To identify effective ventilation guidance and practice to mitigate the indoor airborne transmission of infectious diseases in new build non-domestic buildings

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Executive Summary

Under The Building (Scotland) Act 2003, the Scottish Building Standards system sets minimum standards applicable where new building work is proposed. These mandatory standards, and guidance on how they may be complied with, are published in the Building Standards Technical Handbooks. The building standards system is administered by local authorities who are appointed as the verifiers for their own geographical areas.

Standard 3.14, Ventilation, in Section 3, Environment, of the Building Standards Technical Handbook 2020: non-domestic, states: ‘every building must be designed and constructed in such a way that ventilation is provided so that the air inside the building is not a threat to the building or the health of the occupants’. This requirement is applied at the point construction work takes place and does not apply retrospectively to buildings constructed to lesser previous standards. As such, existing buildings require to have their ventilation systems effectively managed by their owners, operators and occupiers to ensure good levels of indoor air quality are maintained.

Evidence suggests that in poorly ventilated indoor spaces, airborne aerosols are a possible transmission route of COVID-19. It is recognised that the higher the rate of ventilation, the lower the risk of airborne transmission. However, occupant thermal comfort, energy demands and associated carbon emissions will also need to be considered as part of a building ventilation strategy. This short, focussed project gathered evidence to assess whether application of the current ventilation guidance in the Non-Domestic Technical Handbook provides adequate basis for simple operational practices that can be used to effectively mitigate the indoor airborne transmission of diseases such as COVID-19.

An industry survey was conducted to establish what ventilation guidance was being used by industry in practice when designing new or maintaining existing non-domestic buildings. The results indicate a wide range of ventilation design guides and technical literature are being used in practice, from various sources including CIBSE, BB101, ASHRAE, HTM, BSRIA and BS 16798-3.

Examples measures for effective ventilation to mitigate the spread of airborne contaminants have been identified. These include the following: i) CO_2 monitoring (as a proxy for ventilation), ii) examination and maintenance of installed ventilation systems, iii) maximising outdoor airflow by increasing natural ventilation provision, intermittent purge ventilation, extending operation of intermittent ventilation systems and/or installing new passive or mechanical ventilation systems (whilst maintaining setpoints for thermal comfort), iv) diverting direct airflow away from groups of individuals, v) avoiding recirculation of air, vi) use of enhanced filtration and/or air cleaning devices, vii) provision of breaks / fallow periods between occupants, and viii) ensuring negative pressure in toilets.

Whilst current industry standards for ventilation may be acceptable to minimize the risks of COVID-19 transmission if implemented correctly, a principal issue is whether these are being met a) in use and b) maintained over time. There remains virtually no reliable data on ventilation performance in practice for non-domestic buildings. Therefore, in order to provide greater assurance that adequate ventilation is provided in new non-domestic buildings, the following recommendations for change are provided:

- The phasing out of recirculation of air and replacement over time with heat exchanger systems which prohibit the mixing of intake and extract air to avoid airborne pathogen transmission.

- An increase in the recommended mechanical ventilation supply rate in building regulations from 8 l/s/p to 10 l/s/p is suggested for occupied rooms, in addition to the need for greater clarity in the definition of supply rates and consideration of occupancy limits, based on the capacity of ventilation systems.

- The introduction of requirements for CO_2 monitoring in multi-occupancy high risk spaces to help identify airborne transmission risk related to poor ventilation and/or high occupancy, to prompt and inform behaviour change. This should be provided with clear guidance and appropriate information specifically tailored to the user group, to enable monitors to be used effectively.

- The consideration of infectious disease transmission in building ventilation regulations through the provision of explicit advice on the risk of far-field (>2m) aerosol airborne transmission. The importance of ventilation in mitigating this risk should be highlighted (e.g. in Section 3.14.1).

- The identification of ventilation performance standards and enhanced measures to ensure that compliance is achieved in use (building regulations) and maintained over time (other legislation). The introduction of a performance-based framework for assessing ventilation performance in non-domestic buildings (e.g. through an annual building 'health-check' / 'MOT', or for new retrofit works), would help ensure regular assessment of performance and verification of compliance over time.

- The requirement for a building ventilation maintenance plan, to support the regular inspection, cleaning and maintenance of ventilation systems in practice.

- Provision of a communications / labelling strategy for building ventilation systems (like the domestic energy 'quick start guides') to provide a clear, simple explanation to building users on what the ventilation strategy is, and how to use it. Whilst Standard 3.14.10 requires key information on the ventilation system to be provided on completion, the provision of short, visual instructions (for instance, next to ventilation systems or controls) would help ensure accessibility to all users and support understanding and effective operation of ventilation systems in practice.

Research outline

1. Background / context

In the context that people spend a substantial amount of time in non-domestic buildings engaging in various activities including working and socialising, it is recognised that it is important to ensure adequate ventilation and good IAQ to support occupants' health and wellbeing. This has been further highlighted by the global COVID –19 pandemic as a direct link has been established between transmission of the virus that causes COVID –19 and direct, indirect, or close contact with infected people, including through the inhalation of the airborne respiratory droplets and aerosols exhaled by infected individuals.

Infected aerosols can be held in the air for long periods of time as well as being carried over short distances. Therefore, in an indoor environment which is poorly ventilated, the risk of infection through inhalation of aerosol pathogens increases. This has underlined the need to establish and maintain good quality ventilation in buildings in order to mitigate the airborne transmission of infectious diseases, such as COVID - 19 and Flu, in workplaces and public buildings[1].

Well-designed natural ventilation has many benefits, including financial and environmental. However, it is recognised that IAQ can only be as good as the outside air quality and in some cases careful positioning of air intakes or use of filtration may be necessary. In other cases, mechanical systems or systems that combine natural with mechanical (hybrid) may be the best ventilation solution for the building.

2. Aims and Objectives

The purpose of this study is to undertake a short, focused exercise to assess whether application of the current ventilation guidance in the Non-Domestic Technical Handbook provides an adequate basis for simple operational practices that can be used to effectively mitigate the indoor airborne transmission of diseases such as COVID-19.

The objectives of this project are:

1. To identify any evidence of where the guidance in Standard 3.14 needs to be updated in order to provide greater assurance that adequate ventilation is provided in new non-domestic buildings, which mitigates the transmission of infectious diseases such as COVID-19.

2. To identify what guidance is being used by industry and the practices being followed for new buildings and new building work.

3. To establish where the guidance in Standard 3.14 does not align with current industry guidance or practice being followed.

[1] HSE, 2022, Ventilation in the workplace

4. To identify examples of the measures generally taken to improve the ventilation provision to mitigate the spread of airborne contaminants and how ventilation currently operates as part of a COVID-19 strategy for a building.

5. To identify and describe what an effectively ventilated building should achieve in terms of mitigating COVID-19 transmission. Provide detail on what this should look like in practice. Where issues of concern are flagged, identify whether building specific/use guidance would be beneficial.

Literature Review

1. Context

1.1 The University of Strathclyde has been commissioned by the Building Standards Division (BSD) of the Scottish Government to undertake research to identify effective ventilation guidance and practice to mitigate the indoor airborne transmission of infectious diseases in new build non-domestic buildings.

1.2 Under the Building (Scotland) Act 2003[2], the Scottish Building Standards system sets minimum standards applicable where new building work is proposed. These mandatory standards, and guidance on how they may be complied with, are published in the Building Standards Technical Handbooks. The building standards system is administered by local authorities who are appointed as verifiers for their own geographical areas.

1.3 Standard 3.14, Ventilation, in Section 3, Environment, of the Building Standards Technical handbook 2022[3]: non-domestic, states: every building must be designed and constructed in such a way that ventilation is provided so that the air quality inside the building is not a threat to the building or the health of the occupants. This requirement is applied at the point construction work takes place and does not apply retrospectively to buildings constructed to lesser previous standards. As such, existing buildings require to have their ventilation systems effectively managed by their owners, operators and occupiers to ensure good levels of indoor air quality (IAQ) are maintained.

1.4 This project is intended to be a short, focussed exercise aimed at gathering evidence that will be used to assess whether application of the current ventilation guidance in the Non-Domestic Technical Handbook provides an adequate basis for simple operational practices that can be used to effectively mitigate the indoor airborne transmission of diseases such as COVID-19. Or whether there are specific further provisions that would be beneficial in enabling this.

1.5 The objective of this project is to identify any evidence of where the guidance in Standard 3.14 needs to be updated in order to provide greater assurance that adequate ventilation is provided in new non-domestic buildings, which mitigates the transmission of infectious diseases such as COVID-19.

1.6 The project will identify what guidance is being used by industry and the practices being followed for new buildings and new building work. Work will also be required to establish where the guidance in Standard 3.14 does not align with current industry guidance or practice being followed.

1.7 The study will establish how ventilation currently operates as part of a COVID-19 strategy for a building and describe what an effectively ventilated building should achieve in terms of mitigating COVID-19 transmission. Detail will be provided on what this should look like in practice.

[2] Building (Scotland) Act 2003

[3] Building standards technical handbook 2022: non-domestic

2. Background

2.1 People spend a substantial amount of time in non-domestic buildings engaging in various activities including working and socialising. The air quality within these buildings can have a significant effect on occupants' health and wellbeing therefore the provision of adequate ventilation to ensure good IAQ is maintained is important.

2.2 The subject of ventilation and IAQ has been further highlighted by the global COVID–19 pandemic. Transmission of the virus that causes COVID–19 can occur via direct, indirect, or close contact with infected people, including through the inhalation of the airborne respiratory droplets (>5-10μm in diameter) and aerosols (<5μm) exhaled by infected individuals.

2.3 Infected aerosols can be held in the air for long periods of time as well as being carried over short distances. Therefore, in an indoor environment which is poorly ventilated, the risk of infection through inhalation of aerosol pathogens increases.

2.4 These findings have underlined the need to establish and maintain good quality ventilation in buildings in order to mitigate the airborne transmission of infectious diseases, such as COVID - 19 and Flu, in workplaces and public buildings.

2.5 Well-designed natural ventilation has many benefits, including financial and environmental. However, it is recognised that IAQ can only be as good as the outside air quality and in some cases careful positioning of air intakes or use of filtration may be necessary. In other cases mechanical systems or systems that combine natural with mechanical (hybrid) may be the best ventilation solution for the building.

2.6 Evidence suggests that in poorly ventilated indoor spaces, airborne aerosols are a possible transmission route of COVID-19.

2.7 The World Health Organization[4] published a scientific brief on 9th July 2020 advising that SARS-CoV-2, the virus that causes COVID-19, could be spread from person-person through the airborne transmission of infected aerosols, particularly in indoor settings with poor ventilation.

2.8 Public Health England[5] updated its guidance to note the possibility of airborne transmission in poorly ventilated indoor spaces. The Centers for Disease Control in the US recognise that transmission appears to have occurred when there is inadequate ventilation. This guidance adopts a precautionary approach with the objective of ventilating spaces with outside air by as much as reasonably possible as one measure to reduce transmission risk.

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[4] World Health Organization. Modes of transmission of virus causing COVID-19: Implications for IPC precaution recommendations: Scientific brief, 27 March 2020.

[5] PHE, (2020), COVID-19: epidemiology, virology and clinical features.

2.9 The UK Government issued a paper prepared by the Environment and Modelling Group of the Scientific Advisory Group for Emergencies[6], confirming that ventilation is an important mitigation measure in controlling SARS-CoV-2 transmission.

2.10 The Scottish Government has also published COVID-19 guidance identifying ventilation as an important factor in reducing the risk of aerosol transmission of the virus indoors.

2.11 Maintaining good levels of ventilation remains a key focus in the overall strategy to mitigate the spread of COVID-19 and other airborne pathogens. This will be important particularly in the colder months of the year where adequate non-recycled air ventilation will be crucial.

2.12 It is recognised that the higher the rate of ventilation, the lower the risk of airborne transmission. However, occupant thermal comfort, energy demands and associated carbon emissions will also need to be considered as part of a building ventilation strategy. Ventilation in the workplace or in a publicly accessible building should be considered as part of any COVID-19 risk assessment plan. Building and facilities managers should engage with suitably qualified building service engineers to ensure that they are operating their ventilation system, be it natural, mechanical or a mix of both, effectively.

2.13 Regulation 6 of the Workplace (Health, Safety and Welfare) Regulations 1992[7], places a duty of care on employers, as far as is reasonably practical, to ensure the health of their employees by requiring that, ‘Effective and suitable provision shall be made to ensure that every enclosed workplace is ventilated by a sufficient quantity of fresh or purified air’.

3. Industry, NGO and Governmental Guidance

3.1 Current published industry guidance does not address indoor transmission of pathogens and has traditionally focused on the removal of chemical contaminants rather than airborne transmissible pathogens. Recent guidance on how pathogens such as COVID-19 are transmitted in aerosol droplets in indoor environments highlights the need to amend all ventilation standards and guidance in order to reduce / avoid airborne pathogen transmission in indoor environments.

3.2 CIBSE[8] acknowledged in recent guidance the potential for airborne aerosol transmission of SARS-CoV-2. This guidance adopts a precautionary approach, advocating that indoor spaces should be ventilated as much as reasonably possible.

3.3 WHO[9] updated its guidance to acknowledge the possibility of airborne

[6] SAGE-EMG, (2020), EMG: Role of ventilation in controlling SARS-CoV-2 transmission

[7] The workplace (Health, Safety and Welfare) Regulations 1992

[8] CIBSE, 2021, COVID-19: Ventilation

[9] World Health Organization. Modes of transmission of virus causing COVID-19: Implications for IPC precaution recommendations: Scientific brief, 27 March 2020.

transmission of SARS-CoV-2.

3.4 The UK HSE[10] updated its guidance noting the possibility of airborne transmission particularly in poorly ventilated indoor spaces.

3.5 Centers for Disease Control and Prevention[11] in the US recognises that transmission appears to have occurred when there is inadequate ventilation.

3.6 SAGE-EMG[12] issued a paper confirming that ventilation is an important mitigation measure in controlling SARS-CoV-2 transmission.

3.7 HMSO[13] highlights employers have a duty of care to ensure, as far as reasonably practical, the health of their employees at work. Providing adequate ventilation is an important component of a healthy work environment and is prescribed by law in regulation 6 of the Workplace (Health, Safety and Welfare) Regulations 1992.

3.8 HSE provided updated guidance on building safety in general, and on air-conditioning and ventilation in particular. This is applicable throughout the UK and can be found at:

HSE[14], (2021). Coronavirus (COVID-19): working safely:

HSE[15], (2021). Ventilation and air conditioning during the coronavirus (COVID-19) pandemic.

3.9 BEIS[16] representing the UK government and devolved administrations, has produced guidance for employers, employees and the self-employed to help them understand how they can work safely during the pandemic. This guidance reminds employers of their legal responsibility for the safety of all those entering workplaces. To help employers decide which actions to take, they will need to carry out an appropriate COVID-19 risk assessment, just as they would for other health and safety related hazards. This risk assessment must be done in consultation with unions or workers. Undertaking this risk assessment may require advice from competent persons, such as professionally registered engineers who are chartered or incorporated engineers registered with the Engineering Council.

3.10 CIBSE[17] recently provided guidance on using ventilation as a way of diluting airborne pathogens. It is stated that: “there is good evidence that demonstrates room occupants are more at risk of catching an illness in a poorly ventilated room than in a well-ventilated room.”

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[10] HSE, 2020, Guidance COVID-19: Epidemiology, virology and clinical features

[11] CDC (2020), SARS-CoV-2 Transmission.

[12] SAGE-EMG, (2020), EMG: Role of ventilation in controlling SARS-CoV-2 transmission

[13] The workplace (Health, Safety and Welfare) Regulations 1992

[14] HSE, 2021, Coronavirus (COVID-19) – Advice for workplaces

[15] HSE, 2021, Ventilation and air conditioning during the COVID-19 pandemic (version 5, 16th July 2021) (Paper no longer available).

[16] BEIS/DCMS, (2021), Working safely during coronavirus (COVID-19).

[17] CIBSE, 2021, COVID-19: Ventilation

3.11 CIBSE[18] recently provided guidance on recirculation of air from one space to another. It is stated that: "It is preferable not to recirculate air from one space to another. However, in certain weather conditions, closing recirculation dampers in some systems may make the supply air unacceptably cold (or hot), and this may lead to a reduction in the supply rate of outside air to occupied spaces below the recommended minimum (10 l/s/person for typical offices) so that a comfortable temperature can be maintained. In these instances, there is a balance between two risks: the risk of recirculating contaminated air between multiple rooms or zones against the risk of reducing the supply of outside air and increasing the build-up of contaminants (including the virus) in a single room or zone. Recirculation should be considered only if there is no other way of maintaining an adequate provision of outside air to occupied spaces without causing undue occupant thermal discomfort or energy demand".

3.12 CIBSE[19] recently provided guidance on natural ventilation. It is stated that: "In naturally ventilated spaces, windows and vents are often the mechanism for providing outside air. In colder months, the natural forces that drive air through these openings (wind, indoor/outdoor temperature difference) are greater, so windows and vents do not need to be opened as wide. Opening only high-level vents can increase the mixing of the incoming outside air with air in the space and ensures that incoming air is warmed before it reaches the occupied zone. This makes it possible to introduce more cold outside air into the space without causing significant discomfort. It is better to open all windows or vents only a small amount to aid mixing and warming. If natural ventilation openings are the only mechanism for delivering outside air into a space, it is important that these are not completely closed when the spaces are occupied; this can result in very low ventilation rates, and increased risks of airborne viral transmission."

3.13 CIBSE[20] recently provided guidance on Nondispersive infrared (NDIR) CO_2 monitors. It is stated that: "Nondispersive infrared (NDIR) CO_2 monitors are useful devices that help to assess whether adequate ventilation is being provided to an occupied zone. In many spaces, a supply of outside air at 10 l/s/person is prescribed, which will result in a maximum CO_2 concentration of 800-1000ppm. Indoor ventilation dilutes exhaled CO_2 from occupants, and so the CO_2 concentration in a space is often used to help indicate ventilation rates. CO_2 concentrations that regularly exceed 1500ppm indicate poorly ventilated spaces, and attention should be given to improving the outside air provision to such spaces".

3.14 CIBSE[21] recently provided guidance on Germicidal ultraviolet (GUV) devices. It is stated that: "Germicidal ultraviolet (GUV) devices have been proposed for air cleaning. These use light on the UV-C spectrum and have been shown to inactivate coronaviruses. There is significant emerging evidence of the efficacy of UV-C sources at a wavelength of 254nm to deactivate SARS-CoV-2. There are still uncertainties about a variety of factors affecting UV performance, including dose and exposure time,

[18] CIBSE, 2021, COVID-19: Ventilation
[19] CIBSE, 2021, COVID-19: Ventilation
[20] CIBSE, 2021, COVID-19: Ventilation
[21] CIBSE, 2021, COVID-19: Ventilation

and how these might depend upon the ventilation rate of outside air. In addition, consideration will need to be given to the specific room and system configuration, air flow, distribution, and humidity, as well as the safe deployment of UV for occupants and building operations personnel".

3.15 ASHRAE[22] recently provided guidance defining acceptable Indoor Air Quality as "air in which there are no known contaminants at harmful concentrations, as determined by cognizant authorities, and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction".

3.16 ASHRAE[23] recently provided guidance outlining that if airborne infectious particles are to be counted as harmful even in small concentrations, either the amount of fresh air supplied to a room needs to be dramatically increased or the ventilation strategy needs to be reconsidered to protect the occupants. Current standards already have predetermined values to meet the acceptable indoor air quality. For example, the ASHRAE standards dictate a minimum ventilation rate of 5 l/s per person or 0.9 L/s.m^2 in educational facilities. For office buildings, the minimum values are 2.5 l/s per person or 0.06 l/s.m^2.

3.17 ASHRAE[24] recommend, 'Mitigation of infectious aerosol dissemination should be a consideration in the design of all facilities, and in those identified as high-risk facilities the appropriate mitigation design should be incorporated. The design and construction team, including HVAC designers, should engage in an integrated design process in order to incorporate the appropriate infection control bundle in the early stages of design. Based on risk assessments, buildings and transportation vehicles should consider designs that promote cleaner airflow patterns for providing effective flow paths for airborne particulates to exit spaces to less clean zones and use appropriate air-cleaning systems.'

3.18 SAGE-EMG[25] recommend, 'In the longer term consideration of infectious disease transmission needs to be embedded into building ventilation regulations and associated statutory guidance in the same way that energy, comfort and air quality have been incorporated. Building regulations should identify performance standards and enhanced measures taken to ensure that compliance is achieved in use. As Part F: Ventilation in England is currently under review there is an opportunity to consider this further and immediately as part of the current review process. Further regulation and guidance may be required to ensure that existing buildings can meet necessary standards.' Note also the recent revisions to Part L which require CO_2 sensing for all new-build offices and within 'high-risk' occupiable rooms - https://airqualitynews.com/2022/01/26/feature-what-the-updated-building-regulations-mean-for-air-quality/

3.19 REHVA[26] note that infection risk is not currently addressed in current ventilation standards as a design criterion. As such, REVHA (p.27) recommend,

[22] ANSI/ASHRAE Standard 62.1-2019 Ventilation for Acceptable Indoor Air Quality, Atlanta, 2019.
[23] ANSI/ASHRAE Standard 62.1-2019 Ventilation for Acceptable Indoor Air Quality, Atlanta, 2019.
[24] ASHRAE 2020 Position Document on Infectious Aerosols, p.9
[25] SAGE-EMG, (2020), EMG: Role of ventilation in controlling SARS-CoV-2 transmission, p.8
[26] REHVA 2021, REHVA COVID 19 Guidance version 4.1

‘Building codes, standards, and guidelines should be revised and updated to improve preparedness for future epidemics’.

3.20 The European guideline, Indoor Air Quality and its Impact on Man[27], report N 11, expresses the dilution of pollutants as a function of the ventilation rate effectiveness which can be engineered to suit the room, occupant type, and the risk at hand.

3.21 REHVA[28] in the case of infected particles it is recommended to supply as much outside air as possible. According to REHVA, mechanical ventilation should be activated more often (24/7) when possible, with lower rates during quiet times) and at least to start ventilating before and after busy hours while the density of occupancy needs to be decreased, when possible. This will increase the distance between people and lower the pollutant emission rate. With or without mechanical ventilation, window airing should be used to boost the air exchange rate. Toilet windows on the other hand need to remain closed and mechanical extraction activated at all times to create negative pressure and prevent contaminated particles from entering other parts of the building through doors or by an unforeseen route through nearby open windows.

3.22 REHVA[29] recommend avoiding the use of centralized recirculation as typical local air filters within these systems are not effective at filtering out viral material which tends to be too small for the filter as confirmed in recent studies by REHVA (2020)

3.23 The European Centre for Disease Control (ECDC)[30] emphasise the importance of ventilation in mitigating COVID-19 transmission by concluding that appropriate ventilation of indoor spaces could be critical to help lower the risk of COVID-19 transmission in the community.

3.24 ECDC[31] provide a comparison of national COVID-19 guidelines for heating, ventilation and air-conditioning (HVAC) systems in EU/EEA countries and the UK, which are complemented by guidelines from other countries and from international professional associations.

[27] European collaborative action 'Indoor air quality and its impact on man'

[28] REHVA 2021, REHVA COVID 19 Guidance version 4.1

[29] REHVA 2021, REHVA COVID 19 Guidance version 4.1

[30] ECDC, (2020), European Centre for Disease Control: Guidelines for the implementation of non-pharmaceutical interventions against COVID-19. 24 September 2020

[31] ECDC, (2020), European Centre for Disease Control: Guidelines for the implementation of non-pharmaceutical interventions against COVID-19. 24 September 2020

4. Effective ventilation to mitigate the spread of airborne contaminants

Table 1. Summary of ventilation measures to mitigate the spread of airborne contaminants

Mitigation strategies suggested	CIBSE 2021	REHVA 2020	ASHRAE 2020	SAGE-EMG 2020
IAQ monitoring (including CO_2) in the occupied zone to ensure ventilation is operating adequately in multi-occupant spaces	✓	✓		✓
During an epidemic, default CO_2 sensor settings should be changed so yellow/orange warning is set to 800ppm and red warning up to 1000ppm in order to trigger prompt action to achieve sufficient ventilation		✓		
Ventilation systems should be examined to identify areas / spaces that may be under ventilated and to verify that systems are functioning as designed	✓		✓	
Carry out regular filter replacement and maintenance of mechanical ventilation systems, performed with common protective measures including respiratory protection	✓	✓		
Increased use of natural ventilation provision as much as possible, without compromising occupant thermal comfort	✓	✓	✓	✓
Where rotary/thermal wheels are installed to recover heat, a competent engineer or technician should inspect the heat recovery equipment to ensure that leakages are under control	✓	✓	✓	
Disable or reset sensors (e.g. change CO_2 setpoint to a low value) in demand-controlled ventilation systems, in order to maintain operation at nominal speed	✓	✓	✓	
Temporary purge ventilation / airing through intermittent window/door opening or extraction fans. When flushing spaces between occupied periods, operate systems for a time required to achieve three air changes of equivalent clean air supply.	✓		✓	✓
Maintain heating, cooling and possible humidification design setpoints		✓	✓	
Break or fallow periods between occupants				✓
Direct airflow should be diverted away from groups of individuals to avoid pathogen dispersion from infected subjects and transmission		✓		
Maximise outdoor air flow from mechanical systems and avoidance of recirculation of air wherever possible	✓	✓	✓	✓

Extended operation of mechanical ventilation systems (such as intermittent extract fans) before and after the regular period. For instance, switch ventilation on at nominal speed at least 2 hours before building opening time and set it off or to lower speed 2 hours after the building usage time.		✓	✓	✓
In toilets with mechanical extraction, windows should remain closed and mechanical extraction activated at all times to create negative pressure and maintain the right direction of air flows	✓	✓	✓	
Enhanced filtration /UVC within recirculating centralized HVAC systems (only in systems designed for use with these and correctly sized and installed)	✓	✓	✓	✓
Installation of new passive (louvres/ air bricks) or mechanical (extract fans, HVAC) systems				✓
It is recommended to flush the toilets with lids closed to minimize the release of droplets and droplet residues from air flows. Water seals must work at all times.		✓	✓	
Use of local in-room HEPA or UVC air cleaning devices as a short-term mitigation measure, with due consideration to the clean air delivery rate. Only use air cleaners for which evidence is effective and safety is clear.	✓	✓	✓	✓

4.1 A summary of industry ventilation guidance to mitigate the spread of airborne contaminants is provided in Table 1.

4.2 REHVA[32] note that to reduce the risk of airborne transmission, ventilation has to be increased and occupancy time reduced, however in existing ventilation systems it may not be possible to increase the fan speed significantly. It is recommended therefore that at the very minimum, the national ventilation regulations for outdoor air ventilation rate should be met. Where these do not exist, local ‘good practice’ building laws should be followed.

4.3 REHVA[33] recommend conducting a cross-infection risk assessment to improve ventilation solutions during a COVID-19 type outbreak. To support this, REHVA provide an infection risk calculator for different rooms and activities, to estimate the effect of ventilation on COVID-19 airborne transmission. The calculator is based on the standard airborne disease transmission Wells-Riley model and has been calibrated to the SARS-CoV-2 virus with correct quanta emission rates (source strength). REHVA (2020, p.4) state that, ‘current technology and knowledge already allows the use of many rooms in buildings during a COVID-19 type of outbreak if ventilation meets existing standards and a risk assessment is conducted’.

[32] REHVA 2021, REHVA COVID 19 Guidance version 4.1
[33] REHVA 2021, REHVA COVID 19 Guidance version 4.1

4.4 REHVA[34] state, 'Regarding the airflow rates, more ventilation is always better, but to dilute the aerosol concentration the total airflow rate in L/s per infected person matters. This makes large spaces ventilated according to current standards reasonably safe, but smaller rooms occupied by fewer people and with relatively low airflow rates pose a higher risk even if they are well ventilated. Limiting the number of occupants in small rooms, reducing occupancy time and applying physical distancing will in most cases keep the probability of cross-infection to a reasonable level. For future buildings and ventilation improvement, Category I ventilation rates can be recommended as these provide significant risk reduction compared to common Category II airflow rates according to ISO 17772-1:2017 and EN 16798-1:2019.'

Table 2. Default predefined design ventilation air flow rates for an office (from EN 16798-1)[35]

Category	Total design ventilation air flow rate for the room		Corresponding CO_2 concentration above outdoors in ppm for non-adapted persons
	L/(s per person)	l/(s*m^2)	PPM (above outdoors)
I	20	2	550ppm
II	14	1.4	800ppm
III	8	0.8	1350ppm
IV	5.5	0.55	1350ppm

4.5 SAGE-EMG[36] and CIBSE[37] recommend that multi-occupant spaces that are used regularly and are poorly ventilated (below 5 l/s/person or above 1500ppm CO_2) should be identified and prioritised for improvement. Spaces where there is likely to be an enhanced aerosol generation rate (e.g. through singing, loud speech, aerobic exercise) should aim to ensure sufficient ventilation to maintain CO_2 concentrations below 800ppm (typically 10-15 l/s/person). Additional mitigations are also recommended, such as face coverings for audiences and restricting the size of groups and duration of activities.

4.6 SAGE-EMG[38] highlight that engineering expertise may be required to assess ventilation effectiveness and any mitigation measures should be building specific, taking into consideration the ventilation type, nature of the building and users, activities and the length of exposure.

4.7 SAGE-EMG[39] explain that, 'Virus survival in air decreases with increasing temperature and humidity. In most environments this effect is likely to be less important than the ventilation rate, however environments with low temperature and

[34] REHVA 2021, REHVA COVID 19 Guidance version 4.1, p.27
[35] European Commission 2019, Ventilation rate
[36] SAGE-EMG, (2021). EMG and SPI-B: Application of CO2 monitoring as an approach to managing ventilation to mitigate SARS-CoV-2 transmission, 27 May 2021.
[37] CIBSE, 2021, COVID-19: Ventilation
[38] SAGE-EMG, (2020), EMG: Role of ventilation in controlling SARS-CoV-2 transmission, p.2
[39] SAGE-EMG, (2020), EMG: Role of ventilation in controlling SARS-CoV-2 transmission, p.2

low humidity (e.g. chilled food processing, cold stores) may pose an enhanced risk (medium confidence)'.

4.8 CIBSE[40] note that, 'The risk of exposure follows a law of diminishing returns as the ventilation rate is increased. That is, the ventilation rate should be increased above the minimum statutory rates wherever possible, but this must be balanced against the need to moderate energy demand and carbon emissions and to ensure the thermal comfort of occupants.'

5. Use of Ventilation Guidance within Industry

5.1 The HSE conducted a national YouGov survey of 12,890 workplace employees (between 16th March and 6th April 2022) on COVID-19 and ventilation. The survey found that almost one third of ventilation controllers and users feel that their organisation is following government guidance 'completely' on how to reduce the risk of Covid-19 infection. More than a quarter of ventilation controllers received their guidance on ventilation from Public Health England (Figure 1). Written guidance was the most popular form across all providers (Table 3).

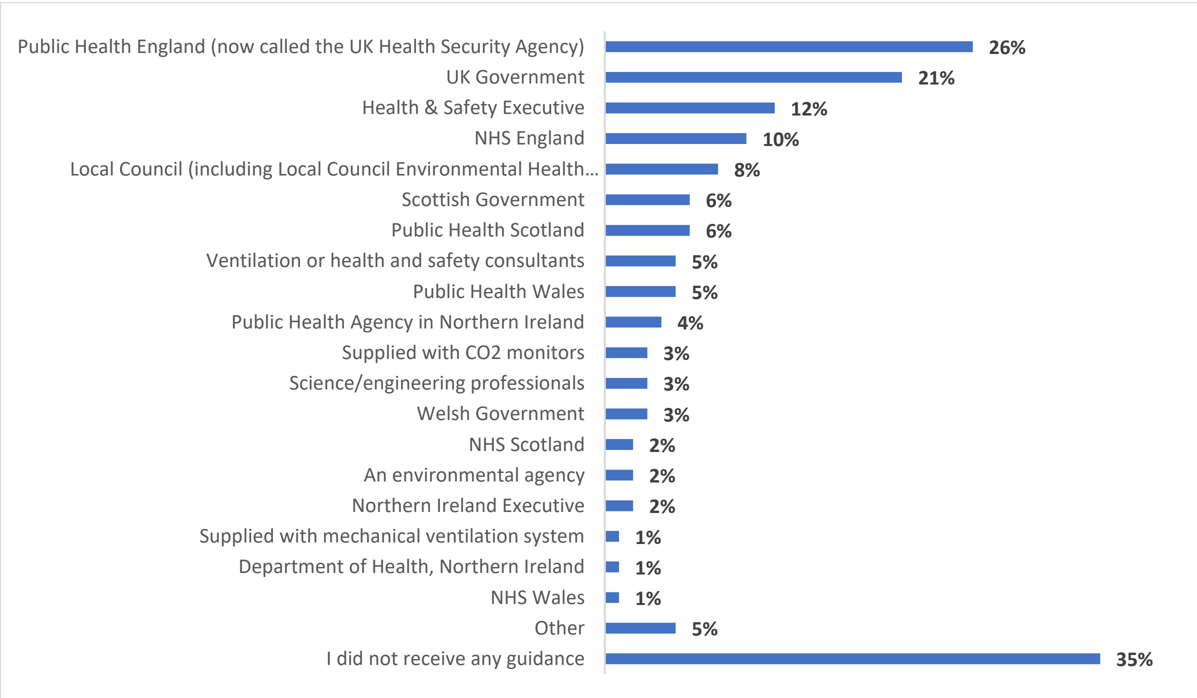

Figure 1. Where did you receive guidance on how to improve ventilation in your organisation? Please select all that apply (1,507 ventilation controllers)
Alt Tag: Bar Chart illustrating percentage of ventilation controllers that received ventilation guidance from each source, with 35% stating they did not receive any guidance.

5.2 Of all guidance sources, ventilation / health and safety consultants and NHS Wales were deemed the most successful. Some suggestions were provided by respondents to make the guidance on improving ventilation more useful, as illustrated in Table 4.

[40] CIBSE, 2021, COVID-19: Ventilation, p.i

Table 3. In what form was this guidance on improving ventilation in your organisation? YouGov, 2021 (ventilation controllers)

	Base	Written guidance	Video guidance	Verbal guidance	I'm not sure
Public Health England	390	68%	13%	8%	11%
Public Health Scotland	90	53%	23%	10%	13%
Public Health Wales	80	39%	34%	19%	9%
Public Health Agency in Northern Ireland	67	27%	42%	28%	3%
Health & Safety Executive	183	58%	19%	16%	7%
UK Government	318	66%	15%	9%	10%
Scottish Government	92	57%	20%	14%	10%
Welsh Government	39	46%	28%	13%	13%
Northern Ireland Executive	30	43%	37%	13%	7%
Local Council	123	60%	18%	17%	5%
Ventilation or health and safety consultants	71	35%	20%	39%	6%
An environmental agency	32	47%	28%	13%	13%
NHS England	157	64%	18%	6%	12%
NHS Scotland	33	67%	18%	9%	6%
NHS Wales	21	57%	24%	10%	10%
Department of Health, Northern Ireland	20	65%	15%	15%	5%
Science/engineering professionals	46	52%	17%	28%	2%
Supplied with CO2 monitors	50	56%	18%	10%	16%
Supplied with mechanical ventilation system	22	68%	14%	-	18%
Other	75	59%	5%	21%	15%

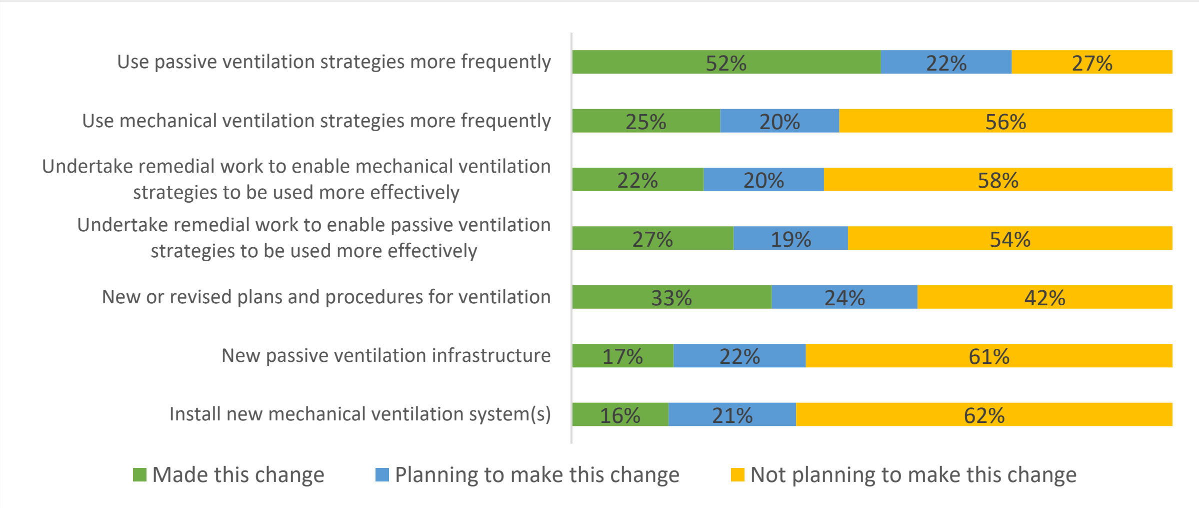

Figure 2. As a result of reading/watching the guidance, which of the following changes did you make or do you plan to make, to improve your organisation's ventilation (Controllers)
<u>Alt Text: Stacked bar chart showing the percentage of Controllers who i) Made this change, ii) Planning to make this change, and iii) Not planning to make this change for various ventilation improvements</u>

5.3 As a result of guidance, more than half of those who have control over ventilation in their workplace have used passive ventilation strategies more frequently (Figure 2).

Table 4. Which of the following would make the guidance on improving your organisation's ventilation more useful? (Controllers)

	Base	Make the guidance briefer	Make the guidance simpler	Include more detail in the guidance	Tailor guidance to building / business	Make guidance available in more languages	Make guidance available in a video format	Make guidance available in a paper format	Make guidance available in an online format	I'm not sure
Public Health England	390	12%	8%	11%	12%	3%	5%	5%	11%	34%
Public Health Scotland	90	11%	16%	10%	19%	4%	11%	2%	6%	21%
Public Health Wales	80	9%	15%	11%	25%	9%	4%	4%	4%	20%
Public Health Agency in Northern Ireland	67	10%	9%	15%	19%	10%	18%	10%	3%	4%
Health & Safety Executive	183	5%	13%	12%	19%	5%	5%	7%	7%	27%
UK Government	318	11%	12%	11%	14%	5%	5%	5%	5%	32%
Scottish Government	92	13%	12%	9%	12%	9%	10%	5%	8%	23%
Welsh Government	39	8%	8%	10%	28%	5%	15%	3%	-	23%
Northern Ireland Executive	30	13%	30%	10%	7%	13%	3%	17%	-	7%
Local Council	123	3%	8%	7%	22%	7%	13%	9%	6%	24%
Ventilation or health and safety consultants	71	8%	13%	11%	13%	4%	13%	7%	7%	24%
An environmental agency	32	13%	16%	9%	19%	6%	16%	3%	6%	13%
NHS England	157	11%	10%	8%	10%	7%	4%	6%	10%	34%
NHS Scotland	33	6%	9%	21%	9%	6%	6%	3%	12%	27%
NHS Wales	21	5%	10%	10%	24%	-	10%	10%	5%	29%

Department of Health, Northern Ireland	20	15%	15%	20%	5%	15%	10%	-	15%	5%
Science/engineering professionals	46	11%	11%	13%	11%	2%	7%	11%	15%	20%
Supplied with CO2 monitors	50	8%	6%	14%	8%	4%	6%	-	10%	44%
Supplied with mechanical ventilation system	22	9%	18%	14%	-	5%	9%	5%	9%	32%
Other	75	4%	5%	7%	19%	-	1%	-	4%	60%

6. Contemporary research findings

6.1 Sick Building Syndrome and the spread of Viruses and other pathogens

6.11 Studies by Bodin-Danielsson et al.[41] (2014) prior to COVID-19, explained that densely packed open-plan offices were already suspected of making employees sick.

6.12 Recent Studies by Lu J. et al.[42] highlight those viruses and other pathogens are not the typical pollutants and even small and temporary exposure has been proven to lead to infections. Studies of viral infections spread through indoor spaces document clearly that mechanically induced, mixing airflow can pose a greater risk of infection spread as it pushes turbulent air deep into rooms, possibly picking up infected droplets along the way.

6.13 T. Lipinski et al.[43] recognised that COVID-19 is one of the most contagious viruses that mankind has experienced.

6.2 Airborne Transmission of Pathogens

6.21 T. Lipinski et al.[44] highlighted that the widely accepted mechanism of COVID-19 transmission is by droplet and contact methods as backed-up by the WHO, but the possible air transmission route has been broadly documented by new scientific research and the WHO is not ruling out this possibility.

[41] Bodin-Danielsson, C., Chungkham, H.S., Wulff, C. and Westerlund, H., 2014. Office design's impact on sick leave rates. Ergonomics, 57(2), pp.139-147.

[42] Lu, J. et al. (2020). COVID-19 Outbreak associated with air conditioning in restaurant, Guangzhou, China,.
[43] Lipinski, T. et al. (2021), Review of ventilation strategies to reduce the risk of disease transmission in high occupancy buildings
[44] Lipinski, T. et al. (2021), Review of ventilation strategies to reduce the risk of disease transmission in high occupancy buildings

6.22 T. Lipinski et al.[45] highlighted that since COVID-19 has an approximate diameter of 60140 nm, Stokes' law applies for ventilation in buildings whereby the air flow exhibits a laminar behaviour. For very small diameter particles of less than 0.1mm, the terminal velocity is almost negligible which further amplifies the fact that if COVID-19 was proven to be airborne then the virus and its potent materials could be airborne for long durations especially if enclosed environments are not ventilated adequately. These droplets are small enough to remain airborne for long periods of time (up to several hours), until they are inhaled by or land on the uninfected person. Airborne transmission is not yet widely accepted for various transmissible respiratory diseases.

6.23 Roy and Milton[46] outlined in their research into airborne transmission of communicable infection that measles and tuberculosis for example are proven to be preferentially airborne transmitted diseases. These diseases have been controlled with widely available drugs and vaccines however prior to the development of suitable vaccines and available drugs, ventilation was a key component in tackling the epidemics by quickly removing foul air from buildings using natural ventilation.

6.24 Talic and colleagues'[47] systematic review and meta-analysis assessed many public health measures for reducing COVID-19 but did not assess the effectiveness of interventions designed to reduce the presence of virus in inspired air, such as filtration, window opening, or the installation of ventilation.

6.25 Ashworth[48] highlighted in his BMJ article that the climate implications of some of these measures mentioned above could be challenging, but they are potentially important considerations in the design of buildings, workplaces, and homes for "antiviral sustainability." These factors are also potentially important modifiers for other measures like home isolation and social distancing or people density. In addition, ventilation may be a key determinant of the propensity for superspreading events, which seem to be a major determinant in the transmission of COVID-19.

6.3 The Transmission of Pathogens in poorly ventilated spaces

6.31 Fennelly[49], Morawska & Milton[50], and Guo Z.-D et al.[51] state that poorly ventilated places are considered to be high risk, and, on a precautionary principle, current advice is for buildings to be as well ventilated as possible[52].

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[45] Lipinski, T. et al. (2021), Review of ventilation strategies to reduce the risk of disease transmission in high occupancy buildings

[46] Roy, C.J. and Milton, D.K., (2004). Airborne transmission of communicable infection-the elusive pathway.

[47] Talic, S., et al. 2021. Effectiveness of public health measures in reducing the incidence of covid-19, SARS-CoV-2 transmission, and covid-19 mortality: systematic review and meta-analysis.

[48] Ashworth, (2021), Effectiveness of public health measures against covid-19 – ventilation has a major role

[49] Fennelly, K.P., 2020. Particle sizes of infectious aerosols: implications for infection control

[50] Morawska, & Milton. (2020). How can airborne transmission of COVID-19 indoors be minimised?

[51] Guo, Z.-D. et al. (2020). Aerosol and surface distribution of severe acute respiratory syndrome coronavirus 2 in hospital wards

[52] World Health Organization. Modes of transmission of virus causing COVID-19: Implications for IPC precaution recommendations: Scientific brief, 27 March 2020.

6.32 Ventilation is a primary strategy used in hospitals and other facilities to control infectious diseases[53].

6.33 According to Chirico et al.[54], ventilation may lead to the infection spread. Ventilation systems are capable of acting as a route to transfer infectious diseases such as SARS, measles, tuberculosis, chickenpox, influenza, rhinovirus, and smallpox[55,56]

6.34 The infectious agents of several other diseases (tuberculosis, measles, chickenpox) are recognised to be transmissible via the air-borne route, either by short-range (face-to-face, conversational) exposure or by longer-range aerosols[57]. Measles and varicella zoster (the virus causing chickenpox) can also be efficiently transmitted through direct contact during their acute phase of infection (e.g. by kissing). During a close contact situation, all transmission routes can be potentially responsible for infection.

6.35 As the most important climate factor, solar radiation was significantly correlated with the COVID-19 prevalence[58].

6.36 Temperature, simulated sunlight, and humidity are among significant factors affecting the infectious SARS-CoV-2 durability in aerosols[59,60].

6.37 Additionally, in enclosed spaces, low humidity, air conditioning, and low UV light may cause viral aerosol to survive longer[61].

6.38 REHVA[62] states, ‘Relative humidity (RH) and temperature contribute to virus viability, droplet nuclei forming, and susceptibility of occupants' mucous membranes. The transmission of some viruses in buildings can be altered by changing air temperatures and humidity levels to reduce the viability of the virus. In the case of SARS-CoV-2, this is unfortunately not an option as coronaviruses are quite resistant to environmental changes and are susceptible only to a very high relative humidity above 80% and a temperature above 30 ℃ which are not attainable and acceptable in buildings for reasons of thermal comfort and avoiding microbial growth’.

6.39 Results from this study indicated that the main transmission route for COVID-19 was person to person contact.

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53 Correia et al. (2020). Airborne route and bad use of ventilation systems as non-negligible factors in SARS-CoV-2 transmission.

54 Chirico, et al. (2020). Can air-conditioning systems contribute to the spread of SARS/MERS/COVID-19 infection? Insights from a rapid review of the literature

55 Shiu, et al. 2019. Controversy around airborne versus droplet transmission of respiratory viruses

56 Li, et al. (2020) The role of children in transmission of SARS-CoV-2: A rapid review.

57 Tellier, Ret al. 2019. Recognition of aerosol transmission of infectious agents: a commentary.

58 Rosario et al. (2020). Relationship between COVID-19 and weather: Case study in a tropical country.

59 Ratnesar-Shumate, et al. 2020. Simulated sunlight rapidly inactivates SARS-CoV-2 on surfaces.

60 Biryukov, et al. 2020. Increasing temperature and relative humidity accelerates inactivation of SARS-CoV-2 on surfaces.

61 Bulfone, et al. (2020). Outdoor Transmission of SARS-CoV-2 and other Respiratory Viruses

62 REHVA 2021, REHVA COVID 19 Guidance version 4.1, p.12

6.310 Gordon et al.[63] suggested in their recent studies considering traditional infection control hierarchy outlined below:

1. Elimination (to physically remove the pathogen),
2. Engineering Controls (to separate people and pathogen),
3. Administrative Controls (to instruct people what to do)
4. Personal Protective Equipment (to use masks, gowns, gloves, and other smart PPE), respectively.

6.311 Pathogens and other respiratory viruses like e.g., coronaviruses, influenza, respiratory syncytial virus, and tuberculosis transmit through the air[64,65,66]

6.312 SARS-CoV-2 is a common disease between humans and animals that has turned into a pandemic[67].

6.313 A number of outbreaks in confined indoor crowded spaces such as offices, churches, restaurants, ski resorts, shopping centres, worker dormitories, cruise ships and vehicles indicate that virus transmission is particularly efficient in these types of indoor environments[68].

6.314 Qian et al.[69] studied 318 COVID-19 outbreaks with three or more cases of transmission, and in all except one, the virus transmission occurred in indoor spaces.

6.315 Park et al.[70] reported an incidence of COVID-19 outbreak in an eleventh-floor office of a call centre in South Korea where 44.5 % of the occupants (94 out of 216 people) were found to be infected; however, the rate of secondary infections to the household members of the symptomatic patients was only 16.2 %

6.316 Increased rates of transmission occur not only for buildings, but also on public transportation where people are likely to be in the presence of an infected person in a crowded indoor space for relatively long periods of time and, therefore, exposed to airborne particles[71].

6.4 The use of Natural Ventilation and Stratification Ventilation Methods to reduce pathogen transmission

6.41 Ventilation is the process of providing outdoor air to a space or building by natural or mechanical means[72].

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[63] Gordon, et al. (2020). Built Environment Airborne Infection Control Strategies in Pandemic Alternative Care Sites.
[64] Kramer et al. 2006. How long do nosocomial pathogens persist on inanimate surfaces? A systematic review.
[65] Sjödin, et al. (2020). COVID-19 outbreak on the diamond princess cruise ship
[66] Tang, J. W. (2009). The effect of environmental parameters on the survival of airborne infectious agents.
[67] Sjödin, et al. (2020). COVID-19 outbreak on the diamond princess cruise ship
[68] Leclerc et al. (2020). What settings have been linked to SARS-CoV-2 transmission clusters?
[69] Qian et al. 2021. Indoor transmission of SARS-CoV-2.
[70] Park, et al. 2020. Contact tracing during coronavirus disease outbreak, South Korea
[71] Luo, et al. 2020, October. Transmission of SARS-CoV-2 in public transportation vehicles: a case study in Hunan Province, China
[72] ISO, (2017): https://www.iso.org/obp/ui/#iso:std:iso:16814:ed-1:v1:en

6.42 Appropriate distribution of ventilation (e.g. placement of supply and exhaust vents) ensures that adequate dilution is achieved where and when needed, avoiding the build-up of viral contamination[73,74].

6.43 Good ventilation practices are already in place in many hospital settings, as part of everyday and emergency measures to protect against droplet and contact transmission[75,76].

6.44 Bhagat et al.[77] summarised in a recent study of the most effective ventilation systems that despite the various mechanisms generating disturbances indoors, it is clear that in many cases stratification 'wins'.

6.45 Bhagat et al.[78] noted that a small temperature difference across a doorway or window will organise the flow so that the cool air flows through the lower part and warm air through the upper part of the opening.

6.46 Linden[79] explained that it is notoriously difficult to mix a stratified space with mixing efficiencies (the ratio of the kinetic energy needed to change the potential energy required) typically well below 20 %.

6.47 Bhagat et al.[80] further detailed that the presence of stratification emphasises the need to measure CO_2 at a height where individuals are breathing, and away from sources of fresh air such as an open window, where concentrations are typically much lower than the room average, if one is to obtain an estimate for the load of potentially infectious particles. Consequently, if designed properly, displacement ventilation, which encourages vertical stratification and is designed to remove the polluted warm air near the ceiling, seems to be the most effective at reducing the exposure risk. Mixing ventilation distributes the air throughout the space and does not provide any potentially clean zones. It also has to work against the tendency of the room to stratify, while displacement ventilation takes advantage of it, and can simply and cheaply be implemented by installing extraction vents or fans at the top of the space.

6.48 Gilkeson et al.[81] explained in a study that many hospitals are naturally ventilated in ward areas, including in some rooms used for critical care. However, if the airflow passage is obstructed (e.g. by closing windows and doors), airborne pathogen concentration can sharply rise leading to an increased risk of airborne transmission and infection.

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73 Melikov, et al. 2011. Novel ventilation strategy for reducing the risk of airborne cross infection in hospital rooms.

74 Thatiparti, et al. 2016. Assessing effectiveness of ceiling-ventilated mock airborne infection isolation room in preventing hospital-acquired influenza transmission to health care workers.

75 Phiri, 2014. Health Building Note 00-01 General design Guidance for Healthcare Buildings. UK Government.

76 Morawska, et al. 2020. How can airborne transmission of COVID-19 indoors be minimised?

77 Bhagat et al., (2020) Effects of ventilation on the indoor spread of COVID-19

78 Bhagat et al., (2020) Effects of ventilation on the indoor spread of COVID-19

79 Linden, P.F., 1979. Mixing in stratified fluids. Geophysical & Astrophysical Fluid Dynamics

80 Bhagat et al., (2020) Effects of ventilation on the indoor spread of COVID-19

81 Gilkeson et al. 2013. Measurement of ventilation and airborne infection risk in large naturally ventilated hospital wards. Building and environment

6.49 Natural ventilation concepts apply to healthcare facilities in both developed and resource-limited countries in favourable climatic conditions. The design, operation and maintenance of naturally ventilated facilities is not straight forward, and comprehensive guidance is available. For instance, WHO[82] in March, specifies that in a COVID-19 infective ward at least 160L/s/patient have to be provided if natural ventilation is used.

6.410 If ventilation is provided using window openings (aeration) or other means (fixed openings, e.g., natural ventilation), an estimation of the possible outdoor flow rate can be made using CEN Standard, EN16798-7:2017[83].

6.5 The role of Sunlight and Ultra-Violet Irradiation

6.51 In environments where it is difficult to improve ventilation, the addition of local air cleaning or disinfection devices such as germicidal ultraviolet (GUV, or UVGI-ultraviolet germicidal irradiation) may offer benefits. Under laboratory conditions GUV has been shown to be effective against a suite of microorganisms including coronaviruses[84], vaccinia[85] and Myco-bacteria[86] and even influenza[87,88]. Several studies show that inactivation decreases with increased humidity for both bacterial and viral aerosols[89]. Darnell et al.[90] showed that SARS-CoV-1 could be inactivated by UV-C, while Bedell et al.[91] showed a UV-C decontamination device could inactivate MERS-CoV at 1.22 m, with almost a 6 log reduction in 5min. There is no data yet for SARS-CoV-2, but the data for other coronaviruses suggest it is highly likely that it is susceptible to UV-C.

6.52 Noakes et al.[92] concluded in their studies of airborne virus transmission that one application that grew dramatically during the multi-drug resistant tuberculosis outbreaks of the 1980s documented by Young and Wormser[93], is the 'upper-room' system in which lamps are placed in the upper part of the room, either on the walls or mounted on the ceiling, directing the UV light into the upper zone with louvers and limiting UV exposure in the occupied space[94]. Upper-room GUV is a good

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82 WHO (2020a) Modes of transmission of virus causing COVID-19: Implications for IPC precaution recommendations: Scientific brief, 27 March 2020.

83 CEN EN16798-7:2017 Energy performance of buildings – ventilation for buildings – Part 7

84 Walker and Ko, 2007. Effect of ultraviolet germicidal irradiation on viral aerosols.

85 McDevitt et al. 2007. Characterization of UVC light sensitivity of vaccinia virus.

86 Xu et al. 2003. Efficacy of ultraviolet germicidal irradiation of upper-room air in inactivating airborne bacterial spores and mycobacteria in full-scale studies. Atmospheric Environment

87 McDevitt et al., 2012. Aerosol susceptibility of influenza virus to UV-C light.

88 McLean, R.L., 1961. The effect of ultraviolet radiation upon the transmission of epidemic influenza in long-term hospital patients. *Am Rev Respir Dis*, *83*(2 Part 2), pp.36-8.

89 McDevitt et al., 2012. Aerosol susceptibility of influenza virus to UV-C light.

90 Darnell et al. 2004. Inactivation of the coronavirus that induces severe acute respiratory syndrome, SARS-CoV.

91 Bedell, et al. 2016. Efficacy of an automated multiple emitter whole-room ultraviolet-C disinfection system against coronaviruses MHV and MERS-CoV.

92 Noakes, et al. 2015. Modeling infection risk and energy use of upper-room ultraviolet germicidal irradiation systems in multi-room environments.

93 Young and Wormser, 1994. The resurgence of tuberculosis. Scandinavian journal of infectious diseases.

94 Xu et al. 2003. Efficacy of ultraviolet germicidal irradiation of upper-room air in inactivating airborne bacterial spores and mycobacteria in full-scale studies. *Atmospheric Environment*

technology to consider in crowded, poorly ventilated environments where aerosol transmission could occur and where the ability to increase ventilation is limited. McLean[95] presented data showing interruption of influenza transmission in a hospital setting. It has been estimated that upper-room GUV may reduce infection risk by an amount equivalent to doubling the ventilation rate.

6.6 The use of CO_2 sensing as a marker for inadequate ventilation (including natural and mechanical ventilation)

6.61 Rudnick & Milton[96] explained that it seems reasonable to consider CO_2 as a marker for air that has been exhaled. Indeed, it has been shown that CO_2 concentration can be linked to the probability of infection.

6.62 Bhagat et al.[97] concluded that even though CO_2 is denser than air, our observations show that it is carried with the flow as would virus particles. A simple balance of a person breathing out at a concentration of 45 000 p.p.m. at a rate of 10 l min−1 and supplied with the recommended 10 l.s.p., implies that a steady concentration above the background would be 750 p.p.m. Carbon dioxide concentrations above this value, especially at the breathing level, may indicate that the ventilation is inadequate and that remedial action should be taken. The risk of infection is thought to increase with exposure time. It is also the case that CO_2 levels increase over time once people begin to occupy a space. Consequently, it may be appropriate to add some exposure time as well as simply the CO_2 concentration level to a warning system.

6.7 The transmission behaviour of pathogens in mechanical ventilation systems

6.71 Recent studies by Wessendorf et al.[98] closely examined the prerequisite of a unique super-spreading event in Germany during the SARS-CoV-2 pandemic, where nearly half of the participants became infected including children. The study systematically analyzed infection rate, potential individual, and environmental risk factors for infection as well as the role of the ventilation system.

6.72 Wessendorf et al.[99] highlighted that an important factor associated with infection risk was the ventilation system and the individual proximity to the ventilation outlets. Individuals close to the air-outlets that contained air with low amount of fresh air had the highest infection risk compared to those close to the air-inlets.

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[95] McLean, R.L., 1961. The effect of ultraviolet radiation upon the transmission of epidemic influenza in long-term hospital patients. *Am Rev Respir Dis*, *83*(2 Part 2), pp.36-8.

[96] Rudnick and Milton, 2003. Risk of indoor airborne infection transmission estimated from carbon dioxide concentration. Indoor air

[97] Bhagat et al., (2020) Effects of ventilation on the indoor spread of COVID-19

[98] Wessendorf, et al. 2021. Analysis of the Dynamics, Outcome, and Prerequisites of the first German SARS-CoV-2 Superspreading Event.

[99] Wessendorf, et al. 2021. Analysis of the Dynamics, Outcome, and Prerequisites of the first German SARS-CoV-2 Superspreading Event.

6.73 The results of the study by Wessendorf et al.[100] are in line with previous studies by Santarpia et al.[101], Günther[102] and Pokora et al.[103], that demonstrated SARS-CoV-2 to be able to become air-borne under certain conditions and that the ventilation system can have an influence on virus spread.

6.74 Wessendorf et al.[104] concluded that the air filters in the venue were not capable of intercepting virus particles supporting the notion outlined by Pokora et al.[105] and Nazarenko[106] on the importance of proper indoor ventilation systems.

6.75 Wessendorf et al.[107] explained that spending the break of the event outside decreased the possibility of infection underscoring the benefit of proper ventilation to lower the amount of aerosols. Due to the nature of the event, the spatial distribution of the participants was not fixed throughout the evening, and not perfectly recapitulated, so this information carries some error. However, allowing for multiple positions per person we used all available information. Assuming further error in the spatial data to be random, this might lead to a dilution of effects, i.e. true associations may remain undetected. Complementary analyses including e.g. the persons' functions during the event show consistent results, so we see no evidence suggesting bias in the findings of the study.

6.76 In environments with lower ventilation rates intended primarily to control indoor air quality (which may also include some hospital emergency, acute admissions, general ward and clinic areas), the likelihood of infected persons sharing air with susceptible occupants is high[108,109,110], posing an infection risk contributing to the spread of the infectious disease.

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[100] Wessendorf, et al. 2021. Analysis of the Dynamics, Outcome, and Prerequisites of the first German SARS-CoV-2 Superspreading Event.
101 Santarpia, et al. (2020). Aerosol and surface contamination of SARS-CoV-2 observed in quarantine and isolation care
[102] Günther et al. (2020). SARS-CoV-2 outbreak investigation in a German meat processing plant.
[103] Pokora et al. (2021) Investigation of superspreading COVID-19 outbreak events in meat and poultry processing plants in Germany: A cross-sectional study.
[104] Wessendorf, et al. 2021. Analysis of the Dynamics, Outcome, and Prerequisites of the first German SARS-CoV-2 Superspreading Event.
[105] Pokora et al. (2021) Investigation of superspreading COVID-19 outbreak events in meat and poultry processing plants in Germany: A cross-sectional study.
[106] Nazarenko (2020). Air filtration and SARS-CoV-2. Epidemiol Health
[107] Wessendorf, et al. 2021. Analysis of the Dynamics, Outcome, and Prerequisites of the first German SARS-CoV-2 Superspreading Event.
[108] Booth, et al., (2013) Effectiveness of surgical masks against influenza bioaerosols
[109] Pease et al., (2021) Investigation of potential aerosol transmission and infectivity of SARS-CoV-2 through central ventilation systems. *Building and environment*
[110] Sornboot et al., (2019) Detection of airborne Mycobacterium tuberculosis complex in high-risk areas of health care facilities in Thailand.

6.77 Various studies have been performed on the survival of airborne pathogens[111,112,113,114,115,116]. The SARS-CoV-2 virus has been shown to be stable in airborne particles with a half-life of more than one hour[117], so it can potentially be inhaled by susceptible individuals causing infection and further spreading of the disease. As 'stay-at-home' lockdown measures are gradually relaxed, much of the population may return to spending increasing amounts of time in inadequately ventilated workplaces, offices, schools and other public buildings, where they may be exposed to a risk of acquiring viral infections by inhalation.

6.78 The recirculation of air is a measure for saving energy, but care must be taken, as it can transport airborne contaminants (including infectious viruses) from one space and distribute them to other spaces connected to the same system, potentially increasing the risk of air-borne infection in areas that otherwise would not have been contaminated. This concern has been noted previously in regard to the possible recirculation of biological agents during terrorist attacks that have investigated the effectiveness of eliminating recirculation (e.g. providing 100% outside air to spaces and exhausting all of it) as a counter measure following an indoor release of the agent[118]. A study modelling the risk of airborne influenza transmission in passenger cars also provided a case against air recirculation in such situations[119].

6.8 Evidence of Aerosol Transmission of COVID-19 particles in Case Study Buildings and superspreading events

6.81 The Centers for Disease Control and Prevention, Respiratory Viruses Branch, Division of Viral Diseases[120] (2021) documented several aspects during the COVID-19 pandemic to support the risk of aerosol transmission of SARS-CoV-2. First, mounting evidence for pre- and asymptomatic transmission, where the spread of droplets through coughing and sneezing cannot be a major factor, must raise questions about aerosol transmission.

6.82 Furthermore Leung et al.[121] concluded that aerosols generated by speech could theoretically contain enough SARS-CoV-2 virus particles to support

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111 Kim et al. (2016) Extensive viable middle east respiratory syndrome (MERS) coronavirus contamination in air and surrounding environment in MERS isolation wards.

112 Kormuth et al., (2018) Influenza virus infectivity is retained in aerosols and droplets independent of relative humidity.

113 Pease et al., (2021) Investigation of potential aerosol transmission and infectivity of SARS-CoV-2 through central ventilation systems. *Building and environment*

114 Marr et al., (2019) Mechanistic insights into the effect of humidity on airborne influenza virus survival, transmission and incidence.

115 Pyankov et al., (2018): Survival of aerosolized coronavirus in the ambient air.

116 Tang, J. W. (2009). The effect of environmental parameters on the survival of airborne infectious agents.

117 van Doremalen et al. (2020). Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1.

118 Persily et al., (2007) Building retrofits for increased protection against airborne chemical and biological releases. National Institute of Standards and Technology

119 Knibbs et al., (2012) The risk of airborne influenza transmission in passenger cars.

120 Centers for Disease Control and Prevention (2021) Scientific Brief: Sars-Cov-2 Transmission

121 Leung, et al. 2020. Respiratory virus shedding in exhaled breath and efficacy of face masks.

transmission, and these aerosols can remain airborne for up to ten minutes. In addition, coronaviruses can be emitted in aerosols through normal breathing.

6.83 In addition to this Guo, Z.-D. et al.[122], Ong, S. W. X. et al.[123], Chia, P. Y. et al.[124] and Liu, Y. et al.[125] outlined in their recent studies that field studies in hospital wards have detected SARS-CoV-2 RNA both in vent openings and in the air. Morawska & Cao[126], Kim et al.[127] and Yu, I. T. S. et al.[128] concluded that these findings are not unexpected seeing as similar observations have been made for both SARS and Middle East Respiratory Syndrome (MERS).

6.84 Nissen et al.[129] investigated ventilation openings in one COVID-19 ward and central ducts that expel indoor air from three COVID-19 wards at Uppsala University Hospital, Sweden, during April and May 2020. In this study they found SARS-CoV-2 RNA in vent openings in ward rooms harbouring COVID-19 patients. Viral RNA was also detected in fluid placed in open dishes suspended below vent openings. Similar levels of viral RNA were detected in exhaust filters and open petri dishes with cell medium at least 44 to 56 m from the three investigated COVID-19 wards. Only a small fraction of each filter was analysed implying that a large number of particles emanating from COVID-19 wards can disperse to greater distances than can be explained by droplet transmission routes.

6.85 Nissen et al.[130] explained that in previous studies, the effect of ventilation has not shown any obvious impact on the risk for spread of droplet-transmitted diseases, probably since droplets are more governed by gravity as outlined in previous studies of airborne ventilation transmission by Qian & Zheng [131].

6.86 Nissen et al.[132] concluded that the ventilation system in the investigated Uppsala University Hospital has a relatively low air flow; between 1.7 and 3 total air changes per hour (ACH) for each room, depending on room volumes. Qian & Zheng[133] summarised that the recommendation for airborne infection isolation rooms is 12 ACH in most guidelines. Notably, the relative air humidity in the investigated environment was low, between 30 and 31%.

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[122] Guo, Z.-D. et al. (2020). Aerosol and surface distribution of severe acute respiratory syndrome coronavirus 2 in hospital wards
[123] Ong, S. W. X. et al. (2020) Air, surface environmental, and personal protective equipment contamination by severe acute respiratory syn-drome coronavirus 2 (SARS-CoV-2) from a symptomatic patient.
[124] Chia, P. Y. et al. (2020). Detection of air and surface contamination by SARS-CoV-2 in hospital rooms of infected patients.
[125] Liu, Y. et al. (2020) Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals.
[126] Morawska, L. & Cao, J. (2020), Airborne transmission of SARS-CoV-2: The world should face the reality.
[127] Kim et al. (2016) Extensive viable middle east respiratory syndrome (MERS) coronavirus contamination in air and surrounding environment in MERS isolation wards.
[128] Yu, I. T. S. et al. (2004). Evidence of airborne transmission of the severe acute respiratory syndrome virus.
[129] Nissen (2020): Long-distance airborne dispersal of SARS-CoV-2 in COVID-19 wards.
[130] Nissen (2020): Long-distance airborne dispersal of SARS-CoV-2 in COVID-19 wards.
[131] Qian & Zheng (2018). Ventilation control for airborne transmission of human exhaled bio-aerosols in buildings.
[132] Nissen (2020): Long-distance airborne dispersal of SARS-CoV-2 in COVID-19 wards.
[133] Qian & Zheng (2018). Ventilation control for airborne transmission of human exhaled bio-aerosols in buildings.

6.87 Recent Studies by Quraishi et al.[134] outlined that low air humidity has been suggested to increase the risk of airborne SARS-CoV-2 dispersal.

6.88 Studies by Bin, S. Y. et al.[135], Ong, S. W. X. et al.[136] and Correia, G.[137] outlined that detection of SARS-CoV-2 as well as other coronavirus RNA in ventilation openings has been reported before.

6.89 Nissen et al.[138] documented, in relation to their field study of the ventilation system in the investigated at Uppsala University Hospital, the detection of viral RNA in the exhaust filters over 50 m from patient care areas was unexpected.

6.810 Nissen et al.[139] explained that the placement of the petri dishes, either just below the ceiling in ward rooms or at distances around at least 50 m from patients in central vent ducts indicates that dispersal by means other than larger droplets must occur, since larger droplets are considered to precipitate by gravity within one or two meters from a source as concluded in studies by Siegel, J. et al.[140].

6.811 Burridge HC et al.[141] outlined in detail a number of environmental factors affecting the survival of SARS-CoV-2 on surfaces this is important to understand when evaluating how the virus behaves during airborne transmission through the surfaces of ventilation and air conditioning equipment such as ductwork fans and filters.

- — Temperature effects have been reported to be significant, with higher temperatures decreasing survival times as outlined in recent studies by Dietz et al.[142]. Burridge HC et al.[143] suggested that comfortable indoor temperatures should be maintained and the use of air conditioning should be minimized wherever practical with the appropriate supply of outdoor air remaining a priority.
- — Humidity has been shown to also have an effect on the virus, with drier conditions being more suitable for virus survival as detailed in a recent study

[134] Quraishi, et al. (2020). A. Indoor temperature and relative humidity in hospitals: Workplace considerations during the novel coronavirus pandemic.
[135] Bin, S. Y. et al. (2016). Environmental contamination and viral shedding in MERS patients during MERS-CoV outbreak in South Korea
[136] Ong, S. W. X. et al. (2020) Air, surface environmental, and personal protective equipment contamination by severe acute respiratory syn-drome coronavirus 2 (SARS-CoV-2) from a symptomatic patient.
[137] Correia et al. (2020). Airborne route and bad use of ventilation systems as non-negligible factors in SARS-CoV-2 transmission.
[138] Nissen (2020): Long-distance airborne dispersal of SARS-CoV-2 in COVID-19 wards.
[139] Nissen (2020): Long-distance airborne dispersal of SARS-CoV-2 in COVID-19 wards.
[140] Siegel, et al. (2007). Guideline for isolation precautions: Preventing transmission of infectious agents in health care settings.
[141] Burridge HC et al. (2021) The ventilation of buildings and other mitigating measures for COVID-19: a focus on wintertime
[142] Dietz, et al. (2019). Novel coronavirus (COVID-19) pandemic: built environment considerations to reduce transmission systems
[143] Burridge HC et al. (2021) The ventilation of buildings and other mitigating measures for COVID-19: a focus on wintertime

by Biryukov et al.[144]. Burridge HC et al.[145] concluded that while higher humidity is preferable to reduce viral infection, there are numerous health issues related to high humidity and promotion of mould growth. Burridge HC et al. advise that in cold weather the relative humidity should be maintained at between 40 and 50%, rather than below 30%, which is typical of many indoor environments in winter aligning with guidance provided in recent studies by Dietz et al.[146].

- — Light is also demonstrated as an effective method for SARS-CoV-2 deactivation with 90% of the virus inactivated every 6.8 to 14.3min depending on the intensity of simulated natural light as explained in recent studies by Schuit M et al.[147], Burridge HC et al.[148]. Detailed studies by Bedell, Buchaklian and Perlman[149] concluded that UV-C light has been shown to deactivate other strains of coronavirus Burridge HC et al.[150] recommended that while the use of artificial light cleaning technologies is not suggested as a replacement for disinfectant cleaning practices, well-lit rooms, particularly via natural lighting is preferred based on evidence from SARS-CoV-2 and other viruses as outlined in recent studies by Dietz et al.[151] and Schuit et al.[152].

6.812 Burridge HC et al.[153] outlined that it is now well known that SARS-CoV-2 has different survival times on different surfaces, with laboratory inoculations of SARS-CoV-2 survival rates varying from 3 h for paper and tissue to up to 72 h (3 days) on hard, smooth surfaces such as plastic and stainless steel (and also on surgical masks) as outlined in recent studies by van Doremalen et al.[154] Riddell et al.[155] outlined in studies that glass and bank notes have survival times in the region of 3 days, with cloth and wood reported at 2 days.

6.813 Burridge HC et al.[156] concluded that airborne infection risk is reduced when the ventilation provision of outdoor air is maximized. Operating the existing indoor

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[144] Biryukov, et al. 2020. Increasing temperature and relative humidity accelerates inactivation of SARS-CoV-2 on surfaces.

[145] Burridge HC et al. (2021) The ventilation of buildings and other mitigating measures for COVID-19: a focus on wintertime

[146] Dietz, et al. (2019). Novel coronavirus (COVID-19) pandemic: built environment considerations to reduce transmission systems

[147] Schuit et al. (2020). Airborne SARS-CoV-2 Is Rapidly Inactivated by Simulated Sunlight

[148] Burridge HC et al. (2021) The ventilation of buildings and other mitigating measures for COVID-19: a focus on wintertime

[149] Bedell, et al. 2016. Efficacy of an automated multiple emitter whole-room ultraviolet-C disinfection system against coronaviruses MHV and MERS-CoV.

[150] Burridge HC et al. (2021) The ventilation of buildings and other mitigating measures for COVID-19: a focus on wintertime

[151] Dietz, et al. (2019). Novel coronavirus (COVID-19) pandemic: built environment considerations to reduce transmission systems

[152] Schuit et al. (2020). Airborne SARS-CoV-2 Is Rapidly Inactivated by Simulated Sunlight

[153] Burridge HC et al. (2021) The ventilation of buildings and other mitigating measures for COVID-19: a focus on wintertime

[154] van Doremalen et al. (2020). Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1.

[155] Riddell et al. (2020) The effect of temperature on persistence of SARS-CoV-2 on common surfaces

[156] Burridge HC et al. (2021) The ventilation of buildings and other mitigating measures for COVID-19: a focus on wintertime

environment conditioning and controlling equipment in a manner that fixes the outdoor air supply rate to be maximal (with due consideration to the practical limits for a comfortable indoor environment), the airborne risk can be greatly reduced by lowering occupancy in a given indoor space. For example, should the ventilation plant be kept running at the same level (i.e. unchanged absolute outdoor air supply rate) and the occupancy halved (e.g. through week in—week out working) in an indoor space then the chances that infection occurs within is approximately halved. In relation to schools and offices and public buildings Burridge HC et al.[157] highlighted that consideration should be given to purging rooms between meetings, classes and events. This would require the room to be unoccupied between consecutive events during which period all possible efforts are made to increase the outdoor air supply rate (whether by opening windows, doors and ventilation systems).

6.814 Burridge HC et al.[158] summarised that the adequate ventilation of a building space should be regarded as the primary mitigating measure against the spread of airborne diseases. There is strong evidence that COVID-19 can be spread via the airborne route as outlined in studies by Hyde et al.[159]. Burridge HC et al.[160] further concludes that in temperate climates, this leads to the simple advice that all ventilation (by which we refer exclusively to the supply of outdoor, or suitably sterilized or filtered, air) systems be operated to maximize supply and ventilation openings (e.g. windows, vents, louvres, doors, etc.) be opened to the extent permitted by design.

6.815 Table 5. CO_2 and ventilation guidance in different countries in response to COVID-19[161].

WHO	10 l/s/person, 6 ACH in healthcare settings, CO_2 not indicated	https://www.who.int/publications/i/item/9789240021280
USA (CDC)	800 ppm is suggested as a broad indicator	https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html
EU (ECDC)	800-1000ppm	https://www.ecdc.europa.eu/sites/default/files/documents/Heating-ventilation-air-conditioning-systems-in-thecontext-of-COVID-19-first-update.pdf

157 Burridge HC et al. (2021) The ventilation of buildings and other mitigating measures for COVID-19: a focus on wintertime
158 Burridge HC et al. (2021) The ventilation of buildings and other mitigating measures for COVID-19: a focus on wintertime
159 Hyde et al. 2021. Australia must act to prevent airborne transmission of SARS-CoV-2.
160 Burridge HC et al. (2021) The ventilation of buildings and other mitigating measures for COVID-19: a focus on wintertime
161 SAGE-EMG, (2021). EMG and SPI-B: Application of CO2 monitoring as an approach to managing ventilation to mitigate SARS-CoV-2 transmission, 27 May 2021.

EU (REHVA)	10 l/s/p or 950ppm over long time, 800ppm over shorter time	https://www.rehva.eu/activities/covid-19-guidance/rehva-covid-19-faq
Germany	1000ppm	https://www.umweltbundesamt.de/en/press/pressinforma
France	800ppm	https://www.hcsp.fr/Explore.cgi/AvisRapports
Japan	Japan offices below 1000ppm, schools below 1500ppm	https://www.covid19-ai.jp/en-us/organization/aist/articles/article001
Ireland	800ppm in schools	https://www.hpsc.ie/a-z/respiratory/coronavirus/novelcoronavirus/guidance/empl

7. Conclusions

From the wider literature review, the following recommendations are suggested for consideration with regard to inclusion in Section 3.14 of the Standard:

7.1 Provision of Adequate Ventilation of a Building Space to mitigate the spread of airborne diseases

The adequate ventilation of a building space should be regarded as the primary mitigating measure against the spread of airborne diseases. Standard 3.14 states, ‘Every building must be designed and constructed in such a way that ventilation is provided so that the air quality inside the building is not a threat to the building or the health of the occupants’. There is strong evidence that COVID-19 can be spread via the airborne route as outlined in studies by Hyde et al.[162]. Burridge HC et al.[163] further concludes that in temperate climates, this leads to the simple advice that all ventilation (by which we refer exclusively to the supply of outdoor, or suitably sterilized or filtered, air) systems be operated to maximize supply and ventilation openings (e.g. windows, vents, louvres, doors, etc.) be opened to the extent permitted by design.[164]

The WHO and REHVA (see Table 5) recommend ventilation rates of 10 l/s/p in response to COVID-19, however for future buildings Category I ventilation rates (20l/s/p or 2 l/s*m^2) have been recommended as these provide significant risk

[162] Hyde et al. 2021. Australia must act to prevent airborne transmission of SARS-CoV-2.
[163] Burridge HC et al. (2021) The ventilation of buildings and other mitigating measures for COVID-19: a focus on wintertime
[164] Burridge HC et al. (2021) The ventilation of buildings and other mitigating measures for COVID-19: a focus on wintertime

reduction compared to common Category II airflow rates (14 l/s/p or 1.4 l/s*m^2)[165]. In comparison, Standard 3.14.5 'Mechanical Ventilation' recommends that mechanical air supply is provided at a rate of at least 8 l/s/p for occupiable rooms, based on sedentary occupants and the absence of other requirements (such as the removal of moisture), or compliance with guidance in BS 5720:1979 or CIBSE Guide B: 2016.

7.2 Phasing out the Recirculation of extract air in Mechanical Ventilation Systems

Recommend phasing out of recirculation of air and replacement over time with heat exchanger systems which prohibit the mixing of intake and extract air to avoid airborne pathogen transmission.[166]

7.3 Installation of Carbon dioxide sensing to identify instances of poor air quality

To note. Part F in England now requires CO_2 sensing in all mechanically ventilated buildings[167] (Table 6). Linked with 7.1 above, there is a growing awareness of the need to combine fresh air per person allowances and CO_2 build up, pointing the way to more flexibility in how fresh air can be provided to allow management of varying occupancy patterns – see 7.5 below. CO_2 sensing is an effective proxy for ventilation and/or occupancy and is equally applicable to both mechanically ventilated and naturally ventilated buildings. To limit airborne pathogen transmission, CO_2 sensing is recommended for both naturally ventilated and mechanically ventilated situations to detect instances of poor ventilation and/or high occupancy.[168]

Table 6. Changes to Part F (Ventilation)[169]

Notable changes in part F (Ventilation) of Building Regulations 2021	**Notes**
Proposed increase in mechanical ventilation rates for occupiable rooms in offices not adopted	Requirement is for outdoor air to be supplied at the greater of 10 l/s/p or 1 l/s/m^2 floor area
Minimising the ingress of external pollutants through proper siting of vents	Ventilation intakes should be located away from the direct impact of the sources of local pollution
Requirement to monitor indoor air quality (IAQ) in all new build offices and 'high risk' occupiable rooms	Small spaces up to 125m^3 vol or 50m^2 area, and large spaces over 800m^3 / 320m^2 exempt

[165] REHVA 2021, REHVA COVID 19 Guidance version 4.1, p.27
[166] Lu, J. et al. (2020). COVID-19 Outbreak associated with air conditioning in restaurant, Guangzhou, China, 2020.
[167] Watts, 2022, Feature: What the updated building regulations mean for air quality
[168] Bhagat et al., (2020) Effects of ventilation on the indoor spread of COVID-19
[169] Watts, 2022, Feature: What the updated building regulations mean for air quality

Performance based ventilation strategies can now be assessed against individual volatile organic compounds (VOCs), based on data from Public Health England	This may prove to be more complex than testing against a total volatile organic compound (TVOC) limit
Ventilation systems should be capable of operating in a way that prevents the recirculation of air unless adequate filtering or disinfection systems are used	Where recirculation is unavoidable, suitable systems include those that incorporate UV-C germicidal irradiation or HEPA filtration within the recirculated air stream. HEPA filters will need larger plant and ductwork sizes which can cause significant issues for retrofit projects

7.4 Maintenance

Guidance to standard 3.14 states, ‘A mechanical ventilation or air conditioning system should be designed, installed and commissioned to perform in a way that is not be detrimental to the health of the occupants of a building and when necessary should be easily accessible for regular maintenance.’

Updated 2022 guidance 3.14.10 (p.263-264) on commissioning and written information states, ‘Correct use and maintenance of the ventilation systems will assist in delivering the designed ventilation to the dwelling whilst minimising energy use and environmental problems such as noise and thermal discomfort.’ To assist with this, the guidance provides a list of information that should be provided to building occupants, including instructions of how and when maintenance should be carried out.

The Workplace (Health, Safety and Welfare) Regulations 1992 (Regulation 5) states that mechanical ventilation systems should be regularly cleaned, tested and maintained. The requirement of a building ventilation maintenance plan at design stage therefore would help support the regular inspection, cleaning and maintenance of ventilation systems in practice.

7.5 Occupancy levels

Currently air change rates are often building capacity or average room capacity based. Standard 3.14 Non-domestic provides a range of options for determining ventilation supply rates, with an occupancy-based requirement of 8 l/s/p for occupiable rooms with sedentary occupants (in the absence of other requirements such as the removal of moisture). Consideration should be given to occupancy limits based on capability of ventilation systems to supply 10 l/s/person in a room – setting room capacity levels based on this.

Moreover, an increase in the required mechanical ventilation rates from 8 l/s/p to 10 l/s/p is suggested for occupied rooms in Standard 3.14, in addition to the need for greater clarity in the definition of supply rates.

7.6 Air cleaning equipment

Recent research[170] demonstrates that air cleaners incorporated at system level may be beneficial at dealing with elimination of viral transmission, they do not provide fresh air and therefore do not override the need to eliminate recirculation of air. In this context they could be considered as a retrofit option alongside heat recovery.

In-room systems are of limited localised benefit – but on the same basis as above and not as a substitute for elimination of recirculated air.

Research remains inconclusive regarding the use of limited recirculation plus air cleaning as an interim measure. This would need further research and would ultimately depend greatly on the quality of the air cleaning equipment.

[170] SAGE-EMG, (2020), EMG: Potential application of Air Cleaning devices and personal decontamination to manage transmission of COVID-19.

Survey results

1. Background

An online survey was conducted from 17 February – 22 April 2022 by the University of Strathclyde and was distributed and collated with the assistance of Six-Cylinder Research. The questionnaire was distributed to around 1,500 CIBSE members in Scotland and the UAE, and to the CIBSE HVAC Systems Group (330+ members) on LinkedIn and via our own networks, mainly in Scotland. Initial mailings were followed up with reminder group mailings plus specific targeting of individuals from whom we hoped or expected to receive a response. Responses were received from 21 people in total; whilst this was much lower than expected, the responses were thorough, providing an interesting insight into industry practices and perceptions. The findings are outlined below. A complete set of responses is provided in Appendix A.

2. Responses to questionnaire

Q0. Primary role of respondents

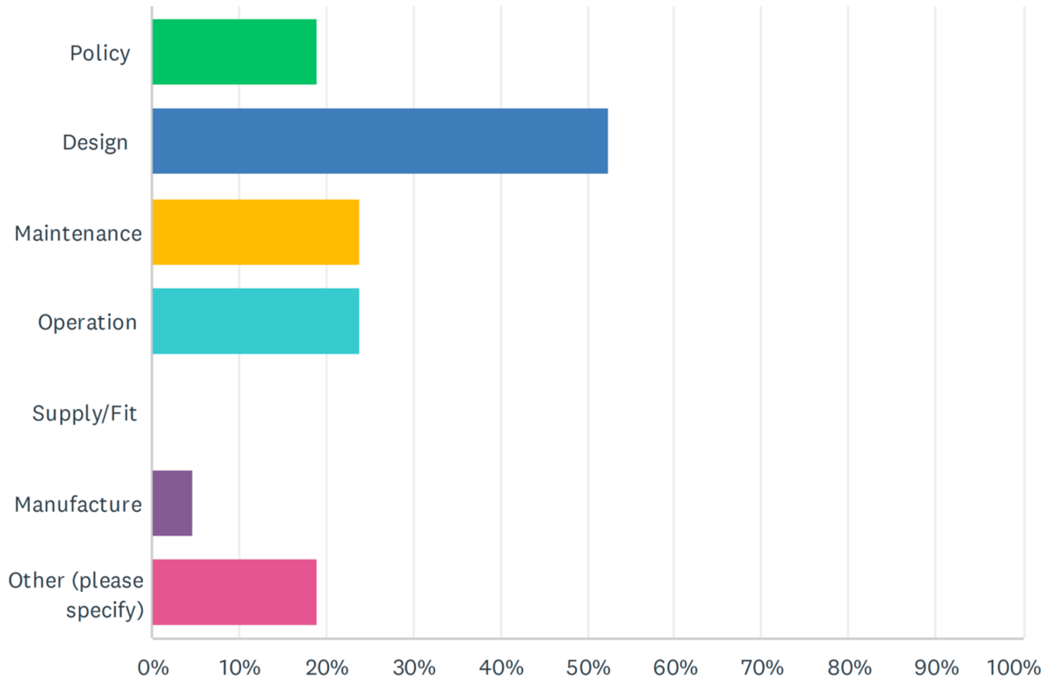

Figure 3. What is your primary role in relation to the consideration of ventilation in buildings
Alt Text: Bar chart showing the primary role of respondents, including design (52%), operation (24%), maintenance (24%), policy (19%), other (19%), and manufacture (5%).

Over 50% of respondents' main role with regards to the ventilation was in design, followed by maintenance (24%) and operation (24%). Other roles included energy (5%), performance standards (5%) and air leakage of buildings (5%), as illustrated in Figure 3.

Q1. What design guides and technical literature on ventilation do you currently refer to and apply when:

CIBSE ventilation guidance was referred to and applied by most respondents (62%) when designing new non-domestic buildings. Other ventilation guidance used by respondents include ASHRAE, Part F, Scottish Building Technical Standards, SHTM03, HTM03, BB101, BS EN 16798-3, TM52, BCO Guides, Passive House, WELL, BREEAM and Net Zero Public Sector Buildings standard.

When maintaining or assessing ventilation provision in existing non-domestic buildings, additional guidance documents were mentioned, including BSRIA, REHVA, BESA SFG20, HSE publications and TM26.

Q2. Do you face challenges regarding accessing appropriate design guides and technical literature when designing ventilation systems for new non-domestic buildings?

One third of respondents stated that they face challenges accessing appropriate guidance when designing ventilation systems for new non-domestic buildings. Some highlighted the complexity of meeting regulations, emphasizing that as a result, the wrong choice is often made. As explained by one respondent,

> ‘While accessing the actual documents is not an issue, much of the guidance during COVID has been unhelpful, conflicting, and generally unworkable. This causes issues and conflicts between various groups. Resolution eventually comes from pragmatism, not necessarily being able to fully align with recommendations and putting in mitigation measures. Pre-pandemic nobody knew what ventilation was, now everyone is an expert and has an opinion. Every stakeholder group has its own blend of guidance. We need definitive guidance, and whether it is retrospective or not’.

Challenges concerning the design of hybrid ventilation systems was mentioned:

> ‘If designing a hybrid, non-standard solution such as mixed mode part mechanical and part natural system then being sure of the performance can rely on manufacturer’s data and sometimes dynamic simulation. These can be contentious when using them to demonstrate compliance with standards.’

> ‘Non-domestic building types e.g. Schools, Hospitals and commercial uses etc. have different Ventilation standards which traditionally Architects have deferred to M&E Building Services Engineers. Recently there have been moves away from Mechanical on to Natural forms of Ventilation or more accurately mixed (HYBRID) systems.’

To resolve the challenges of accessing appropriate guidance, some respondents explained they typically design to the highest standards or agree a minimum standard for air quality and monitor it (10%). One respondent stated that to resolve challenges, they discuss the issue with other like-minded professionals or conduct on-line research.

Q13. Need for new ventilation guidance: What existing guidance to you find most reliable for managing indoor air quality and do you think these are sufficient to reduce transmission of airborne infectious diseases? If not sufficient, what is lacking?

The need for new or additional knowledge and guidance regarding the design, operation or maintenance of ventilation systems as a result of the COVID-19 pandemic is clear, as illustrated in Figure 4. In particular, the need for technical guidance for ventilation system design and the revisitation of standards with infection control in mind were highlighted:

> ‘There has been emergency interim advice on operating ventilation systems in the pandemic, but there is no consensus on what the future of ventilation system design should be. This is now required’
>
> ‘There has been little technical advice, more advice focused on the user’
>
> ‘Guidance is generally not available - standards need to be revisited specifically with infection control in mind (additional to thermal comfort, TVOCS/CO_2)’
>
> ‘Information not readily available’
>
> ‘I don't think existing guidance links enough to airborne pathogen suppression/transmission’
>
> ‘CIBSE guides are generally the best, but these do need reviewed to see if any changes need to be made in light of the pandemic. For example, the generally accepted figure of 8 litres per second per person of fresh air as being adequate for dilution of contaminants needs to be verified again’

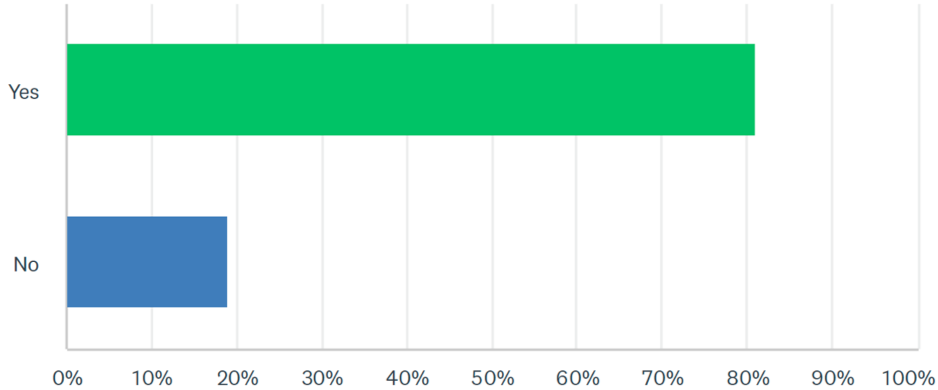

Figure 4. The COVID-19 pandemic has placed a greater emphasis on good ventilation as a means of mitigating airborne transmission. Has this resulted in a need for new or additional knowledge or guidance regarding the design of new ventilation systems and/or the operation and maintenance of existing ventilation systems?

Alt text: Bar chart showing the percentage of respondents who stated ‘Yes’ (81%) and ‘No’ (19%).

Q5. The COVID-19 pandemic has placed a greater emphasis on good ventilation as a means of mitigating airborne transmission.
Has this resulted in a need for new or additional knowledge and guidance regarding the design of new ventilation systems and/or the operation and maintenance of existing ventilation systems?

Some respondents noted the need for improved monitoring of CO_2 or air quality in buildings:

> ‘Guidance is improving however believe there should be more focus on specific targets for air quality relative to not just CO_2 but VOC's, particulate matter and potential ozone & nitrogen dioxide depending on the building type/space activity. There needs to be a better regulation and more scientific approach on the deployment of air quality monitoring/sensing technology’

> ‘I would have liked to have seen CIBSE Covid guidance reinforce the need for colour indicating CO_2 sensors in occupied spaces such as open plan offices and classrooms’

Nevertheless, the usefulness of CIBSE, SAGE, BS EN 16798-3 and/or REHVA guidance was emphasized:

> ‘Guidance documentation provided by CIBSE and REHVA provided a good basis to advise clients on how they should be operating and maintaining their buildings during the pandemic’

> ‘CIBSE covid guidance has provided good advice on design and modifications to existing systems’

> ‘CIBSE has provided valuable information’

> ‘CIBSE guidance has been helpful, however there is still some speculation as to what should be used’

> ‘BS EN 16798-3:2017 provides useful assessment process for ventilation rates and filtration depending on the outdoor air quality. It is not user friendly to understand, but strategy is good’

Q3. Do you face challenges when inspecting and maintaining existing ventilation systems?

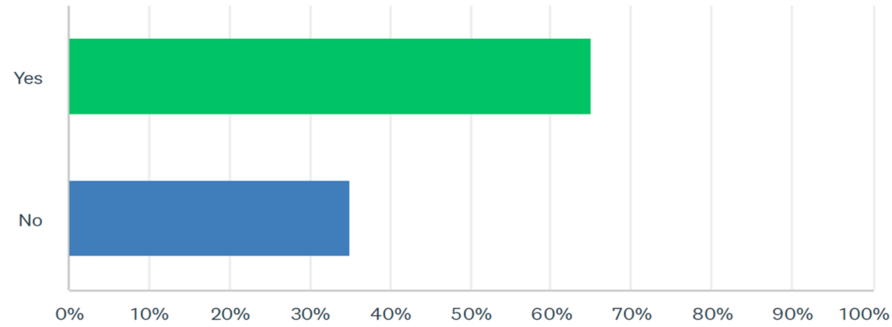

Figure 5. Do you face challenges when inspecting and maintaining existing ventilation systems?
Alt text: Bar chart showing the percentage of respondents who stated ‘Yes’ (65%) and ‘No’ (35%).

65% of respondents stated that they face challenges when inspecting and maintaining existing ventilation systems (Figure 5). Insufficient access was highlighted as a key issue (25%), followed by a lack of accurate ‘as built’ and commissioning information (20%). As one respondent explained,

> ‘Existing ventilation provision within tenant demised spaces which are maintained by the landlord are rarely easy to access, inspect, maintain, clean, check fire dampers etc. and this is further hampered by tenant fit outs paying little or no cognizance to such considerations’.

Other challenges mentioned include, ‘incorrectly commissioned BMS sensors and controls’, poor installation of ventilation systems, the requirement for intrusive surveys (such as commissioning validation) to determine the performance of existing ventilation systems, and poor upkeep of operation and maintenance manuals.

Respondents provided the following suggestions to help resolve these issues:

> ‘Coordination for access is critical in some spaces’

> ‘The key issue is that which still pervades the construction sector, lack of credible or accurate commissioning information. Contracts need to be written around much stronger carrot/stick approach to this’

> ‘Agree minimum air quality standards and monitor the ventilation systems’

Q4. Has the COVID-19 pandemic affected the way you design and/or maintain ventilation systems?

80% of respondents stated that the COVID-19 pandemic affected the way they design and/or maintain ventilation systems. For instance, an increased emphasis on mechanical ventilation solutions was noted, as explained by one respondent,

> ‘Natural ventilation in non-domestic buildings is less likely to be considered viable as good ventilation rates cannot be guaranteed - resulting in more use of mechanical ventilation’.

This is supported by other respondents, who stated,

> 'Reinforced belief that MVHR in winter is the only way to provide safe air flows in buildings, natural ventilation suits summer only'

> 'Natural ventilation was popular but now definitive and positive air changes seen as necessary'

> 'There is a tendency to assume that mechanical is now required to provide ventilation in cold weather where the heat loss or draughts from openable windows is a problem'

Some respondents highlighted the move towards greater ventilation rates and greater attention to monitoring of ventilation performance in practice:

> 'Much greater ventilation rates applied'

> 'We are more likely to insist that higher ventilation rates are required'

> 'More focused checks on air movement within occupied spaces, filtration levels, frequency of change and the like'

> 'Enhanced ppm, additional CO_2 monitoring, additional works to spaces'

> 'Consideration of enhancing fresh air rates for mechanical ventilation systems e.g. aligning with well-being standards such as WELL'

The move away from recirculation of air was also mentioned:

> 'Recirculating systems are now probably out - although there can be misunderstandings over these and what actually constitutes 'recirculating' in a way that is detrimental to infection spread'

> 'No recirculatory systems in schools serving more than one space now'

> 'We currently operate on 100% fresh air supply in accordance with CIBSE/REHVA guidance -this has a substantial impact to our energy burden'

> 'Carefully consider of appropriateness of using recirculating systems'

Q6. Typically, how does the building type and the activities within it affect:
a) the design and operation of the ventilation system in new buildings and
b) the inspection and maintenance of ventilation systems in existing buildings?

Do you feel that this has changed due to the COVID-19 pandemic**?**

Building type and activities are fundamental when considering the design, operation and maintenance of ventilation systems in new buildings. The importance of occupancy levels, susceptibility of occupants, activity level, user groups, pollutant sources, building orientation, building form, room volume, access, energy targets and indoor environmental requirements (temp, RH, pressure differentials) were acknowledged by respondents:

> ‘SAP determines this anyway as that will determine the efficiency of the building and therefore the ventilation system. Orientation, size, people, use, all have a bearing. Given most systems are continual nowadays, they don’t particularly require user involvement’
>
> ‘Building type dictates occupancy that will identify higher risk groups requiring increased levels of ventilation’
>
> ‘Occupancy density, activity type (e.g. sedentary or active), vulnerability of occupants (e.g. healthcare setting or nursing homes)’
>
> ‘Pollutants vary by building type’
> ‘Occupancy & activity levels may impact on the design and operation of ventilation systems. Environmental conditions (temperature, humidity, pressure differentials) for spaces and building types will also impact on the design of ventilation systems. These requirements will also impact on the complexity of the system, zoning and controls’
>
> ‘Building type/activities may impact on the regularity/frequency of maintenance depending on the user group or function of the space. Maintenance and inspection requirements may also be more onerous depending on the space/activity type e.g. healthcare buildings having more stringent inspection and maintenance requirements governed by SHTMs/HTMs, health &safety guidelines dictating level and regularity of inspections & maintenance (e.g. LEV systems) and other industry/sector specific requirements (e.g. licensing requirements for facilities like pharmaceutical production facilities)’

Most respondents (72%) feel that the impact of building type and activities has changed due to the COVID-19 pandemic. Reasons mentioned include: i) an increased focus on inspection and maintenance, ii) a move away from natural ventilation strategies, iii) increased attention to the impact on winter thermal comfort of natural ventilation, iv) more monitoring of CO_2 and airflow rates, v) better awareness of the importance of ventilation and building performance, and vi) an increased focus on air distribution and air cleanliness.

Q7. Clients’ concerns: Do clients who engage ventilation professionals currently have any concerns about the extent and quality of the guidance and advice that is available to them on ventilation and the transmission of airborne viruses such as COVID-19?

Some respondents highlighted concerns from clients regarding the extent and quality of ventilation guidance and the transmission of airborne viruses, such as COVID-19. Concerns were raised regarding the availability of ventilation guidance for a post-pandemic world:

> ‘We are aware of Clients seeking advice on how they should approach designing, maintaining and operating their systems in a post pandemic world. The guidance produced in response to the pandemic was intended to deal with short term measures during the pandemic during reduced building occupancy and operations. The recommendations and measures implemented may have had a potential impact on building energy consumption and associated carbon emissions. Feedback from Clients is that there is a lack of guidance in relation to ventilation that takes account of lessons learned from the pandemic and how that can be applied to ventilation design, operation and maintenance.

Q8. Impact of building users: Do you perceive that owners/operators of buildings know where to source expert knowledge to inspect and advise on the ventilation system in their building?

Respondents were asked if they believe owners/operators of buildings know where to source expert knowledge to inspect and advise on the ventilation system in their building, of which only 35% answered ‘Yes’. Some suggestions were made on how this might be improved, including the establishment of a register of qualified individuals or a non-commercial trade-body for ventilation:

> ‘Perhaps a register of appropriately qualified individuals/companies would be an appropriate route to consider?’

> ‘Start with providing this information to them, perhaps when a local or central authority has to write to owners/operators of buildings to collect property taxes and service charges’

> ‘Public information with good visualisation/graphics can help to make tangible something which you cannot ordinarily see’

> ‘A non-commercial ventilation-specific trade body needs to be established’

> ‘Make sources more widely available and in plain English, for example cut out jargon’

> ‘CIBSE need to be at the forefront here letting people know where the expert knowledge is’

> ‘Reference to CIBSE Member consultants made more well-known’

It is interesting to note that most respondents (85%) do not believe occupants can be relied upon to interact with the building and take specific actions in relation to ventilation to reduce infection risk. Some highlighted the trade-off between natural ventilation and thermal comfort:

> ‘This will mostly apply to natural ventilation. Even when there is a high risk of infection thermal comfort will always take precedence so even if a user is advised to open a window, they will shut it as soon as thermal comfort is compromised. Automatic control is better’

> ‘In naturally ventilated buildings, people won’t open a window if it’s cold. As a firm of M&E Consultants in a naturally ventilated building, our mechanical engineers need to be reminded to open the window, they don't do it as its cold, draughty & noisy when they do’

> ‘Buildings get cold when windows are opened. People don’t open them - but more so than pre-pandemic’

Others noted a lack of knowledge or understanding among occupants to operate ventilation systems effectively:

> ‘Some occupants will be infants and others will not have the cognitive ability to understand. They cannot be relied upon to interact with the building. Others will be visitors, who are unlikely to take specific actions unless there is an emergency’

> ‘Each building is different, and the effectiveness of occupant interaction is very much dependent on occupant familiarity with the space/surroundings they are within, the frequency of time spent in the buildings and the confidence & awareness of individuals to take actions to reduce infection risk. This would require a lot more education of building users on the principles of ventilation and how they may be relevant to the spaces people occupy’

> ‘Lack of knowledge of the systems and measures to take’

> ‘Lack of understanding and knowledge, and mostly apathy’

> ‘May be beyond their pay grade and it is for others to worry about’

> ‘Actions taken in good faith may have a negative outcome. Some occupants may be concerned their actions could harm others if they get it wrong’

While others noted issues with control of ventilation:

> ‘Okay if there is a window to open, but building users in general have no control over building ventilation’

> ‘Individual operation of natural ventilation or temperature control systems is deemed to be selfish and inconsiderate’

> ‘Having some kind of warning or information about air quality is one thing, being able to act upon it is another. There may be a tendency to ignore the warning, at least for a while, if it is inconvenient and too difficult and disruptive to take action’

Q9. Carbon dioxide monitors: Do you believe that CO_2 monitors are useful in identifying poor ventilation and alerting building users when indoor air quality drops to undesirable levels?

Q10. Do you believe that building occupiers/occupants are likely to link higher CO_2 levels with concerns about risk of infection?

Q11. Do you believe that occupants can be relied upon to interact with the building and take specific actions in relation to ventilation to reduce infection risk?

Q12. Beyond CO_2 monitoring, what other methods may be used to demonstrate an effectively ventilated building?

Respondents were asked a series of questions relating to perceived indoor air quality (IAQ) and their views on the role of CO_2 monitors in identifying poor ventilation and whether or not occupants were likely to make the link between CO_2 levels and IAQ and act upon this to improve their indoor environments. They were also asked what other methods beyond CO_2 monitoring may be used to demonstrate an effectively ventilated building. The responses, as summarized in Figure 6, evidence a good level of knowledge and understanding of ventilation assessment methods among respondents, ranging from pollution measurements (VOCs, PM), airflow assessment (tracer gas, pressure differentials, smoke testing, airflow) and ventilation system commissioning (maintenance and records).

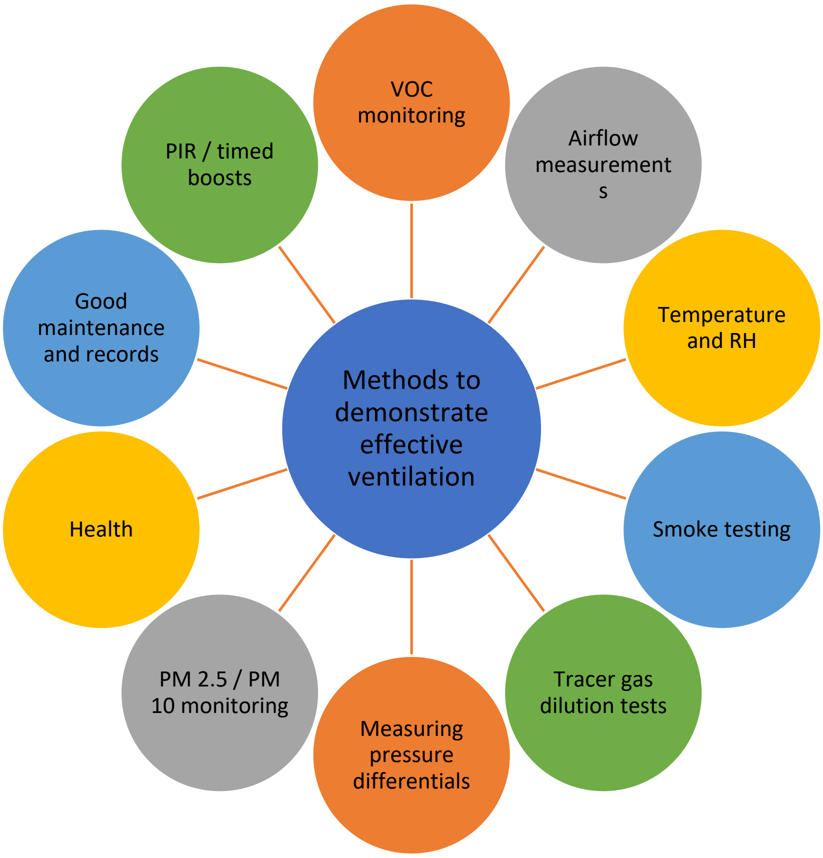

Figure 6. Beyond CO_2 monitoring, what other methods may be used to demonstrate an effectively ventilated building.
Alt text: Radial diagram showing different methods to demonstrate effective ventilation, including VOC monitoring, airflow measurements, temperature and RH, smoke testing, tracer gas dilution tests, measuring pressure differentials, PM2.5 / PM10 monitoring, health, good maintenance and records, and PIR/timed boosts.

Q14. Self-regulation of ventilation systems

Respondents were asked to provide their views and/or experience of the extent to which ventilation systems can be self-monitoring, removing the need for occupant interaction and monitoring. Most agreed, highlighting the benefits of sensor-based ventilation control (PIR, CO_2, temp, RH) for both indoor air quality and energy performance:

> ‘Self-monitoring is desirable, the use of VAV system can help balance energy demand’

> ‘A continual system will be self-monitoring as it is providing ventilation constantly, this can also be aided by any monitor you wish, PIR, humidity sensor, timed boost, etc.’

> ‘We have been designing ventilation systems with variable air flow to suit a building occupancy, internal temperature and occupancy CO_2 for over 20 years, its the most energy effective way to do it’

> ‘Yes, we have presence/absence detection & CO_2 monitoring which are used to manage ventilation. It works and is reasonably reliable’

However, some important caveats were noted concerning the maintenance and validation of systems:

> ‘It is critical where there is a reliance on self-monitoring systems that appropriate maintenance, inspection and validation of systems is regularly undertaken relative to the type of building/space type’

> ‘Yes, this can be effective and desirable, providing systems and sensors are well maintained’

> ‘Automatic systems can work well but the maintenance of the controls and the ventilation equipment needs to be improved to ensure they work as intended. Such systems probably would need a check on a six-monthly basis.’

> ‘Tragically there is evidence the world over that the ventilation systems in use failed. The result was the pandemic. Pressure monitors in negatively and positively pressurised rooms were not accurate, and assumptions of good ventilation and IAQ were made, when clearly this was not the case, as hospitals, educational centres, offices, and other places of work became infection hot spots. Every building has unique characteristics, and every building will need a bespoke solution, based upon permeability’

Moreover, the benefit of occupant control in certain circumstances was also highlighted:

> ‘This type of system doesn’t need user involvement, but we shouldn’t discourage user involvement as we need to educate as to why we need ventilation anyway’

> ‘Self-monitoring systems that are automatically controlled can be desirable however is very much dependent on the building type, activity levels and the buildings complexity. In many instances simpler, more cost-effective user driven controls may be appropriate particularly within a building where the occupants are familiar with and/or well educated in the design & operational intent of the ventilation systems.’

Q15. Changes to existing ventilation systems: Have you encountered situations where physical changes to an existing ventilation system have been needed to improve ventilation in response to concerns over transmission risks?

If yes, was this to a system designed to current building regulations (post-2015) and current industry design guides and operable as designed?

If yes, can you provide a brief summary of the changes made and why they were recommended?

73% of respondents stated they had encountered situations where physical changes to an existing ventilation system had been needed in response to concerns over transmission risks. Changes required included: i) disabling air recirculation, ii) adding direct supply to extract only systems, iii) increasing air throughput, iv) installation of CO_2 monitors, v) adding fans to unventilated spaces, vi) refurbishment of AHUs, vii) improving filtration, and viii) installation of air cleaning devices. As explained by respondents:

> ‘Some spaces had extract ventilation only, using make up air from adjacent spaces, so we have redesigned and added direct supply to the spaces.’

> ‘Buildings with recirculation air handling units have had the recirc[ulation] ability removed to avoid transfer. Thermal wheels have been turned off to avoid cross contamination and Fan Coil Units (FCU’s) that recirculate air through ceiling void have been changed to ducted.’

> ‘It was a system that had a recirculating facility in a fresh air system, it wasn’t really needed as there was a thermal wheel on the system in any case, we had to disable it to comply with the COVID guidance issued in the summer 2020.’

> ‘System designed pre 2015 and in line with standards current at the time. Looked to increase air throughput by a variety of means bearing in mind constraints imposed by building fabric.’

> ‘Wall/window fans added to unventilated spaces, AHUs refurbished with new efficient quiet fans, plate heat recovery, new heater batteries and CO_2 monitor controls. Designed in line with current practice.’

‘Portable or plug-n-play air cleaning devices to enhance the current ventilation provision. These were recommended for ‘no’ or ‘below’ ventilation standard situations.’

‘System was a sealed building and had central supply with recirculation to up to 10 classrooms. Required setting to full fresh air, increase in supply temp to heating coil in main AHU and improved filtration at central AHU.’

‘Existing system in schools - e.g. where vents in doors and walls allow air to transfer between classrooms.’

Survey conclusions

1. Guidance used by industry

The results suggest a wide range of design guides and technical literature on ventilation are being used by industry in practice, from various sources. Whilst the usefulness of CIBSE, SAGE, BS EN 16798-3 and/or REHVA guidance was highlighted by respondents, there were calls for the need to revisit and update building ventilation standards to support consideration of infection control during the design stage, based on lessons learned from the COVID-19 pandemic. Specifically, 81% of respondents stated the need for new or additional knowledge or guidance regarding the design of new ventilation systems and/or the operation and maintenance of existing systems.

2. Inspecting and maintaining ventilation systems

Most respondents stated that they face challenges when inspecting and maintaining existing ventilation systems. The results indicate that more work is needed to address challenges of insufficient access and lack of accurate commissioning information to ensure regular inspection and maintenance of ventilation systems in practice.

3. Impact of building users

Most respondents do not believe that owners/operators of buildings know where to source expert knowledge to inspect and advise on the ventilation system in their building. Moreover, 85% of respondents do not believe occupants can be relied upon to interact with the building and take specific actions in relation to ventilation to reduce infection risk. The results suggest more work is needed to improve public awareness and understanding of workplace ventilation.

4. Sensor-based monitoring and self-regulation of ventilation

As sensors and ventilation systems become more sophisticated, the need for occupant interaction becomes less evident. The benefits of self-monitoring of ventilation systems were emphasized by respondents, provided that the systems are regularly inspected and well-maintained. The results indicate that whilst guidance is important, there is also a need for more attention to the incorporation of performance-based ventilation standards, and the regulation and maintenance of sensor-based ventilation control systems, to achieve energy-efficient control of indoor air quality.

Overall conclusions and issues to consider

1. Main conclusions

The study aimed to establish what ventilation guidance was being used by industry in practice when designing new or maintaining existing non-domestic buildings. The results of the industry survey suggest a wide range of ventilation design guides and technical literature are being used, from various sources including CIBSE, BB101, ASHRAE, HTM, BSRIA and BS 16798-3.

It is widely recognized that the higher the rate of ventilation indoors, the lower the risk of airborne transmission of covid-19, in particular, for long range (>2m) transmission. As such, the adequate ventilation of a building space should be regarded as the primary mitigating measure against the spread of airborne diseases. Whilst ventilation standards in general may be acceptable, a principal issue is whether these are being met a) in use and b) maintained over time. The general feeling has been that, if buildings were meeting their intended ventilation standards, then Covid-19 transmission risks were minimised. However, in practice there was virtually no reliable data on whether or not this was the case.

Respondents highlighted the requirement for sensor-based monitoring. This is reflected in changes to the Building Regulations in England through changes to Part F (Ventilation) in domestic and non-domestic buildings. There is growing awareness of the benefits of performance monitoring and the need to ensure compliance with legislation in practice. CO_2 monitoring is recommended as a cost-effective strategy to help identify spaces with poor ventilation and/or high occupancy, to inform decisions and to support the active management of ventilation in a space.

The second issue is regarding the current level of requirements to ensure that compliance with regulations is maintained over time. For instance, some changes/retrofit that may not trigger a new warrant may adversely affect the ventilation provision. The need for a building ‘MOT’ is suggested, to establish the idea that buildings, like vehicles, need to meet certain standards, which could go some way towards closing the performance gap. This requirement exists for Legionnaires Disease[171], for example, to ensure regular assessment of performance under HSE legislation. Respondents highlighted challenges when inspecting and maintaining existing ventilation systems. The lack of accurate commissioning information and performance data is a key issue, resulting in a lack of ability to monitor and verify compliance over time.

This raises the question as to whether there is a need for a requirement in the regulations regarding the provision of a maintenance plan, to go some way to ensure regular inspection, cleaning and maintenance of ventilation systems. Whilst Standard 3.14.10 requires key information on the ventilation system to be provided on

[171] HSE, Legionnaires disease: Reviewing what you do

completion, including instructions of how and when maintenance should be carried out, a maintenance plan would help determine how this will be achieved in practice. This could also be related to a possible requirement for a communications/labelling strategy, especially for naturally ventilated spaces to make clear what the ventilation system is and how it is operated. This could adopt the same approach as the domestic energy ‘quick start guide’[172].

2. Summary of suggestions for updates of guidance

- Recommend phasing out of recirculation of air and replacement over time with heat exchanger systems which prohibit the mixing of intake and extract air to avoid airborne pathogen transmission

- An increase in the required mechanical ventilation supply rate from 8 l/s/p to 10 l/s/p is suggested for occupied rooms, in addition to the need for greater clarity in the definition of supply rates and consideration of occupancy limits, based on the capacity of ventilation systems.

- The introduction of requirements for CO_2 monitoring in multi-occupancy high risk spaces to help identify airborne transmission risk related to poor ventilation and/or high occupancy, to prompt and inform behaviour change. This should be provided with clear guidance and appropriate information specifically tailored to the user group, to enable monitors to be used effectively.

- The consideration of infectious disease transmission in building ventilation regulations through the provision of explicit advice on the risk of far-field (>2m) aerosol airborne transmission. The importance of ventilation in mitigating this risk should be highlighted (e.g. in Section 3.14.1).

- The requirement for a building ventilation maintenance plan, to support the regular inspection, cleaning and maintenance of ventilation systems in practice.

- Provision of a communications / labelling strategy for building ventilation systems (like the domestic energy ‘quick start guides’) to provide a clear, simple explanation to building users on what the ventilation strategy is, and how to use it. Whilst Standard 3.14.10 requires key information on the ventilation system to be provided on completion, the provision of short, visual instructions (for instance, next to ventilation systems or controls) would help ensure accessibility to all users and support understanding and effective operation of ventilation systems in practice.

- The identification of ventilation performance standards and enhanced measures to ensure that compliance is achieved in use and maintained over time. The introduction of a performance-based framework for assessing

[172] How your Low Carbon Home Works

ventilation performance in non-domestic buildings (e.g. through an annual building ‘health-check’ / ‘MOT’, or for new retrofit works), would help ensure regular assessment of performance and verification of compliance over time.

Appendix A: Survey Questions

Survey on Health-centred Ventilation Design
by University of Strathclyde for Scottish Government Building Standards Division

Q1. What design guides and technical literature on ventilation do you currently refer to and apply when:
a) designing new non-domestic buildings and
b) maintaining or assessing provision in existing non-domestic buildings?

Q2. Do you face challenges regarding accessing appropriate design guides and technical literature when designing ventilation systems for new non-domestic buildings?
Yes/No
If yes, please elaborate.
If yes, how do you currently resolve these challenges?

Q3. Do you face challenges when inspecting and maintaining existing ventilation systems.
Yes/No
If yes, please elaborate.
If yes, do you have any suggestions that would help resolve these issues?

Q4. Has the COVID-19 pandemic affected the way you
a) design and / or
b) maintain ventilation systems?
If so, how?

Q5. The COVID- 19 pandemic has placed a greater emphasis on good ventilation as a means of mitigating airborne transmission.

Has this resulted in a need for new or additional knowledge and guidance regarding the design of new ventilation systems and/or the operation and maintenance of existing ventilation systems?
Yes/No
If yes, has this been readily available?
Please provide examples if possible.

Q6. Typically, how does the building type and the activities within it affect:
a) the design and operation of the ventilation system in new buildings and
b) the inspection and maintenance of ventilation systems in existing buildings?

Q7. Do you feel that this has changed due to the COVID-19 pandemic?
Yes/No
If yes, how?

Q8. Do clients who engage ventilation professionals currently have any concerns about the extent and quality of the guidance and advice that is available to them on ventilation and the transmission of airborne viruses such as COVID-19?

Q9. Do you perceive that owners/operators of buildings know where to source expert knowledge to inspect and advise on the ventilation system in their building?
Yes/No
Do you have any suggestions on how this might be improved?

Q10. Do you believe that CO_2 monitors are useful in identifying poor ventilation and alerting building users when indoor air quality drops to undesirable levels?
Yes/No
If not, why not?

Q11. Do you believe that building occupiers/occupants are likely to link higher CO_2 levels with concerns about risk of infection?
Yes/No/ Don't know

Q12. Do you believe that occupants can be relied upon to interact with the building and take specific actions in relation to ventilation to reduce infection risk?
Yes/No
If no, why not?

Q13. Beyond CO_2 monitoring, what other methods may be used to demonstrate an effectively ventilated building?

Q14. What existing guidance do you find most reliable for managing indoor air quality and do you think this guidance is sufficient to reduce transmission of airborne infectious diseases?
If not sufficient what is lacking?

Q15. Please provide your views and/ or experience of the extent to which ventilation systems can be self-monitoring - removing the need for occupant interaction and monitoring, e.g. with ventilation rates based on a suitable proxy and the activity levels within the building, and whether you believe this is desirable.

Q16. Have you encountered situations where physical changes to an existing ventilation system have been needed to improve ventilation in response to concerns over transmission risks?
Yes/ No
If yes, was this to a system designed to current building regulations (post-2015) and current industry design guides and operable as designed?
If yes, can you provide a brief summary of the changes made and why they were recommended?

Please indicate whether or not you are willing to have a follow up conversation with us regarding your views.

Yes / No

Scottish Government
Riaghaltas na h-Alba

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