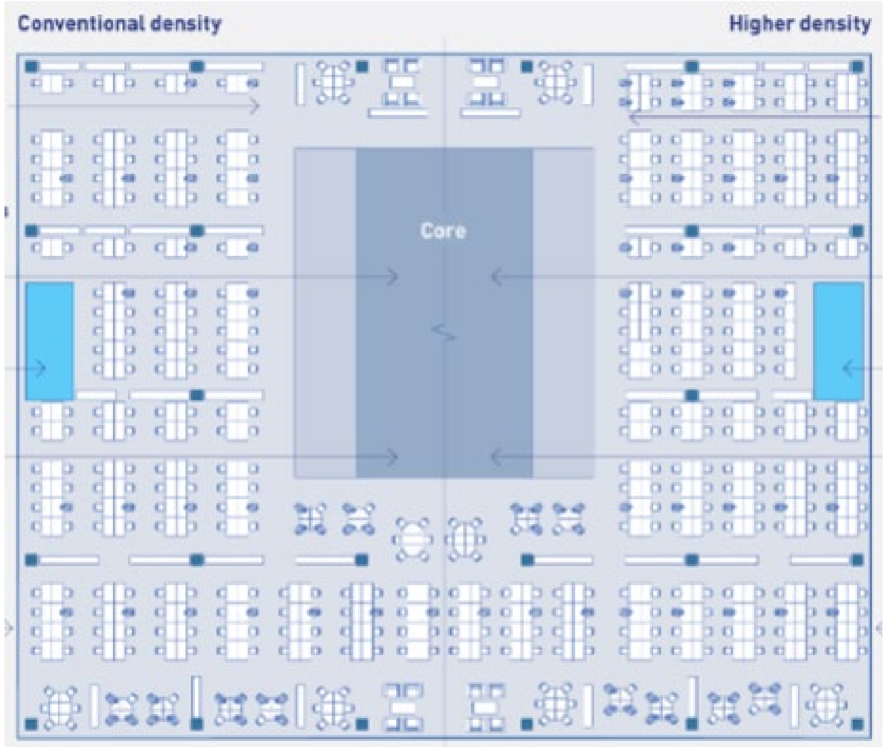
BUILDING OPERATION AND DESIGN SUPPORT (BODS) TOOL



Sample performance venue that could be assessed using BODS tool. Each different shaded area represents different room 'types'.

SCOPE AND PURPOSE

- Building Operation and Design Support (BODS) tool has been developed as a framework that enables building designers, operators or managers to assess the comparative risk of airborne infection at a whole building level and for each space classification within the building.
- The purpose of this tool is to inform building design, refurbishment and maintenance in a way which reduces airborne infection risk without undermining user comfort or environmental sustainability considerations.
- The framework provides a numerical assessment output, based on a set of inputs and assumptions, as well as recommendations on how to improve health resilience in the building.
- It can be used for new buildings and refurbishments at design stage or for existing buildings in operation, with recommendations adjusted according to the type of the development and stage in the construction process.
- The version of the tool issued at the time of writing is a preliminary example presenting the proposed types of assessment on a few building types and is intended for further development.



Sample BCO office layout ('Conventional density') that was used to inform the construction of a universal reference building for Numerical Assessment No 2.

OUTPUTS

NUMERICAL ASSESSMENT NO 1

- Compares the user's building new transmissions with their good practice replicate building's new transmissions.
- Aims to give an understanding of how the risk within the building compares with the risk levels it could achieve by implementing good practice design or operation practices.

NUMERICAL ASSESSMENT NO 2

- Compares the user's building new transmissions with the universal reference building's new transmissions.
- Aims to give an understanding of how the risk within the building compares with the risk in other buildings, in this case with a predefined reference office building, that follows good practice design or operation practices.

RECOMMENDATIONS (QUALITATIVE)

- Qualitative assessment outputting recommendations on improving the health resilience of the building.
- This assessment is based on the numerical outputs as well as the responses of the users to a set of questions about their building.

METHODOLOGY

The BODS tool methodology is split into four main stages.

STAGE 1

USER INPUTS

Information is obtained from the user for the undertaking of numerical calculations and for hierarchical selection of recommendations.

STAGE 2

ROOM LEVEL PPI

Proportion of people infected (PPI) estimates are carried out for each room type. The number of new infections per 100 room occupants is estimated (but not shown as an output to avoid potential misinterpretation).

STAGE 3

BUILDING LEVEL PPI

PPI is estimated at building level by adding the PPI results at room level weighted by the proportion of building occupants in each room type. The number of new infections per 100 building occupants is then estimated (but not shown as an output to avoid potential misinterpretation).

STAGE 4

OUTPUTS

The PPI calculations at room level and building level are repeated for two other hypothetical buildings. The first is a replica of the user's building with set at the recommended (CIBSE) occupant densities and recalculated ventilation rates. The second is a 'typical' office building which also follows good practice design. Two ratios provided as outputs and recommendations are then generated.

BUILDING CHARACTERISTICS

The tool requires the following inputs from the user which are provided for each of the room “types.

USER TYPE

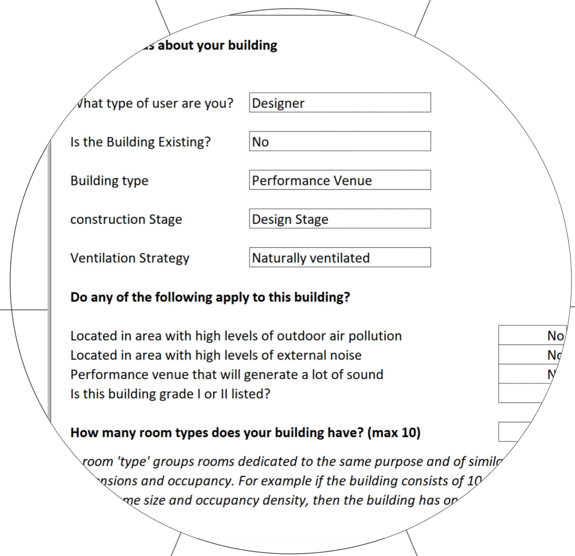
User can select between ‘Designer’, ‘Operator’ or ‘Occupant’. Should determine language used and nature of recommendations provided. Currently only ‘Designer’ mode is operational.

BUILDING TYPE

Information regarding the *primary* use of the building. Currently ‘office’, ‘performance venue’, and ‘restaurant/café/bar’. Determines the available choices for ‘space use’ at room level.

DESIGN RESTRICTIONS

Questions on potential limitations to the design of the building, e.g., is the building listed?, Is It located in an area of high external noise or air pollution?, etc.



CONSTRUCTION STAGE

Allows user to specify between ‘design stage’ or ‘in use’. Should determine the types of recommendations provided. Currently only ‘design stage’ is operational.

VENTILATION STRATEGY

Provides options between ‘naturally ventilated’, ‘mechanically ventilated’ and ‘mixed-mode ventilation’. Impacts on type of recommendations provided.

NUMBER OF ROOM TYPES

Groups rooms dedicated to the same purpose and of similar dimensions and occupancy. So that if a building consists of many rooms that are virtually identical to one another, this can be specified with one single room type.

DEFINING ROOM TYPES

The tool requires the following inputs from the user which are provided for each of the room "types.

NUMBER OF ROOMS

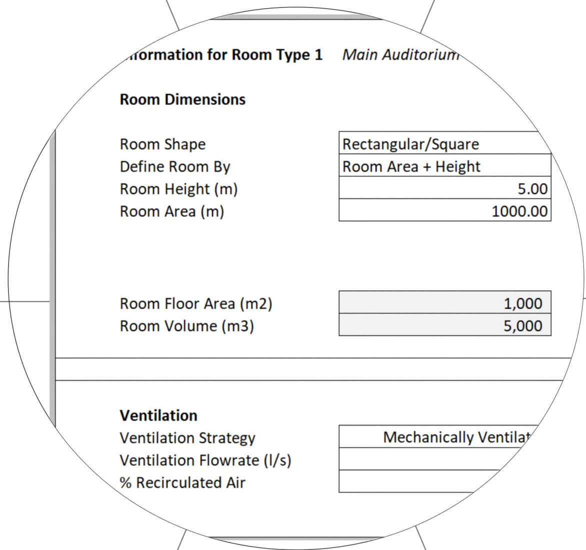
Number of rooms included in this room 'type'. This information allows for the building level PPI to be weighted appropriately by proportion of building occupants in each room type.

SPACE USE

Pre-defined selection of seven space uses per building type (e.g. "transit area" or "bar area"). This determines the activity and therefore the breathing rates of occupants.

ROOM DIMENSIONS

Required to establish room floor area and volume. Different options provided for the specification of room dimensions such as "room area + height" and "room volume + height". Currently only room area + height is operational.



OCCUPANTS

Number of occupant and occupant exposure time (typical time spent inside the room without breaks) is specified, as well as percentage (%) of occupants wearing masks.

VENTILATION RATE

Details of ventilation strategy and flowrates are specified for dilution rate estimates. In addition, user can specify percentage of total ventilation flowrate that consists of recirculated air.

ADDITIONAL SYSTEMS

The provision of air filtering systems, cleaning devices and associated flowrates is specified in this section. This impacts on the overall fresh air provision and dilution rate calculations.

ASSUMED VALUES

Various constants used in the tool calculations and associated references are listed below:

Variable Name	Value	Source
Dose constant (K) [1]	410	(DeDiego, 2008). (Iddon, 2022b)
Community Infection Rate (C) [1]	10%	Arbitrary, as used by (Iddon, 2022b)
Lung deposition fraction [2]	0.54	(Darquenne, 2012)
Concentration of RNA Copies in exhaled droplets [1] – (viral load)	Range of values considered	Following method of Iddon (2022b)
Susceptible breathing rate [3]	(m^3/s) Varies according to occupant activity.	Composite value based on table of values provided in (Adams, 1993)
Infector breathing rate [1]	(m^3/s) Varies according to occupant activity.	Composite value based on table of values provided in (Adams, 1993)
Viral load (mean value) [1]	10^7 RNA copies per ml of respiratory fluid	(Iddon, 2022b)
Viral load (standard deviation) [1]	$10^{1.4}$ RNA copies per ml of respiratory fluid	(Iddon, 2022b)

[1] A more detailed definition for some of these terms is in Section 3.

[2] Fraction of material (in this RNA copies) which are deposited in the lungs following inhalation.

[3] Volume of air inhaled by individuals who are susceptible (people who could potentially get infected by Sars-Cov-2) and individuals who are infectors (currently infected and contagious) dependent on activity.

CHARACTERISTICS OF 'GOOD PRACTICE' REPLICA AND OFFICE BUILDINGS

'GOOD PRACTICE 'REPLICA BUILDING

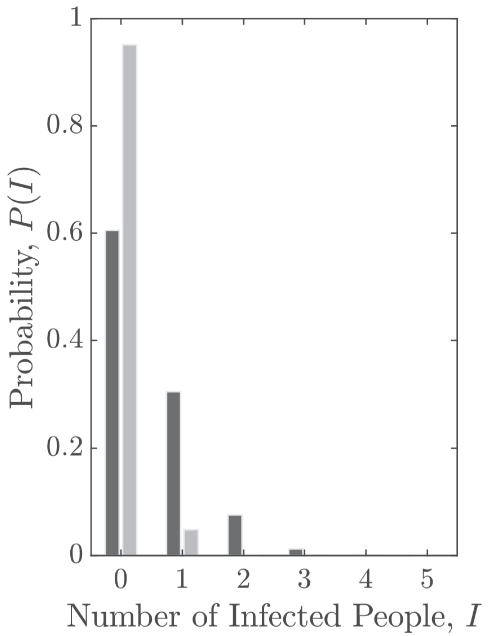
Variable Name	Value	Source
'Good practice' occupancy per area	10 m^2 per person	BCO occupancy density for medium density office.
'Good practice' ventilation rate	12 l/s/person	(BCO, 2019)

'GOOD PRACTICE' OFFICE BUILDING

Variable Name	Value	Source
Typical office floor layout	1 conference room per 20 people, 5 small meeting rooms, 1 large breakout space, 8 cell offices and toilets. 223 occupants	(BCO, 2019) (Hicks, 2020) (Aquila, 2018)
Occupancy density:	8-10 m^2/p (depending on room type)	(BCO, 2019)
Floor height	2.8m	(BCO, 2019)
Ventilation rate	12 l/s/person	(BCO, 2019)

TOOL DEVELOPMENT REFERENCES

The following references were used in the development of the BODS Tool: (Iddon, 2022b) (DeDiago, 2008) (BCO, 2019) (Darquenne, 2012) (Adams, 1993) (Hicks, 2020) (AQUILA, 2018)



The probability of a number of infected people, I, present in the Big Office (dark) and Small Office (light) when CIR = 1%

PPI CALCULATION

- PPI calculations observe that the possibility of airborne infection within a space is dependent on the probability of both an infector and susceptible individual being present within the space at the same time. This methodology has been adapted for application in the BODS tool.
- From room level to building level - the proportion of occupants within a room that become infected after simulating repeated episodes of room use are considered. The tool adds the resultant number of infected individuals at room level to produce a building level figures, estimated as 'infections per 100 occupants' (but not shown as an output to avoid potential misinterpretation).
- Different use of benchmarks – the risk of infection is compared against a fixed benchmark. The BODS tool effectively generates a new benchmark with every calculation (Assessment 1), which is based on a 'good practice' version of the user's building.
- Simplified inputs - The tool also simplifies some of the considered variables. For example, it provides predetermined breathing rates for each definition of 'room use' which reduces flexibility but improves consistency of outputs for users.

(Iddon, 2022b)

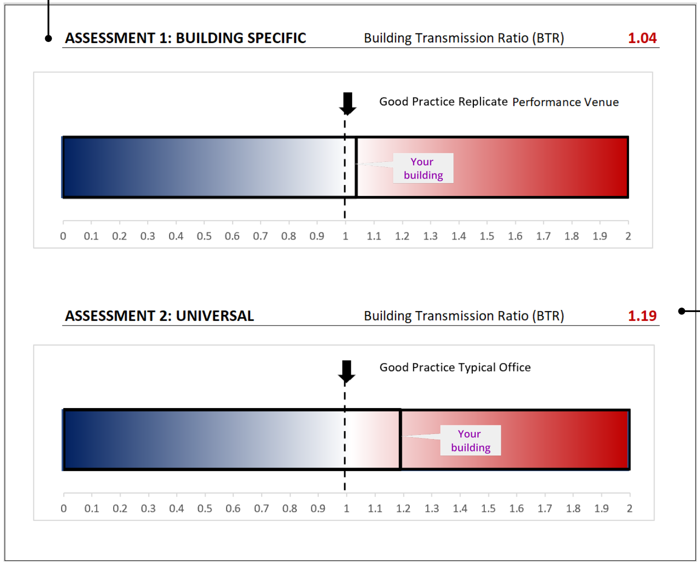
NUMERICAL ASSESSMENTS

ASSESSMENT 1: BUILDING SPECIFIC

- Estimates the ratio of the total number or new transmissions in the *user's buildings* with the total number of new transmissions in a 'good practice' *replicate building*, i.e.:

$$\frac{T_a}{T_r}$$

- This ratio aims to give the user an understanding of how the risk within the building compares with the risk levels it could achieve by implementing good practice design or operation.



ASSESSMENT 2: UNIVERSAL

- Estimates the ratio of total number of new transmissions in the *user's buildings* with the total number of new transmissions in a *universal reference building*, i.e.:

$$\frac{T_a}{T_u}$$

- This ratio aims to give the user an understanding of how the risk within their building compares with the risk in other buildings, by comparing its performance against a predefined reference office building, that follows good design and operation practices.

- A qualitative assessment outputs recommendations on improving the health resilience of the building.
- It is based on the numerical outputs and responses of the users to a set of questions about their building.
- Increasing ventilation rates should come after other potential solutions such as reducing occupancy.
- Recommendations are based on the results of Assessment 1 (Assessment 2 is ignored for this) and are selected according to a hierarchy (No of occupants > decreasing exposure time > increasing ventilation rates).

RECOMMENDATIONS

Room 1
No improvement required

Room 2
Consider reducing the occupancy density

Room 3
Consider reducing the occupancy density

Room 4
Consider reducing the occupancy density

Room 5
No improvement required

RECOMMENDATIONS

Currently the tool provides a limited number of recommendations based on a simple set of conditionals. This sets the basis for future development with the following considerations:

1: Is the number of infections higher than in the reference building?
- If 'FALSE' then no recommendations are required.
- If 'TRUE', the tool displays titles for each room type and assesses the difference between the user's building and the reference building as in the following (2):

2: Is the number of occupants higher than in the reference room?
- If 'TRUE' the tool provides a recommendation to reduce number of occupants in the room types identified as exceeding the reference levels of occupancy.
- If 'FALSE' The tool then asks the following (3):

3: Is the exposure time higher than the reference room?
- If 'TRUE' then the tool recommends reducing exposure time or introducing breaks.
- If 'FALSE' then the tool asks the following (4):

4: Are ventilation rates lower than the reference room even after reduced occupancy?
- If 'TRUE' then the tool recommends increasing ventilation rates, or if that is not possible, installing an air-cleaning device.

The BODS tool is an open access beta version calculator to provide initial guidance into relative airborne infection risk associated with building design and operation.

NEED FOR FURTHER WORK

- General improvements to the interface - the tool is currently in draft mode and requires further improvements before it can be of practical use to building designers, operators and occupants.
- Ventilation effectiveness - the addition of a ventilation effectiveness measure could expand on the issues that tool could provide recommendations for.
- Importing of user geometry - in large buildings, the process of specifying each room type dimensions becomes cumbersome. The tool would benefit of a means of importing these values from existing 3D models.
- Improved recommendations - the tool is currently limited on a handful of recommendations and provides only one recommendation per room type. This could be improved to provide various sets of recommendations per room type according to an established hierarchy.

The BODS tool currently uses simple, static equations but could be developed to include the dynamic effects of changing occupancy and ventilation conditions in the future.

LIMITATIONS

- Impact of room distribution - while the tool considers the number of rooms of each type, it does not consider how floor layout can impact on airborne transmission and therefore on probability of infection.
- The well-mixed assumption - due to the assumption of a well-mixed-space, the tool cannot assess ventilation effectiveness inside a room. This means it cannot provide advice with regards to improvements to the positioning of air supply and extract grilles or furniture layout which may have a big impact on ventilation effectiveness and, consequently, on airborne infection risk.
- Occupancy estimates - currently the tool estimates total occupancy of a building by adding the total occupancy in each room. The tool assumes a static occupancy condition. In reality, occupants will move between rooms at different times but this would require a dynamic tool that considers transient variations affecting PPI, which cannot be supported in a static tool such as this one.

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NEED FOR FURTHER WORK

EXPERIMENTAL THEMES

- More detailed biological work including large-scale experiments to understand transport of biological particles rather than just aerosols as well as the link between CO_2 and biological contaminants.
- Real time data capture and analytics brought together with advanced digital techniques.
- Some monitored large spaces were observed to have poor mixing of air which implies some people are exposed to worse quality air than others. More monitoring is required to identify these issues in other venues and building types to understand how this can be avoided. More data would support greater insight on aerosol transport and associated characteristics.

MODELLING THEMES

- Development of a computational approach for multi-objective building compliance and performance assessments including airborne infection resilience together with energy usage, thermal comfort, building envelope & system optimization, indoor air quality and overheating risk.
- Further development of models and methods including behavioural aspects.
- Linking current AIRBODS metrics with larger epidemiological models to advance tool development.

OTHER THEMES

- Development of better targeting for different building and system typologies when developing more detailed industry guidance including cost, value and inclusivity aspects.
- Support the bridging of the communication and training gap between design and building usage.
- Incorporate filtration and air cleaning with AIRBODS metrics, amongst other things, as potential solutions in some spaces.

12

REFERENCES

REFERENCES

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13

KEY AIRBODS OUTPUTS

PUBLICATIONS

(JONES, 2021)
MODELLING UNCERTAINTY IN THE RELATIVE RISK OF EXPOSURE TO THE SARS-COV-2 VIRUS BY AIRBORNE AEROSOL TRANSMISSION IN WELL MIXED INDOOR AIR

Abstract: We present a mathematical model and a statistical framework to estimate uncertainty in the number of SARS-CoV-2 genome copies deposited in the respiratory tract of a susceptible person, over time in a well-mixed indoor space.
By relating the predicted median for a reference scenario to other locations, a Relative Exposure Index (REI) is established that reduces the need to understand the infection dose probability but is nevertheless a function of space volume, viral emission rate, exposure time, occupant respiratory activity, and room ventilation. A 7h day in a UK school classroom is used as a reference scenario because its geometry, building services, and occupancy have uniformity and are regulated.
The REI is used to highlight types of indoor space, respiratory activity, ventilation provision and other factors that increase the likelihood of far field (m) exposure. The classroom reference scenario and an 8h day in a 20-person office both have an and so are a suitable for comparison with other scenarios. A poorly ventilated classroom (1.2 l s^{-1} per person) has suggesting that ventilation should be monitored in classrooms to minimise far field aerosol exposure risk. Scenarios involving high aerobic activities or singing have; a 1h gym visit has a median, and the *Skagit Choir* superspreading event has.
Spaces with occupancy activities and exposure times comparable to those of the reference scenario must preserve the reference scenario volume flow rate as a *minimum* rate to achieve, irrespective of the number of occupants present.

(IDDON, 2022b)
A POPULATION FRAMEWORK FOR PREDICTING THE PROPORTION OF PEOPLE INFECTED BY THE FAR-FIELD AIRBORNE TRANSMISSION OF SARS-COV-2 INDOORS

Abstract: The number of occupants in a space influences the risk of far-field airborne transmission of SARS-CoV-2 because the likelihood of having infectious and susceptible people both correlate with the number of occupants. This paper explores the relationship between occupancy and the probability of infection, and how this affects an individual person and a population of people. Mass-balance and dose–response models determine far-field transmission risks for an individual person and a population of people after sub-dividing a large *reference* space into 10 identical *comparator* spaces.
For a single infected person, the dose received by an individual person in the *comparator* space is 10 times higher because the equivalent ventilation rate per infected person is lower when the *per capita* ventilation rate is preserved.
However, accounting for population dispersion, such as the community prevalence of the virus, the probability of an infected person being present and uncertainty in their viral load, shows the transmission probability increases with occupancy and the *reference* space has a higher transmission risk. Also, far-field transmission is likely to be a rare event that requires a high emission rate, and there are a set of Goldilocks conditions that are *just right* when equivalent ventilation is effective at mitigating against transmission. These conditions depend on the viral load, because when they are very high or low, equivalent ventilation has little effect on transmission risk.
Nevertheless, resilient buildings should deliver the equivalent ventilation rate required by standards as minimum.

(ADZIC, 2022a)
A POST-OCCUPANCY STUDY OF VENTILATION EFFECTIVENESS FROM HIGH-RESOLUTION CO_2 MONITORING AT LIVE THEATRE EVENTS TO MITIGATE AIRBORNE TRANSMISSION OF SARS-COV-2

Abstract: Mass-gathering events were closed around the world in 2020 to minimise the spread of the SARS-CoV-2 virus. Emerging research on the transmission of SARS-CoV-2 emphasised the importance of sufficient ventilation. This paper presents the results of an indoor air quality (IAQ) monitoring study over 82 events in seven mechanically ventilated auditoria to support the UK government Events Research Programme. Indoor carbon dioxide concentration was measured at high resolution before, during, and after occupancy to allow for assessment of the ventilation systems. Generally, good indoor air quality was measured in all auditoria, with average IAQ found to be excellent or very good for 70% of spaces. In some auditoria, spatial variation in IAQ was identified, indicating poor mixing of the air. In addition, surface and air samples were taken and analysed for the presence of bacteria by culture and SARS-CoV-2 using RT-qPCR in one venue. SARS-CoV-2 RNA was detected on a small number of surfaces at very low copy numbers, which are unlikely to pose an infection risk. Under the ventilation strategies and occupancy levels investigated, it is likely that most theatres pose a low risk of long-range transmission of COVID-19.

(IDDON, 2022c)
MONITORING AND MODELLING THE IMPACT OF VENTILATION ON THE LONG-RANGE EXPOSURE RISK TO SARS-COV-2 LADEN AEROSOLS IN RESTAURANTS

Abstract: The UK Government's Events Research Programme (ERP) aimed to examine the risk of transmission of SARS-CoV-2 at large-scale entertainment events and to explore ways to enable people to attend them safely. It was the largest programme of its kind worldwide.The transmission of the SARS-CoV-2 virus is thought to be primarily via the inhalation of airborne respiratory droplets and aerosols both at close and long range. Building ventilation can reduce the long range inhaled dose, thus the environmental study of the ERP undertook a field study of indoor air quality to evaluate ventilation provision at several large venues during multiple live events. Measured CO2 concentrations at 14 events taking place across 12 restaurants of two large event stadia in the UK, indicate that they were generally well ventilated, and were < 1000 ppm on averageIndividual and population-based risk models show the personal risk in all the restaurants is found to be lower than for the reference scenario, 8 hours in a 20-person office. However, the probability of the presence of infected people and the number of the susceptible people increases with the number of occupants, so population level risks of transmission due to attending restaurants at these events are higher than the reference case and would be dependent upon the occupancy, exposure time and prevalence of COVID-19 in the community at the time.Future measures to mitigate against long range transmission in restaurant scenarios include both reducing occupancy density, exposure time, and introducing equivalent ventilation to poorly ventilated venues.

(MALKI-EPHSTEIN, 2022)
APPLICATION OF CO_2 MONITORING METHODS FOR POST-OCCUPANCY EVALUATION OF VENTILATION EFFECTIVENESS TO MITIGATE AIRBORNE DISEASE TRANSMISSION AT EVENTS

Abstract: The Covid-19 pandemic led to the widespread closure of events. Between April and July 2021, the AIRBODS consortium carried out an Environmental Study as part of the UK government Events Research Programme to assess environmental risk factors for Covid transmission at events. A detailed post-occupancy evaluation of Indoor Air Quality was employed to assess the effectiveness of ventilation systems in operation. CO2 monitors were installed at high spatial resolution throughout the occupied spaces of ten venues around the UK. Data from 55 events was obtained and average and maximum CO2 values were used to classify the spaces in relation to a proposed Air Quality Index. Indoor spaces where ventilation could be improved were rapidly identified and mitigations were tested to reduce the risk of airborne transmission of respiratory diseases.

(ADZIC, 2022b)
POST-OCCUPANCY STUDY OF INDOOR AIR QUALITY IN UNIVERSITY LABORATORIES DURING THE PANDEMIC

Abstract: This post-occupancy study aims to assess the indoor air quality (IAQ) and ventilation performance in workshops and laboratories of a UK university during the COVID-19 pandemic. Supply airflow rates and CO2 were monitored as a proxy for evaluating ventilation performance. Additionally, particulate matter (PM10) was monitored to address the occupant's concerns about dust. Additionally, particulate matter (PM10) was monitored to address the occupant's concerns about dust. Monitoring showed that maximum CO2 values recorded are mostly below 1000 ppm, with weekly averages below 520 ppm. This was expected as the supply airflow rates were significantly larger than recommended 10 l/s per occupant. Despite the large flow rates, PM10 levels in some laboratories were above the threshold value of 50 [μg/m3] supporting the poor IAQ claims of the occupants. The study indicated the room air re-circulation and indoor activities as the likely reasons for the elevated PM10 levels and some practical operational solutions were suggested for IAQ concerns.

(JONES AND IDDON, 2021b)
WHY SPACE VOLUME MATTERS IN COVID-19 TRANSMISSION

Article: It's not just ventilation that removes viable virus from indoor air. To understand the risk of transmission of Covid-19, the University of Nottingham's Benjamin Jones and Chris Iddon say other mechanisms that are dependent on the volume of a space have to be considered.
There is a lot of focus on the role of ventilation in reducing the risk of far-field (>2m separation) transmission of the SARS-CoV-2 virus in indoor environments. However, ventilation is not the only mechanism for removing viable virus from indoor air. Others include the biological decay of the virus and the deposition of aerosols onto surfaces.
These removal mechanisms are space-volume dependent. This means that, in spaces with a larger volume, the *equivalent* ventilation rate is higher, assuming the number of occupants – and the airflow rate per person ($L.s^{-1}$ per person) – is the same. Consequently, the steady-state concentration of viable viral laden aerosols is also lower.
(contd.)

(JONES AND IDDON, 2021b)
COVID IN SCHOOLS – HOW VENTILATION CAN HELP TO COMBAT SPREAD OF VIRUS

Article: As the new academic year gets underway, there is understandable concern over how to curb the spread of COVID in schools. Air-quality specialists in Australia have recommended that air purifiers with high-efficiency particulate air (Hepa) filters be installed in all classrooms.
The Welsh government, meanwhile, has set aside £6 million for air technologies - specifically, carbon dioxide sensors and ozone disinfection machines. Although, implementing ozone disinfection machines is currently on hold, pending evidence to support their use.
This raises several questions. What are these different air cleaning technology options? What can they do that opening a window can't? And how important is ventilation in curbing the spread of COVID?
As indoor air quality experts, we have spent the last 18 months writing COVID ventilation and air cleaning tech guidance, and conducting research on the risk of catching COVID indoors.
We developed what's called a relative exposure index: a tool for comparing the risk of being exposed to the virus in different indoor settings. This was used by the UK government's scientific advisory group for emergencies (Sage) in drafting their ventilation advice for schools, workplaces and other public buildings.
(contd.)

(FITZGERALD, 2022)
BETTER BUILDINGS NEED A BREATH OF FRESH AIR

Article: As the world adapts to living with COVID-19, buildings such as schools, hospitals and office blocks should be well ventilated to reduce risk of transmission. But how can we achieve this while keeping warm and lowering energy consumption? Dr Shaun Fitzgerald OBE FREng, Director of Research in the Centre for Climate Repair at the University of Cambridge, says that good ventilation doesn't mean throwing open all the windows, and that existing buildings need to be better regulated and monitored to ensure they can be warm, safe and climate friendly.
COVID-19 has wreaked havoc on the world in so many devastating ways over the last two years. Importantly, researchers have discovered that ventilation of buildings can effectively reduce the risk of SARS-CoV- 2 virus transmission. In 2021, Sir Patrick Vallance KBE FRS, the government's Chief Scientific Adviser, commissioned a report from the Royal Academy of Engineering on how to reduce the risk of infection indoors, in which experts say the importance of ventilation is too often "neglected" and there is an "urgent need" to improve it.
The Infection Resilient Environments report recommends that multiple occupancy spaces should be well ventilated to minimise the build-up of virus if infectious persons are present. Additionally, the benefits of a well-ventilated space go beyond helping reduce the risk of SARS-CoV-2 transmission; higher ventilation rates can lead to enhanced levels of concentration, reduced likelihood of mould growth, and reduced risk of transmission of other airborne pathogens. While it is easier to ventilate buildings by opening windows during the spring and summer, there are challenges in delivering the appropriate amount of ventilation in colder weather – especially with a focus on reducing buildings' energy consumption and keeping warm.
(contd.)

(FITZGERALD AND IDDON, 2022)
FRESH THINKING ON DESIGNING FOR VENTILATION

Article: How architects can find the balance between fresh air and energy consumption to help reduce the transmission of Covid.
Covid-19 made designers acutely aware of the need for effective building ventilation. Its continued presence means they need to consider its presence as part of a building's wider ventilation strategy.
Chris Iddon, a research fellow at the University of Nottingham, is a ventilation expert looking into the risk of Covid transmission in the built environment and co-author of CIBSE's COVID Ventilation Guidance. He talks of Covid and ventilation in terms of relative exposure risk – see graph below, showing the relationship between aerosol concentration and ventilation rate.
Ventilation is the process of introducing outside air into indoor spaces while removing stale air.
The graph shows that the more outside air you put into a space the lower the risk of occupants inhaling the virus, which is the advice we were all given during the pandemic.
(contd.)

(IDDON, 2022a)
CALCULATING INDOOR INFECTION RISK

Article: To understand how ventilation reduces Covid transmission it is important to look at the level of risk as the number of building occupants increases, says Chris Iddon, who introduces a methodology that addresses the difference in personal and population risk.
Since early in the pandemic, when genomic material of SARS-CoV-2 (the virus that causes Covid-19) had been detected in air samples and well-documented superspreading events were reported, there was an implication of long-range airborne transmission. Accordingly, CIBSE advised increasing ventilation airflows as much as reasonably possible, taking into account occupant comfort and energy use concerns.
However, it is impossible to calculate a universal flowrate that would lead to a constant, universal reduction in transmission risk – not least because the emission rate of viable virion from an infector varies over the time since infection. People also have different emission rates, ranging over several orders of magnitude. Equally, there is no knowledge on dose-response characteristics of SARS-CoV-2 in humans.
(contd.)

(CIRIC, 2021)
COVID - HOW THE DISEASE MOVES THROUGH THE AIR

Article: Masks have been a common sight all over the world since SARS-CoV-2, the novel coronavirus, invaded our lives. We set out to investigate if they work. Our goal was to find out how the virus travels through the air in buildings so we could understand more about the risk of airborne infection – including whether masks can help to control the number of respiratory droplets in the air and therefore reduce transmission.
This is what we know so far.
As we talk, cough and breathe, a jet of air rushes out of our lungs through our mouth and nose – in the process, it gathers respiratory fluid from the lungs, throat, and mouth creating droplets which are then emitted into the air. High energy vocal activities, such as singing and coughing, increase the amount of droplets and provide a greater force to propel these further into the space around us.
Most of the droplets produced are tiny at less than five microns (a micron is a thousandth of a millimetre) – we call these aerosols. Anything larger than this is called a droplet and these can be as large as 100 microns.
Each breath, word or cough will produce many thousands or millions of aerosols and droplets over a spectrum of sizes. Whatever their size, they are propelled forward in a cloud of warm humid air from our mouth towards other people in a shared space. The larger droplets will tend to fall to the ground quickly due to gravity but smaller ones can remain suspended in the air for many hours.
Over the past 18 months, SARS-CoV-2 has been detected in air samples in many different situations, most often in places like hospitals. Generally, PCR tests were used to assess whether SARS-CoV-2 RNA was present. The viral RNA molecules were found in exhaled aerosols, in numbers varying from the 10s to the 100,000s per cubic metre of room air.
(contd.)

(MALKI-EPSHTEIN, 2023)
MEASUREMENT AND RAPID ASSESSMENT OF INDOOR AIR QUALITY AT MASS GATHERING EVENTS TO ASSESS VENTILATION PERFORMANCE AND REDUCE AEROSOL TRANSMISSION OF SARS-COV-2

Abstract: To assess risk factors for COVID-19 transmission and address the closure of mass gathering events since March 2020, the UK Government ran the Events Research Programme (ERP), following which it reopened live events in sports, music, and culture in July 2021. We report the rapid post-occupancy evaluation of Indoor Air Quality (IAQ) and associated long-range airborne transmission risk conducted in the Environmental Study of the ERP. Ten large venues around the UK were monitored with CO_2 sensors at a high spatial and temporal resolution during 90 events. An IAQ Index based on CO_2 concentration was developed, and all monitored spaces were classified in bands from A to G based on their average and maximum CO_2 concentrations from all events. High resolution monitoring and the IAQ Index depicted the overall state of ventilation at live events,and allowed identification of issues with ventilation effectiveness and distribution, and of spaces with poor ventilation and the settings in which long-range airborne transmission risk may be increased. In numerous settings, CO2 concentrations were found to follow patterns relating to event management and specific occupancy of spaces around the venues. Good ventilation was observed in 90% of spaces monitored for given occupancies.
Practical applications: High-resolution monitoring of indoor CO_2 concentrations is necessary to detect the spatial variation of indoor air quality (IAQ) in large mass gathering event venues. The paper summarises COVID-19 ventilation guidance for buildings and defines a methodology for measurement and rapid assessment of IAQ during occupancy at live events that can be implemented by venue managers. Comparisons of the CO_2 concentrations measured during the events identified the spaces at high risk of long-range transmission of airborne pathogens. Building operators should be mindful of the ventilation strategies used relative to the total occupancy in different spaces and the occupant's activities.

EVENTS RESEARCH PROGRAMME REPORTS

Findings from Phases II-III of the Events Research Programme Science Note - Emerging findings from studies of indicators of SARS-CoV-2 transmission risk at the Events Research Programme: environment, crowd densities and attendee behaviour - GOV.UK (www.gov.uk)

Findings from Phase I of the Events Research Programme

EMG-SPI-B: Application of CO2 monitoring as an approach to managing ventilation to mitigate SARS-CoV-2 transmission (contribution to)

Events Research Programme Phase III: Development of Research Protocols - An environmental study on assessing and mitigating the risk of airborne transmission of SARS-CoV-2 at live events using CO2 measurement

Events Research Programme Phase II: Protocol 3 - An environmental study on assessing the risk of airborne transmission of SARS-CoV-2 at live events using CO2 measurement

AIRBODS WP3 Field Studies - Work Statement

PAPERS IN PREPARATION

Hajaali A *et al.* (in preparation) 'Cloud and droplet dynamics within a non-mix and mix environment:'

Abstract: The study of cloud and droplet dynamics during critical events such as coughing is essential to understand the spread and deposition of aerosol droplets infected by SARS-CoV2 and other airborne diseases. Ventilation design has a significant influence on the behaviour of aerosol clouds and plays an important role in reducing infection risk. Our team developed a complex model that couples the momentum, temperature and humidity between the cloud dynamic (LES scalars) and its larger droplets (DPM). The dynamics of the aerosol cloud were numerically investigated under rest and mix conditions within the HERG chamber. The infection risk of a person standing one meter away from the infected person was evaluated under both conditions. A statistical framework shed light on the impact of the backward coupling (droplet -> cloud) which had negligible compared to the forward coupling (cloud -> droplet). The near-field study also provides detailed information on the droplet behaviour which lays the foundation for large-field and coarser simulations.

Adzic F *et al.* (in preparation) 'Does our behaviour impact exposure to the risk of far-field airborne virus transmission in mass-gathering events?'

Abstract: The UK government's Covid-19 Events Research Programme piloted events in a wide variety of outdoor, indoor and semi-outdoor building settings. Prolonged and repeated exposure to poor-quality air indicates an increased risk of transmission, whether due to insufficient ventilation or prolonged time spent in the space. Our environmental study examined variations in individual risk of exposure to long-range airborne transmission based on simulated customer journeys through 26 events in sports and theatre venues.
To indicate how comparative individual risk for attendees varies with time and space throughout larger venues, the accumulated personal exposure to exhaled breath during an event was measured using handheld air quality monitors for 26 simulated customer journeys by three researchers at events at three venues. Additional simulated journeys were generated based on background monitoring of CO_2 concentrations and both datasets were related to crowd densities and contact numbers obtained from video observations. The cumulative exposure measured by researchers in person was between 4 -42% of the exposure that would be accumulated when spending a typical 6-hour day in an office. However, researchers did not linger in higher-risk spaces and simulated journeys with crowd data were created.
Individual risk whilst attending an event is highly variable. It is dependent on social interactions, the environment at the venue and the attendee's interaction with the environment and their journey through an event.

Adzic F *et al.* (in preparation) 'Monitoring indoor air quality in large sports events to reduce the risk of SARS-CoV-2 transmission. '

Abstract: This study applies a carbon dioxide (CO2) monitoring methodology to examine the exposure of occupants to long-range airborne transmission of the SARS-CoV-2 virus in two large sports venues in the UK during the summer of 2021.
CO2, as a proxy for exhaled breath, was monitored in high resolution in Wembley Stadium and Royal Ascot Racecourse. Royal Ascot was monitored over 5 events in June 2021 and Wembley Stadium was monitored for 11 events from April to July 2021. Although both horse racing at Ascot and football matches at Wembley Stadium involve outside spectator areas, the venues also consisted of many bars and concessions, sheltered or dwelling areas, small, enclosed spaces (toilets, corridors, etc.) and private boxes that were indoors. The focus of this paper is on highlighting how well-designed the zones are for their intended use and the impact the event management has on indoor air quality such as rushing to concessions in a short period of time.
In both venues, a total of 62 individual spaces, indoor CO2 concentration was monitored in each event to evaluate the build-up of exhaled breath in the air, and so to understand the adequacy of ventilation relative to the occupancy in the space. The analysis was based on calculating cumulative and hourly exposure to exhaled breath so spaces can be classified and prioritised for ventilation improvement. Royal Ascot events had similar occupancy over 5 days which was about 17% capacity. Wembley stadium events were monitored for a range of occupancies ranging from 3% capacity to 75% of 90 000 available seats.

Adzic F *et al.* (in preparation) 'Evaluation of indoor air quality and risk of transmission of SARS-CoV-2 in toilets and short occupancy areas at mass gathering events.'

Abstract: In 2020, mass gathering events such as music concerts, theatre shows, and sports matches were closed to prevent the spread of SARS-CoV-2. This paper aims to assess the risk of reopening such events by analysing CO2 concentration as a proxy for ventilation in 29 zones over 96 events. Specifically, the focus is on small, enclosed spaces with short occupancy, including toilets, corridors, lifts, and stairwells (TCLS), which are densely and continuously occupied for short durations during events like theatre intervals or half-time at sports events. The findings indicate that the air quality in TCLS was generally good, but there were significant peaks in CO2 concentration during times of high occupancy. Apart from CO2 monitoring, microbiological testing of surfaces and air samples was deployed in selected spaces. Moreover, the relative risk of exposure to SARS-CoV-2 by airborne aerosol transmission was estimated from collected data and conclusions were made on the route of transmission in small, enclosed spaces with short occupancy.

Roberts B *et al.* (in preparation) 'Ventilation assessment in semi-outdoor temporary buildings during mass gathering events to reduce the risk of airborne infection.'

Article: Mass gathering events during the COVID-19 pandemic were cancelled to prevent the spread of the disease. The SARS-CoV-2 virus, which causes COVID-19, is understood to be transmitted via various routes including long-range airborne transmission, which is reduced in highly ventilated spaces. Semi-outdoor spaces such as marquees and tents are commonly used as temporary structures at mass gathering events, but there is scant evidence on the ventilation of these spaces. To allow for an airborne infection risk assessment regarding the use of semi-outdoor spaces for mass gathering events, 61 events were monitored at four venues. Indoor carbon dioxide concentration (as a proxy for exhaled breath) was measured before, during, and after occupancy at high resolution to allow for assessment of the ventilation provision in operation. Average and maximum hourly exposure to exhaled breath was calculated and used to classify spaces. A variety of semi-outdoor spaces, which were occupied in different ways, were compared including a large circus tent used at a music festival and a marquee used for a university graduation ceremony. The results showed that although most semi-outdoor spaces have very high natural ventilation rates, and most are expected to have air quality close to that of the outdoor air. There were, however, several occasions of elevated CO2 concentrations during periods of high occupancy, particularly in marquees of smaller volume, or those without open sides. The circus tent at the music festival, which was densely occupied, showed intermittent, but brief, periods of elevated CO2, indicating that the space was sufficiently ventilated. Thus, under the ventilation strategies and occupancy levels investigated, it is recommended that semi-outdoor spaces such as marquees and large tents are suitable for use in mass gathering events providing they have large ventilation openings to provide the levels of ventilation required to reduce the risk of long-range airborne transmission of virus-laden aerosols.

Roberts B *et al.* (in preparation) 'Measurements of ventilation effectiveness and indoor air quality in toilets at mass gathering events.'

Conference abstract: Mass gathering events were closed in 2020 to reduce the spread of SARS-CoV-2. These events included music concerts, theatre shows, and sports matches. It is known, however, that the long-range aerosol transmission of pathogens, such as SARS-CoV-2, can be reduced with sufficient ventilation indoors. Hence, this paper examines the risk of reopening these events by measuring the CO2 concentration, as a proxy for ventilation, at a series of mass gathering events, with a specific focus on small, enclosed spaces with short occupancy. Toilets, corridors, lifts and stairwells (TCLS) are spaces that are densely and continuously occupied for short durations throughout the events, such as theatre intervals or half-time at sports events. The results showed that the average air quality in TCLS was very good at the majority of the events. However, there were considerable peaks in CO2 concentration in TCLS at times when occupancy was presumed high, indicating that the risk of exposure to exhaled breath, which may contain virus-laden aerosols, is higher in toilets than elsewhere in the venue (although dwell time will be much lower). Recommendations are provided to encourage building designers and operators to be mindful of the ventilation strategies used in toilets given their occupancy and size.

Matharu R *et al.* (in preparation) 'Comparison of Indoor Aerosol Movement Under Different Environmental Conditions'

Abstract: The recent coronavirus (COVID-19) pandemic has amplified the understanding of human expiratory aerosol generating activities and their role in airborne disease transmission. Worries regarding increased airborne microbial burden, particularly severe acute respiratory syndrome–coronavirus-2 (SARS-CoV-2), has raised several questions about the spread of aerosols and airborne disease in buildings. However experimental data on the spread of aerosols in indoor environments are largely unavailable. In this work, a Collison nebuliser was used aerosolise artificial saliva in an indoor walk-in environmental chamber. The chamber was set to 5 air changes per an hour (ACH) and low air movement. Aerosol particle concentrations were detected in two different locations under various temperature (15, 20, 25, 28 and 30oC) and humidity (15, 30, 50 and 75%) combinations. Particle counts were taken using the TSI AeroTrak 3096 at 0.5 m from the aerosoliser and at the chamber outlet, every minute over 100 minutes. Channels included: 0.3 µm, 0.5 µm, 1.0 µm, 3.0 µm, 5 µm and 10 µm. From the results gathered, both the temperature and humidity can be seen to influence the movement and distribution of aerosols.

Matharu R et al. (in preparation) 'Efficacy of Ventilation Strategies and Plastic Partitions in Mitigating the Spread of Aerosols in Indoor Spaces.'

Abstract: During a pandemic, protective physical barriers (such as plastic partition screens) and ventilation strategies, are used to prevent the rapid multi-directional exchange of bio-aerosols that occur when people interact in close proximity. However, it has been notoriously difficult to quantify the impact that such interventions may have from both an epidemiological and an environmental perspective. The aim of this study was to quantify the impact of ventilation (no ventilation/5 air changes per an hour), air movement strategies (mixing/no mixing) and room partitions (small – 50 cm2, medium – 125 cm2, large – 210 cm2) on aerosol concentrations and size distributions in a controlled environmental chamber. Synthetic saliva was aerosolised using a 6 Jet Collison Nebuliser at a flow rate of 12.5 L/min. Particle counters were used to enumerate aerosols, while a DNA marker was used to analyse deposition. The experimental evidence presented here showed that a ventilation rate of 5 air changes an hour (ACH) resulted in a reduction of all aerosol sizes, ranging from: a 20 % reduction for 0.3 µm aerosols to 38 % for 3 µm aerosol counts when compared to no ventilation. The addition of air mixing to 5 ACH resulted in higher reductions from 38 % for 0.3 µm to 88 % in 3 µm, when compared to no ventilation. In the absence of ventilation, the small partition had the greatest impact on aerosol reductions from 7 % for 0.3 µm to 33 % for 3 µm. At 5 ACH, the large partition was the most effective with reductions ranging from 30 % for 0.3 µm to 24 % for 3 µm aerosols. Conversely, once air mixing was introduced, the impact of partitions was minimised due to air homogenisation throughout the chamber. The results suggest that good ventilation is likely to outweigh any impacts of partitions in indoor spaces, however in the absence of ventilation, small and large partitions do have an impact on aerosol numbers. The increase in aerosol concentrations resulting from the installation of the medium partition suggests that partition position, in relation to air flows within indoor spaces, can impact air flow dynamics and lead to unforeseen distributions of aerosols.

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