Application of CO2 monitoring methods for post-occupancy evaluation of ventilation effectiveness to mitigate airborne disease transmission at events

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Abstract

The Covid-19 pandemic led to the widespread closure of events. Between April and July 2021, the AIRBODS consortium carried out an Environmental Study as part of the UK government Events Research Programme to assess environmental risk factors for Covid transmission at events. A detailed post-occupancy evaluation of Indoor Air Quality was employed to assess the effectiveness of ventilation systems in operation. CO_2 monitors were installed at high spatial resolution throughout the occupied spaces of ten venues around the UK. Data from 55 events was obtained and average and maximum CO_2 values were used to classify the spaces in relation to a proposed Air Quality Index. Indoor spaces where ventilation could be improved were rapidly identified and mitigations were tested to reduce the risk of airborne transmission of respiratory diseases.

Keywords

Covid-19; Air Quality; Post-Occupancy; Monitoring; Infection Control

1.0 Introduction

1.1 Background and Context

As the Covid pandemic hit the UK in early 2020, the culture, sports and music sectors, as well as other businesses such as wedding venues and nightclubs, were profoundly restricted in their operations for over a year in 2020-2021. The UK government Events Research Programme (ERP), to-date the largest programme of its kind worldwide, aimed to explore how large-scale events could return more safely by conducting pilot events across different sectors, whilst developing an evidence base to understand factors in COVID transmission, and how to minimise these. The research teams that participated in the programme developed publicly-available evidence relating to transmission risks at several events, contributing to the development of Government policy. Results of Phase I of the study (1), conducted between mid-April to mid-June 2021, contributed to the decision to allow events to be reopened for further studies in Phases II-III of the ERP, and finally to return to normal operations on 19th July 2021.

AIRBODS (Airborne Infection Reduction through Building Operation and Design for SARS-CoV-2) is a UKRI-funded consortium led by Prof Malcolm Cook, which was formed with the primary aim to “deliver guidance on the ventilation operation and future design of non-domestic buildings to quantify the risk of, and reduce the transmission of SARS-CoV-2 in buildings” (2). The AIRBODS team were asked to lead the ERP Environmental Study, primarily to evaluate ventilation and the associated risks of airborne transmission. The Environmental study examined ten indoor and hybrid indoor/outdoor venues of different types, sizes and layouts, monitoring a total of 55 events in these venues. The study set out air quality monitoring, as measured by CO_2, Temperature and Relative Humidity, in 189 distinct spaces and related the air quality also to crowd densities and behaviours in collaboration with the Behavioural Study of the ERP[1]. The study protocols and headline results, and a guidance note on the results of the Environmental and Behavioural Studies of all three Phases were published between April and November 2021 (3).

Whilst the Events Research Programme was the first pilot study of mass-gathering events during the COVID-19 pandemic in the UK, there are examples of other international studies of events. In Borriana, Spain, several mass-gathering events were monitored via a survey of attendee antibodies against SARS-CoV-2 and a

[1] A separate transmission study, which was limited to examining the risk of transmission associated with attending a subset of the events in the third phase of the ERP, found that of those events, outdoor unstructured ERP events, specifically festivals, posed the highest increased transmission risk. The transmission study had data on a few indoor events at theatres that were run at reduced capacity, and found that these posed very low additional risk of transmission to attendees. However, the study had limited data on most of the more crowded indoor events monitored by our study, some of which posed higher risks with regards to levels of ventilation and number of people present in these spaces.

questionnaire survey (4), suggesting that such events could increase COVID-19 transmission and lead to local outbreaks of the disease. A simulated (staged) event also took place in August 2020 in Leipzig, Germany (5). A large, popular multi-use arena, hosted three controlled experimental events to examine the number of close contacts between attendees and CFD simulations examined the effect of different ventilation rates on SARS-CoV-2 transmission. The study found that as long as adequate ventilation was provided, indoor mass gathering events present a low risk of the epidemic spread of COVID-19. Both studies provided valuable evidence at an early stage of the COVID-19 pandemic, however, they either did not measure indoor air quality or were not “real”, but staged events. The present study and wider work surrounding the Event Research Programme addresses these issues by monitoring indoor air quality in real, live, mass-participation events during the pandemic and testing mitigations during event operations.

1.2 Airborne Transmission of Infectious Diseases

There have been numerous calls for the recognition that SARS-CoV-2 can transmit via airborne routes, following several highly publicised super-spreading outbreaks of Covid-19 in 2020. As evidence of airborne transmission of SARS-CoV-2 accumulated and the virus was shown to remain stable and survive in air samples (6, 7), a letter led by Morawska and a group of 239 leading scientists called on the WHO to revisit their assessment of airborne transmission. Aerosol transmission is now widely accepted as a viable and probably dominant mechanism of transmission of Covid. Due to their small size and mass, aerosols smaller than 50 μm can stay suspended in indoor air for a number of hours, moving long distances indoors, before evaporating or dispersing (8). Airborne transmission probably occurs mainly through inhaling virus-laden aerosols smaller than 5 μm (9), which may lead to their deposition in the lungs. Airborne transmission occurring through the spread of virus laden aerosols has been demonstrated over the years for other respiratory viruses such as SARS (10), MERS (11) and rhinovirus and parainfluenza (12) before the start of the COVID-19 pandemic. A number of COVID-19 infection outbreaks in indoor spaces such as restaurants (13), apartment buildings (14) and others (15) were identified, which could only be explained by airborne transmission. The initial dose of the virus was found to be a factor in the high mortality of the second and third waves of the 1918-1919 Spanish flu epidemic (16), indicating that the initial infectious dose may also worsen the severity of the illness with COVID-19. Reducing the initial dose, where possible, may lead to better outcomes following infection and is a desirable target, especially in those people who are already more vulnerable to the virus due to age, underlying health factors or socio-economic background. Providing sufficient fresh air through ventilation strategies has thus been identified to significantly reduce the risk of airborne transmission in indoor spaces for SARS-CoV-2 (17) and it is unquestionably an important strategy in infection control.

1.3 CO_2 as a proxy for exhaled breath

The Scientific Advisory Group for Emergencies-Environmental Modelling Group (SAGE-EMG) and the Independent Scientific Pandemic Insights Group on Behaviours (SPI-B) have recommended enhanced ventilation and CO_2 monitoring during the pandemic and made a series of recommendations for target CO_2 values (18, 19). Although not a direct quantitative indicator of risk, CO_2 is in exhaled breath and is an effective proxy for occupancy relative to the levels of ventilation, which links to the risk of long-range aerosol transmission in indoor spaces (20). Exhaled breath accumulates in space due to insufficient ventilation for the space, or high occupancy for the space (whether temporarily or consistently), or sometimes both factors. Thus, CO_2 concentrations give an indication of the fraction of the indoor air that has been exhaled by its occupants. Concentrations increase with the number of occupants, their respiratory activity, and their body mass, and the rate of removal is solely dependent upon the ventilation rate. Although Temperatures and Relative Humidity data are of interest to building service engineers, with respect to the risk of transmission of Covid, and for simplicity and speed of analysis, only CO_2 levels are discussed in this paper.

2.0 Main content

The Environmental Study examined the risk of airborne transmission indoors based on indicators of indoor air quality. CO_2, an indicator of potentially poor ventilation, was monitored as a proxy for exhaled breath and exhaled aerosols that potentially contain virus particles, at numerous locations throughout the venues of the study. Also measured were: Temperature and Relative Humidity, both as additional indicators of air quality and ventilation, and for a selection of indoor venues, air movement and ventilation of the venues. These data will be examined in the future by the AIRBODS project, for the purpose of proposing specific improvements to the venues and to advance the field of ventilation science and design of public spaces through further modelling, and will not be discussed further here. The methods of monitoring and classifying the data are discussed below

2.1 Space Classification

First investigation of the venues found that ventilation strategies and space utilisation varied widely across the venues, and the majority of venues were observed to have a mixture of different spaces with different uses within them. For example, an outdoor

stadium will typically have indoor concession stands, bars and toilets. Large venues have dedicated ingress and egress zones and these sometimes also serve as unstructured standing-only food and drink areas, or have shops and other concession stands in them, so that some attendees may end up spending substantial time in various areas of the venue even though these are not officially designated as "spectator" zones. These types of spaces were often found to become "pinch point" areas of high concentration and restricted flows of both people and air, posing a higher risk for disease transmission from close contacts, droplet inhalation and/or poor air quality with risk of aerosol transmission.
Thus, all venues were divided into various spaces based on the space classification system described in *Table 1* below, which classifies spaces based on ventilation strategy, and usage by attendees, where "structured" activities are more likely to involve allocated seating or event management (eg sports event with allocated seating, or theatre event), and "unstructured" events allow attendees to spend time throughout the venue as they prefer (eg, race or music festival). In total, 179 individual spaces were monitored across 10 sports, music and theatres venues, over 55 events, as presented in *Table 2* below.

(a) Ventilation classification	(b) Use classification
• Outdoors • Outdoors, sheltered • Indoors, naturally ventilated, high ventilation • Indoors, naturally ventilated, low ventilation • Indoors, mechanically ventilated	• Arrival and Departure Areas • Dwelling Areas • Concessions / Bars-Standing • Bars / Restaurant-Seated • Main Activity Areas (Structured) • Main Activity Areas (Unstructured) • Private Boxes / Meeting Rooms • Toilets, Corridors, Lifts,Stairwells (small, enclosed, short occupancy)

Table 1 Space Classification Criteria: (a) ventilation classification (b) use classification

Events	Venue	Dates of events (phase and date range)	No. of events	No. of spaces
World Snooker Championships	Crucible Theatre, Sheffield	Phase I 17/4/21 – 02/05/21	11	16
Emirates FA Cup Semi-Final	Wembley stadium, London	Phase I 18/04/21	1	16
Carabao Cup Final	Wembley stadium, London	Phase I 25/04/21	1	20
Good Business Festival	ACC Exhibition Centre, Liverpool	Phase I 28/04/21	1	2
Circus Presents 'The First Dance'	Circus Nightclub (warehouse club), Liverpool	Phase I 30/4/21 - 01/05/21	2	4
BRIT Awards	The O2, London	Phase I 11/05/21	1	24
Emirates FA cup Final	Wembley stadium, London	Phase I 15/05/21	1	26
EUROs 2020	Wembley Stadium, London	Phases II & III 13/06/21 – 11/07/21	8	26 - 31
Royal Ascot Races	Royal Ascot Racecourse, Ascot	Phase II 15/06/21 – 19/06/21	5	31
Download Festival Pilot	Castle Donington, Donington Park	Phase II 18/06/21 – 20/06/21	3	3
Opera at The Grange Festival, Hampshire	The Grange, Northington	Phase III 02/07/21 – 18/07/21	12	31
A Little Night Music	Leeds Playhouse Theatre and Opera North, Leeds	Phase III 14/07/21 - 17/07/21	6	9
Comedy Nights	Piccadilly Theatre	Phase III 17/07/21 – 23/07/21	3	28

Table 2 Events and Venues monitored by the Environmental Study during the three Phases of the UK Government's Events Research Programme

2.2 Monitoring Methods

CO_2 sensors, logging temperature and relative humidity, as well as CO_2, were installed in all identified indoor spaces in the venues and some sheltered outdoor spaces. The sensors used were Duomo Explora, wireless, battery-powered loggers that monitor concentrations of CO_2, temperature, and relative humidity. At a sampling interval of 2 minutes, the data logged was then encrypted and securely transmitted wirelessly via LoRaWAN (Long Range Wide Area Network) to the cloud. The CO_2 sensors in the loggers were non-dispersive infrared (NDIR), capable of measuring within a range of 400–5000 ppm at an accuracy of ±30ppm (±3% of reading). These CO_2 sensors have a built-in auto-calibration algorithm that tracks minimum CO_2 values over eight-day intervals and compares them to a zero-point mark of 400 ppm. To ensure auto-calibration was reliable and there were no CO_2 data drifts, sensor baseline values were checked at times when venues were unoccupied, at night, when CO_2 readings are expected to match outdoor levels. The minimum CO_2 values during events monitored were also checked to check for any unreliable data. The logged data was accessed and downloaded from an online database and also viewed in real-time on a dashboard. In total, 385 sensors were used in the study. Sensors were installed as appropriate to each venue and in consideration of the geometry of the venue spaces, practical restrictions on wall fittings and the need to place them discreetly, but generally, several loggers were placed in each space on walls at a height of 2.3 m, away from vents, doors or windows, and/or under auditoria seats, as relevant. The number of devices depended on the size of the room but as a general rule 1-2 sensors were used in every space if researchers were not present, to provide redundancy, and depending on room size either 4 sensors were placed or up to 50 in an auditorium space. An example of this is shown in *Figure 1* below, which depicts one typical installation at the Ascot Racecourse. The individual spaces monitored in this section of the venue, a restaurant and three private boxes, are highlighted in yellow and the sensors installed are marked on the drawing with red circles.

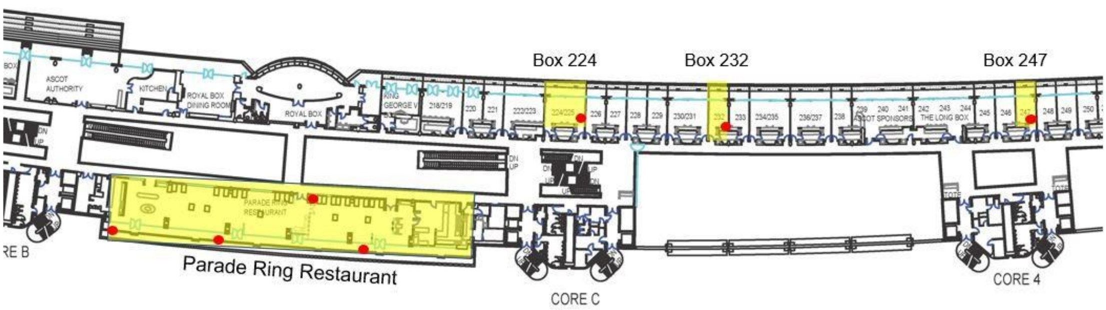


Figure 1 - Installation of CO_2 sensors at Ascot racecourse. Zones monitored marked in yellow, sensors marked in red.

2.3 Air Quality Classification

Although the risk of infection transmission in poorly ventilated environments has now been well-argued, it is understandably difficult to establish a ventilation flow rate that can be considered “safe”. The risk of disease transmission is highly variable depending on the infectiousness of the patient, their aerosol-generating ability, aerosol generation activity, and the susceptibility of people sharing the space. However, it seems from past outbreaks and modelling work (21) that it is the very poorly ventilated spaces that are at greater risk, and those spaces that are ventilated to current building regulation standards pose a much lower risk. Many countries are now specifying CO_2 values of 800 - 1000ppm (equivalent to 10-12l/s/person) as an appropriate target for ventilation rates. In the UK, current guidance from SAGE-EMG recommends that spaces with CO_2 levels consistently above 1500ppm should be improved (18).

Approved Document F of the building regulations and CIBSE Guide A provides a range of suggested airflows for various indoor space types that typically range from 5 to 10 l/s/person. These values originate from studies on occupant comfort to “stuffiness” (the general release of bioeffluents from occupants), where it has been determined that a high level of comfort in occupied spaces can be delivered with 8l/s/person and therefore 10l/s/p has often been chosen as a reasonable figure to provide occupant comfort, whilst balancing the energy requirements to deliver outside air.

Recently BSEN16798, an international standard on energy-efficient delivery of occupant comfort provided 4 levels of IAQ level of expectation based on occupancy, as presented in *Table 3* below. The categories are related to the level of expectations the occupants may have. A normal level for an office space would be “Medium”. A higher level may be selected for occupants with special needs (children, elderly, persons with disabilities, etc.). A lower level will not provide any health risk but may decrease comfort and satisfaction with the space. Interestingly this standard is also most likely referring to the psychological discomfort of exposure to general bioeffluents from occupants, rather than the emission of pathogens from occupants, and neither standard considers the risk posed by poor ventilation. of exposure to indoor air pollutants emitted from building materials and furnishings, or to the increased risk of exposure to pathogens such as viruses and bacteria.

Category	Expectation of indoor environmental quality	CO_2 above outdoors (ppm) assuming CO_2 emission of 20 l/hr/person	Total Indoor CO_2 values (ppm)
I	High	550	950
II	Medium	800	1200
III	Moderate	1350	1750
IV	Low	1350	1750

Table 3 Recommended targets for CO_2 levels for Indoor Air Quality, adapted from *BSEN16798*

There is no direct correlation between CO_2 concentrations and virus concentrations in indoor air due to the complex relationship between CO_2 and ventilation and that between CO_2 in exhaled breath and virus concentration in exhaled breath. For the purpose of the ERP Environmental Study, it was assumed that all CO_2 present indoors above a standard baseline outdoor value of 400ppm, has been exhaled by people in the space. The exact number of virus particles in the air is unknown and depends on whether there are infected people present at all and, if so, how many infected people are present in the space, their viral load (which can vary by orders of magnitude between people), and their breathing rate and its relation to their activities.

Following from existing standards as outlined above and from SAGE-EMG recommendations, *Table 4* below presents the indoor Air Quality Bands from A to G that formed the basis for the analysis in this study, where air quality is concerned only with reducing risk of infections as much as practicable. Those indoor spaces with CO_2 levels falling in the bands F and G, both of which are above 1500 ppm, are a priority for improvement. The air quality bands allow a detailed comparison of the performance of different spaces, allow for setting of more detailed future targets for air quality for different types of spaces based on their occupancy, use, intended operations and possible concerns relating to infection control.

For each space, at each event, average and maximum CO_2 values during each event were determined from the air quality monitors and input into a database. The event duration was defined as the time in which the venue was occupied by attendees. In almost all cases the attendees spent time flexibly moving from one space to another, except in some performance venues where the event was more structured; therefore, no event spaces were ever “unoccupied” during an event.

The Air Quality database was then used to examine the ventilation performance and effectiveness of all 179 individual spaces, aggregated across all events monitored by the Environmental Study. For each space, an average performance was determined based on the average (mean) CO_2 value for all events monitored in this space, where the CO_2 values were only considered during occupied times in the duration of an event, with the understanding that this represents performance under various typical occupancy scenarios. For each space, the maximum CO_2 value recorded at all events was also identified, usually occurring during times of maximum occupancy. The spaces were then classified into Average and Maximum AQ bands following *Table 4* below. This database has been expanded to include details of event management, occupancy and of crowd densities determined by the Behavioural Study of the ERP in collaboration with the Behavioural Study research team and will form the basis for future studies.

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

Table 4 Classification for Air Quality bands from A to G used for the Events Research Programme

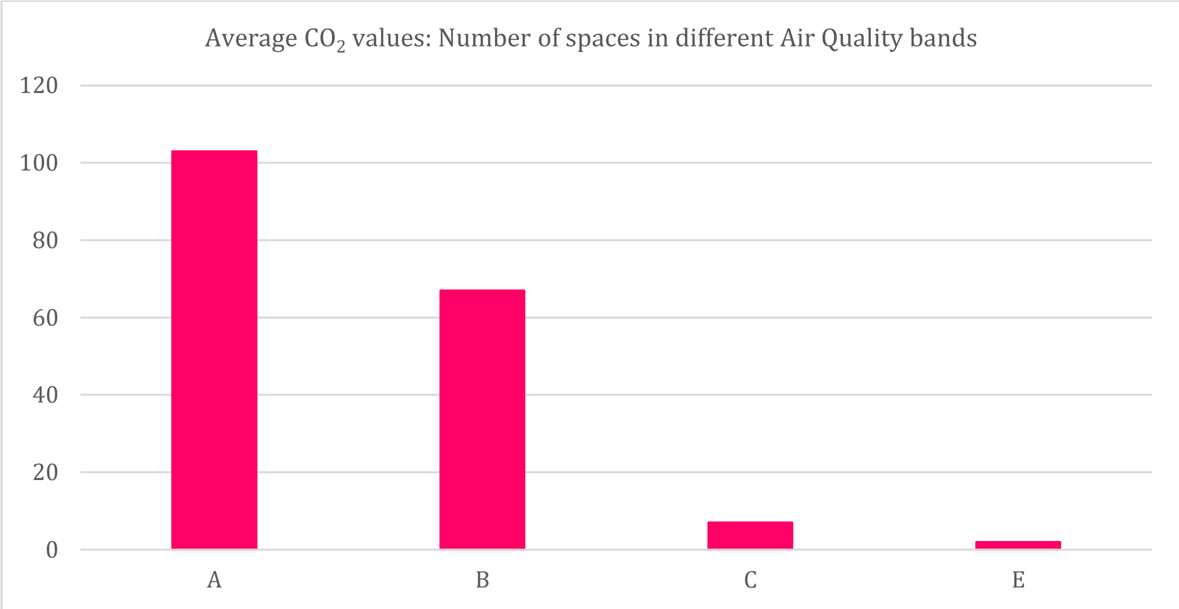
2.4 Results

2.4.1 Overall air quality across the board: ERP Phase I

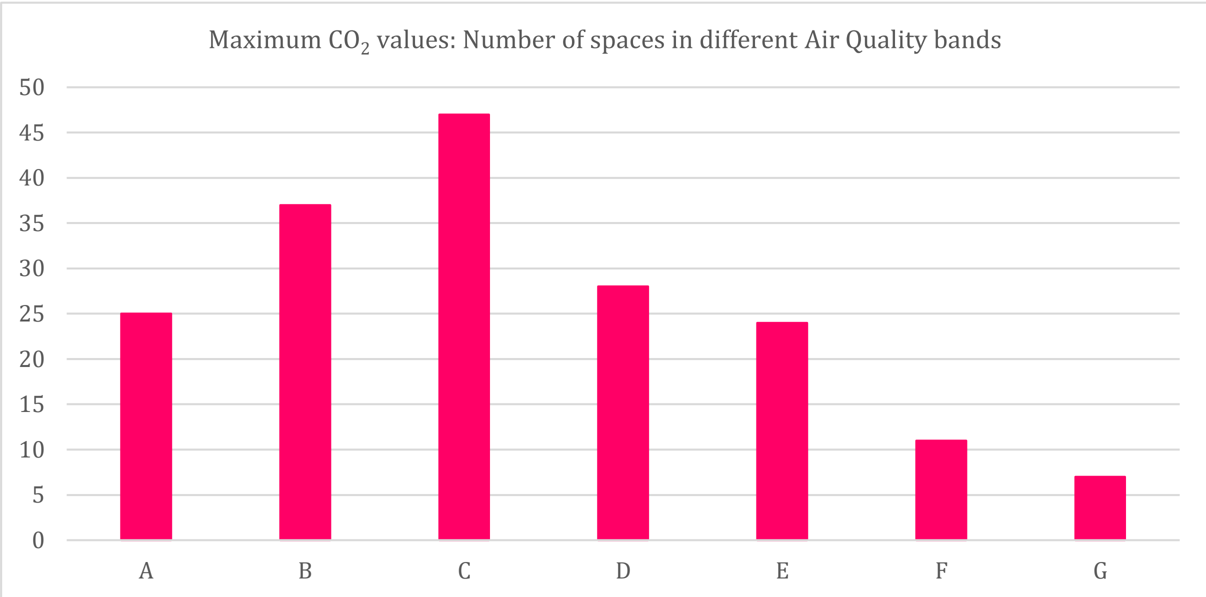
Mechanically-ventilated systems were identified at the O2 arena, at the ACC Liverpool, at the Grange Opera theatre, the Crucible Theatre, Piccadilly Theatre and Leeds Playhouse, all of which had installed or recently improved modern mechanical ventilation systems in the spectator or social areas. Mechanical ventilation was also in use at some restaurants at the Ascot racecourse, and with some exceptions, in most of the indoor spaces and restaurants at Wembley stadium. It should be noted that although all venues were allowed to operate at full capacity, this was not achieved during the ERP. Some naturally ventilated systems were also identified, at Ascot, Wembley Stadium, the Circus nightclub and Download festival.

For mitigation against COVID-19, indoor spaces where aerosol generating activities occur (such as singing, aerobic activity or dancing) are encouraged to adopt a ventilation strategy capable of maintaining CO_2 values at or below 800 ppm, or, in the ERP Air Quality bands A or B. The study finds that across the board, in Phases I, II and III of the ERP, average air quality was in bands A or B in 170 out of 179 monitored spaces, at almost all venues, as presented in *Figure 2* below. Maximum CO_2 values varied more than this: 10% of spaces were in air quality in bands F to G at peak times and at peak occupancies, the highest of which was found at a very large venue at around 75% occupancy. Time series of the data for these spaces revealed that these peak values were sometimes observed to persist for more than an hour or two, as will be discussed in the next sections. In some cases, high CO_2 values were observed where the ventilation strategy was not well developed or sometimes where ventilation systems were found to be faulty or poorly maintained.

Indoors, across all venues, the number of occupants correlated very closely with CO_2 levels in the air. In numerous settings, CO_2 levels were found to follow patterns relating to event management. For example, they rose in standing concession areas during intervals, arrival times and departure times, and in seated restaurants during occupied times. It was observed that whenever high CO_2 values that were concerning were observed, these were found mainly in relation to high occupancy and high crowd density that may have been outside of the original specification of the mechanical ventilation systems, even though these were most probably designed to deliver good ventilation performance on average for the spaces. These results indicate that, in large spaces serving a large number of people, there may need to be thought given to peak-time operations and the ability to provide higher ventilation rates in certain scenarios.



2(a)



2(b)

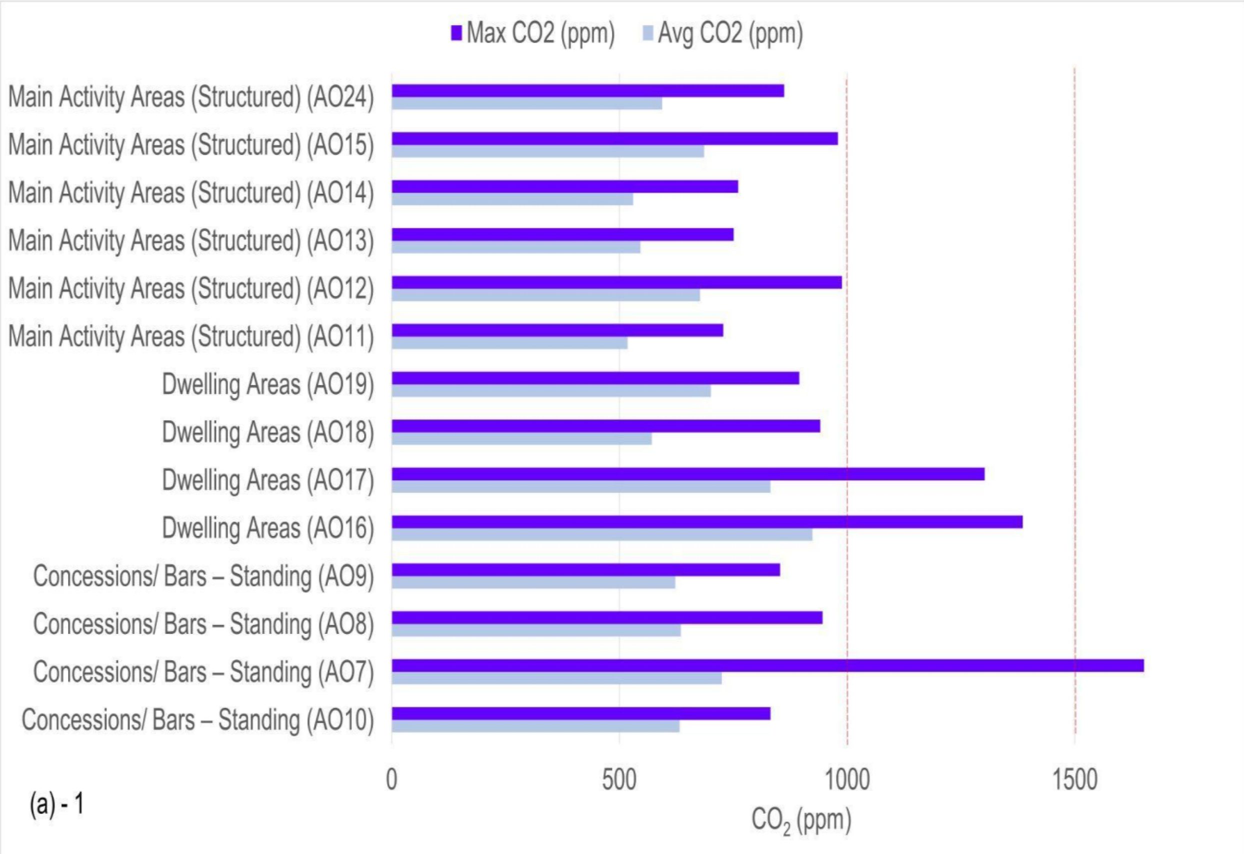
Figure 2. The number of spaces across the ten monitored venues aggregated by air quality bands: (a) Average and (b) Maximum CO_2 values. Data includes all venues and events from ERP Phases I, II and III. (Figures reproduced following the published figures in (2))

2.4.2 Air quality distribution in large venues across different spaces

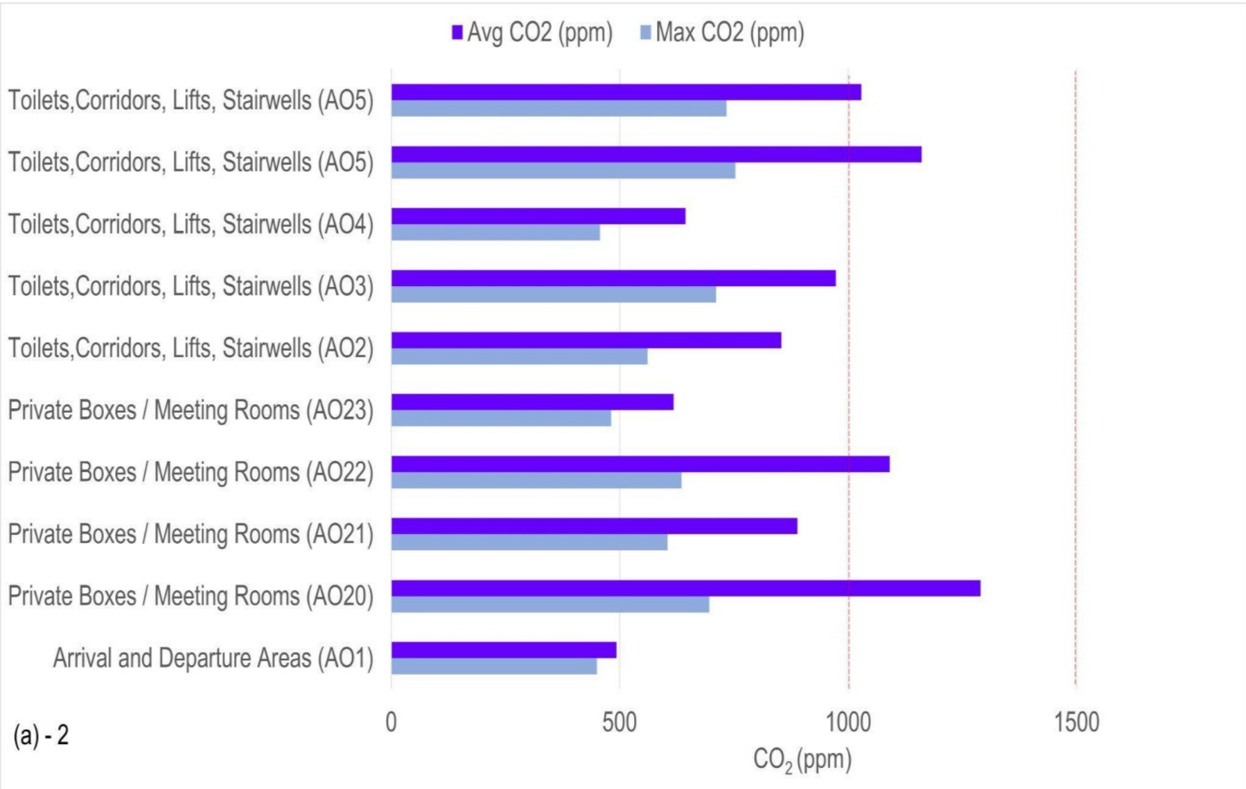
Results are presented below from the O2 arena and Wembley Stadium events held on the 11th of May and the 15th of May 2021 respectively, with occupancy of about 20% venue capacity, to illustrate the variation of average and maximum CO_2 levels across a number of different spaces at the same event. The O2 Arena is a multi-purpose arena located in South-East London, inside the O2 centre complex. Spectator areas in the O2 arena are the stalls, level 1 and level 2 seating. During the Brit Awards event, stalls were reserved for performing artists and stage installations, so spectators had access to level 1 and level 2 seating in the arena bowl, as well as concessions/bars in the arena concourse. The O2 has a capacity of 20 000, and 3312 attendees attended the Brit Awards event. For the Brit Awards in the O2 arena, 24 individual spaces were monitored, out of which the majority were indoors and mechanically ventilated.

Wembley Stadium is located in North West London and it has a capacity of 90,000, with 18,720 spectators attending the FA Cup Final event on the 15th of May. Spectator areas are stretched over five levels and are all outdoors. Although the main activity areas of Wembley stadium are outdoors, the majority of spaces such as private boxes, restaurants and bars are indoors and their ventilation strategies vary depending on the space. For the FA Cup Final at Wembley stadium, 20 individual spaces were monitored.

In both venues, spaces monitored included main activity areas (spectator seating), private boxes, standing and seated bars, concessions and restaurants, dwelling areas and toilets, lifts and corridors. *Figure 3* below highlights the main activity areas where maximum CO_2 levels never exceed 1000 ppm. This was expected at Wembley Stadium, as the main activity areas are outdoors in the stadium bowl and the average CO_2 recorded is equivalent to the outdoor levels of approximately 400 ppm. The O2 arena, although being an indoor space, had high ventilation rates in the seating area. However, in the O2 arena, increased average and maximum CO_2 values were recorded in dwelling areas, bar concessions, private boxes and toilets and stairwells. Similar observations were made from monitoring Wembley stadium bars, restaurants, boxes and toilets. From both venues, it can be concluded that recorded values vary significantly across same use classification spaces and all spaces generally. A large variation between maximum CO_2 values recorded and average values indicates that the air quality notably varies with time, which is likely caused by increased crowd density at certain times.



Max CO2 (ppm)
Avg CO2 (ppm)
Main Activity Areas (Structured) (AO24)
Main Activity Areas (Structured) (AO15)
Main Activity Areas (Structured) (AO14)
Main Activity Areas (Structured) (AO13)
Main Activity Areas (Structured) (AO12)
Main Activity Areas (Structured) (AO11)
Dwelling Areas (AO19)
Dwelling Areas (AO18)
Dwelling Areas (AO17)
Dwelling Areas (AO16)
Concessions/ Bars – Standing (AO9)
Concessions/ Bars – Standing (AO8)
Concessions/ Bars – Standing (AO7)
Concessions/ Bars – Standing (AO10)
0
500
1000
1500
CO_2 (ppm)
(a) - 1

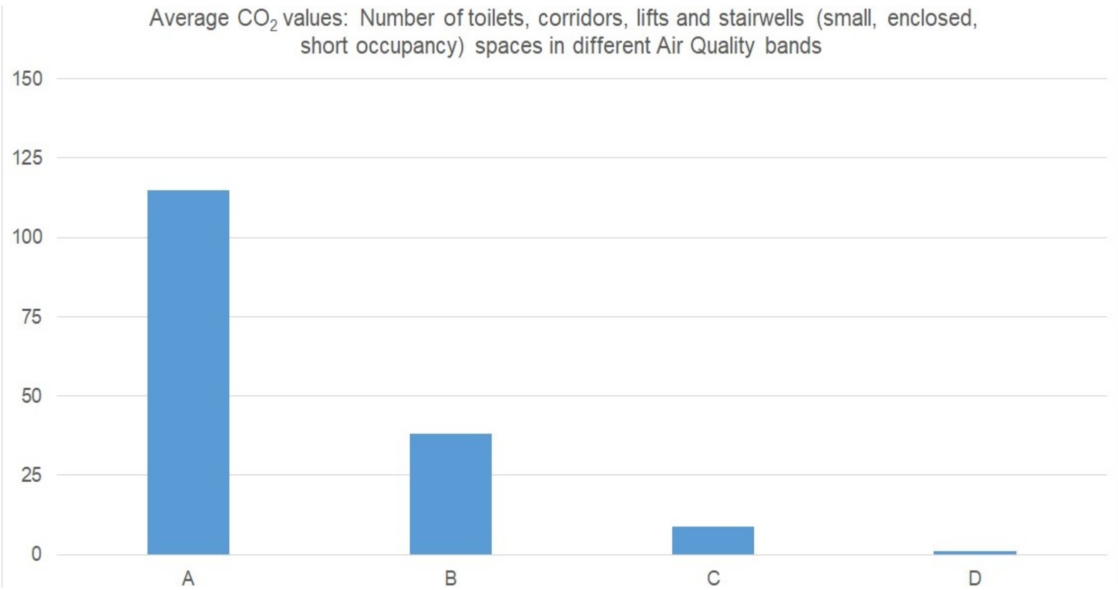


Avg CO2 (ppm)
Max CO2 (ppm)
Toilets,Corridors, Lifts, Stairwells (AO5)
Toilets,Corridors, Lifts, Stairwells (AO5)
Toilets,Corridors, Lifts, Stairwells (AO4)
Toilets,Corridors, Lifts, Stairwells (AO3)
Toilets,Corridors, Lifts, Stairwells (AO2)
Private Boxes / Meeting Rooms (AO23)
Private Boxes / Meeting Rooms (AO22)
Private Boxes / Meeting Rooms (AO21)
Private Boxes / Meeting Rooms (AO20)
Arrival and Departure Areas (AO1)
0
500
1000
1500
CO_2 (ppm)
(a) - 2

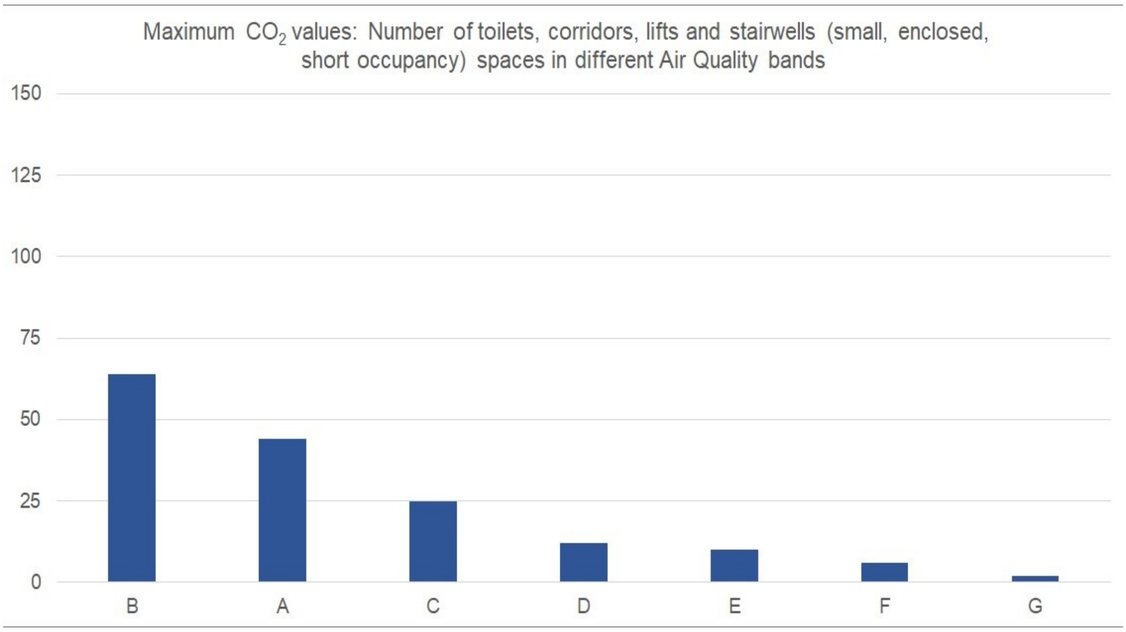
Figure 3 Average and Maximum CO_2 values measured in two large venues (a1) and (a2) O2 arena (b1) and (b2) Wembley Stadium

2.4.3 Types of spaces more prone to poor air quality

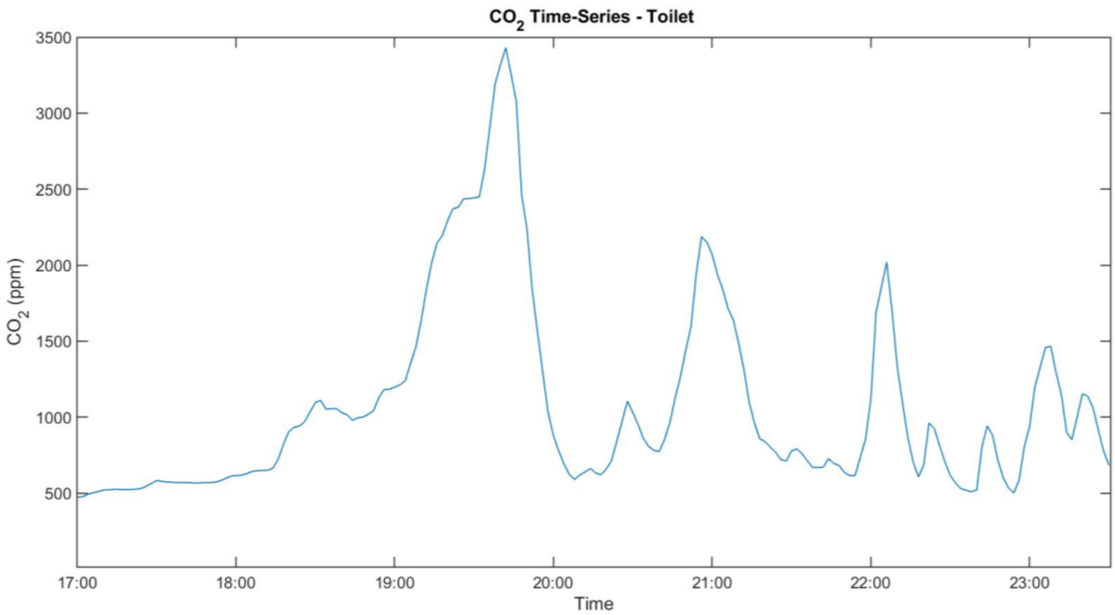
An example of spaces more prone to poor air quality are toilets, corridors, lifts, stairwells (small, enclosed, short occupancy) which are normally not designed for high ventilation rates as their occupancy is supposed to be transient and low. However, these spaces should be considered if long queues occur at events, as has been found to be the case: in particular around women's toilets in the O2 arena, as shown in *Figure 3(a2)* above. In *Figure 4* below, 23 toilets, corridors, lifts and stairwell spaces monitored in six different venues over 27 events, are shown in aggregate (as 162 individual episodes). Average and maximum air quality bands were calculated and these are presented in terms of frequency of occurrence. The average air quality in these small, enclosed spaces is most frequently in A class (71%), but maximum air quality bands vary; these are most frequently in B class (39%) and are often in bands D and above. To understand this in further detail, an example is shown in Figure 3(c) of time-series for a single toilet space from a high occupancy (almost full capacity) event at Wembley stadium in July 2021. The figure indicates very high levels of CO_2 persisting for an hour at a time, with sharp peaks and steep decay rates. However, CO_2 values above 2000 ppm were observed for 46 minutes in total over the duration of the event. The longest continuous interval of CO_2 was recorded just before the event started, and this lasted 36 minutes.



4(a)



4(b)



4(c)

Figure 4 Monitored air quality in toilets, corridors, lefts, stairwells (small, enclosed, short occupancy) at all ERP events, separated into Air Quality bands. (a) Average CO_2 ; (b) Maximum CO_2 ; (c) CO_2 Time-Series in a single toilet at a high capacity event at Wembley Stadium.

2.4.4 The Impact of Occupancy distribution and ventilation distribution and strategy

The following section presents results from three venues where ventilation efficiency is understood through observations of the distribution of CO_2 around the spaces. Results from the auditorium area of a small theatre, The Crucible, are compared with results from the Piccadilly Theatre, a larger venue with a high ceiling, and with high occupancy unstructured events at the Circus nightclub.

Results from the Crucible in *Figure 5* below show clearly the impact of increasing occupancy on the resulting CO_2 values with average CO_2 values of only ~ 600ppm when at ~ 30%. During the highest occupancy, the CO_2 values increase rapidly with the average peaking at >1000ppm, then reducing to ~ 900ppm as demand-controlled ventilation increases. However, the results demonstrate the space is not well mixed, with CO_2 values varying by nearly 400ppm from the back row to the front of the auditorium. The back row of the theatre peaks at nearly 1400ppm and stays above 1000ppm for the entire event.

This variation in the space demonstrates the limitations of using CO_2 sensors only at the extract to control ventilation in a large space that may not be well mixed.

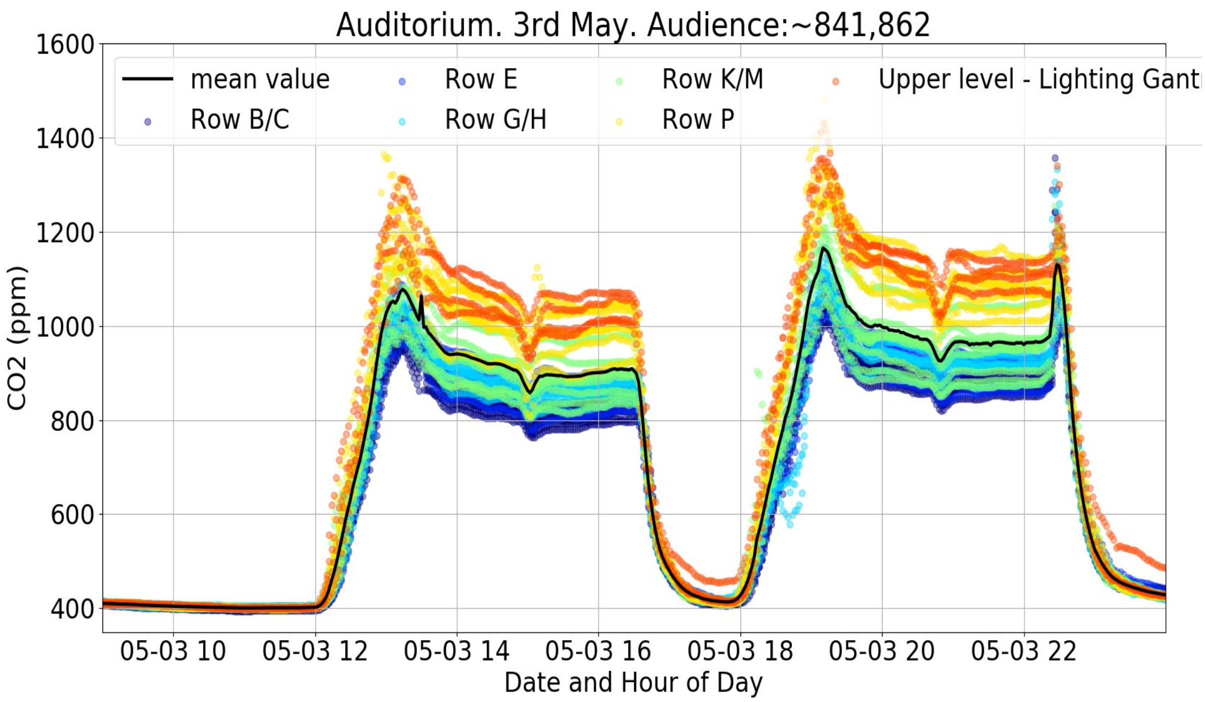
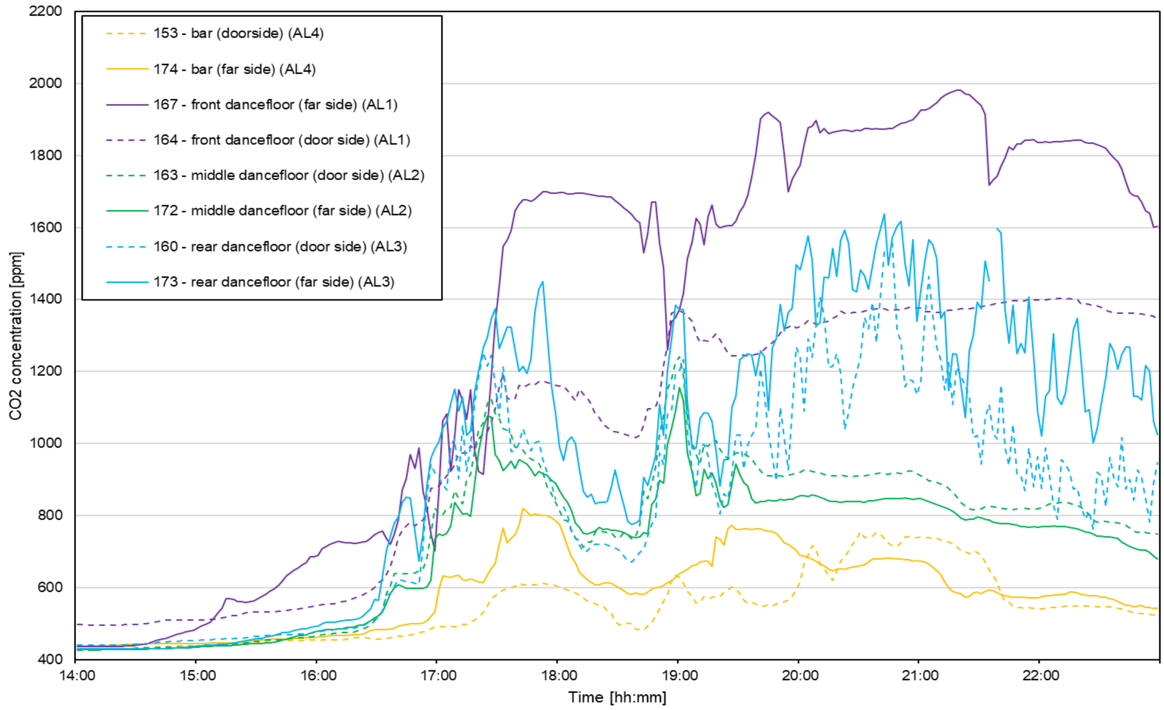


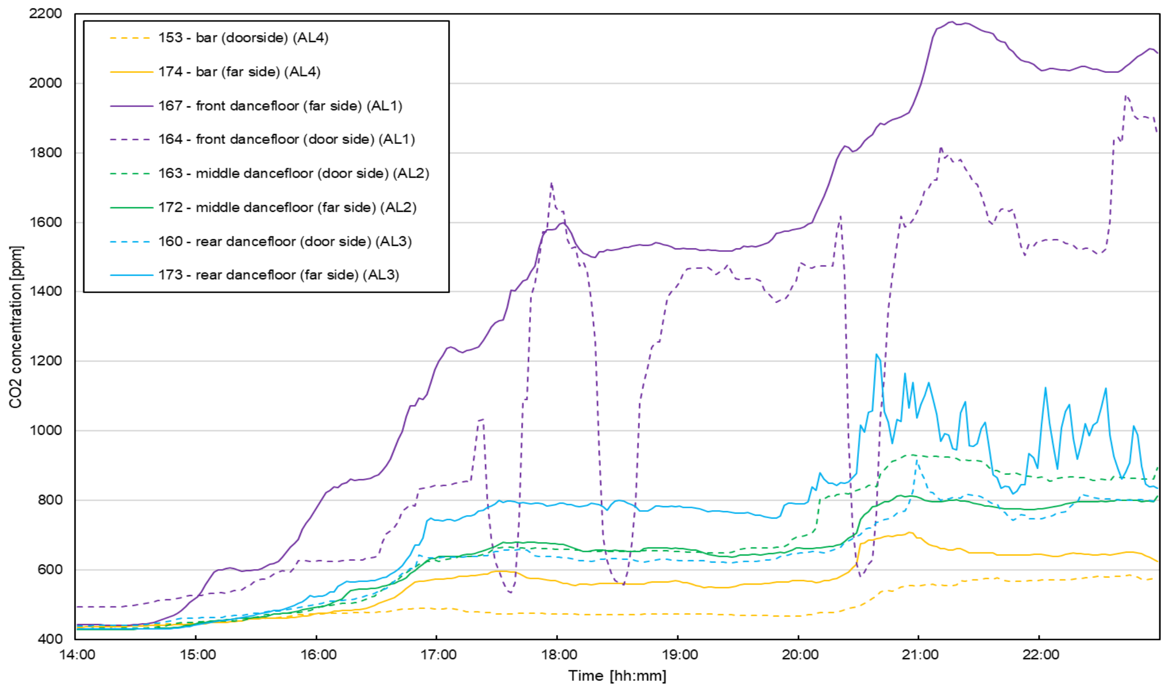
Figure 5 Ventilation distribution at a small theatre as observed from 44 CO_2 monitors around the space

The combination of poor ventilation provision and high crowd density at the Circus nightclub events contributed to the highest indoor CO_2 concentrations observed in the Events Research Programme pilots in Phase I. Thirty-three sensors, protected by security cages, were installed in the venue. The nightclub events were hosted in a unique venue: a 34,000 m^3 Victorian-era warehouse. The building was naturally ventilated via six large warehouse door openings (49 m^2) that were distributed along one side of the building at regular intervals. In one half of the building there was a dance floor and stage area, at the other end there was a bar. At the bar end, the three large openings were fully open. At the dance floor end, the openings were restricted by metal shutters and hanging vertical plastic “butchers” screens, to reduce noise egress from the venue. However, this endeavour restricted the ventilation to the dancefloor and stage area. It was in this area that the crowd density was highest, due to the clustering of people around the stage. The activities of the crowd: singing, dancing, shouting, etc., further increased the CO_2 emission in this area. For analysis, the nightclub was divided into four zones. At the front dancefloor/stage was classified as exposure index Class E, but the maximum values were in Class G, indicating that incoming outdoor air was particularly poorly distributed further from the door area. The distribution of CO_2 values around the space can be observed in *Figure 6* below.

The exposure index target for ventilation of areas with enhanced aerosol generation is Class B. Comparing the two consecutive Nightclub events, Event 1 and Event 2, it was observed that the difference in CO_2 concentrations between each of the four zones was greatest on Event 2. At Event 2 CO_2 concentration was generally higher in front of the stage than elsewhere (by >900 ppm), indicating a poorly mixed space, or uneven occupancy. This situation was only identified because a large number of sensors, 33 of them, were used to monitor the space.



6(a)



6(b)

Figure 6. Measured CO_2 concentration from a subset of sensors. Two sensors for each of the four zones. Dashed lines denote a sensor on the side of the building that has door openings. (a) Circus Nightclub Event 1. (b) Circus Nightclub Event 2.

Three comedy performance events in Piccadilly theatre were monitored in July 2021 and data from the event on the 17th of July, the event with the highest occupancy of the three is shown in *Figure 7* below. This theatre has 3 main auditorium sections: Stalls, Royal Circle and the Grand Circle. Each auditorium section was divided into monitoring zones with 3 to 4 rows in each one. In total 17 zones were set up.

In Piccadilly theatre, the outside fresh air was supplied through two main air handling units (AHU) capable of providing a combined fixed air flow rate of 10.5 m^3/s. When the theatre is fully occupied (i.e. all 1232 spectator seats are sold) this fresh air flow rate would equate to 8.5 l/s per person. In the theatre, the fresh air is supplied through the ceilings of the stalls, grand and royal circles, and auditorium dome, while the air is extracted from low level extract terminals located in the stalls and above the stage. During the performance, the supply air was cooled to around 16 °C before supplying to the spectator area and the temperature of the extracted air was around 22.5 °C, whilst the measured average indoor temperature was around 21.5 °C.

CO_2 data from the Piccadilly theatre event highlights that the space is well mixed, with the Grand Circle showing lower values than the other two auditorium levels. The values recorded never exceed 800 ppm in all three spectator areas. The data shows constant levels of CO_2 indicating a continuous and sufficient fresh air ingress in the auditorium.

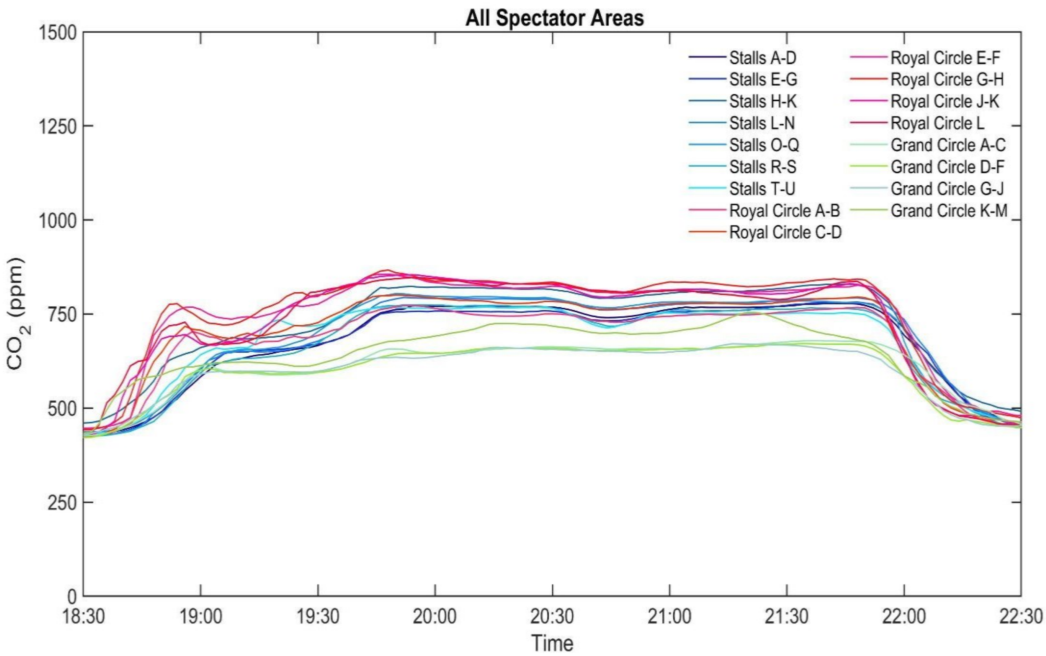


Figure 7 CO_2 data from 17 monitors distributed around a large theatre with a high ceiling, on three different levels, indicating a well ventilated and uniform space.

3.0 Conclusions

The COVID-19 pandemic has highlighted the vulnerability of the built environment to infectious disease transmission in indoor air via the airborne route. Energy-saving has rightly dominated targets for ventilation and building performance for many years, but the unintended consequences of this have resulted in increasingly airtight indoor spaces where ventilation and air conditioning systems are set to recirculate stale air, leakage from outdoors is minimised and occupants have very little control of their environment or understanding of how it works. To save on energy costs and improve performance for health as well, demand control ventilation may be a reliable solution.

Ventilation is a vital mitigation measure against COVID-19 transmission and the scale of the pandemic has only emphasised the need to ensure that the indoor built environment is designed and maintained with health outcomes in mind. Outside of the membership of CIBSE, there is less understanding in the wider community of what ventilation is, and how it is achieved ***effectively.*** The quality of ventilation across the entire UK building stock is not fully understood at present. There is growing evidence from a number of sectors that suggests that a wide range of building types may not always be adequately ventilated, especially in the winter months; this may be due to operation, maintenance, design, or refurbishment and repurposing of existing buildings in operation. Additional consideration of the ventilation requirements in UK building regulations may be needed in future with a view to improve post-occupancy indoor air quality and build resilience to future infectious diseases.

The Environmental Study at the Events Research Programme demonstrated on a large scale how CO_2 monitoring can be used to inform venue building managers operators and event managers quickly and robustly about areas that may need improvement in ventilation, and under which operational scenarios these improvements might be necessary.

The high-resolution monitoring has highlighted some cases leading to variable and sometimes poor air quality. It reveals that for the purpose of infection control, ventilation strategies need to be based on realistic occupancy scenarios which include a variation of occupancy in time and space. Some typical problem areas were identified by the study, such as toilets, stairwells and corridors, that may not have been designed for prolonged occupancy and are therefore more poorly ventilated, yet for disease transmission may become hotspots when the occupancy is increased due to e.g. long queues.

CO_2 monitoring is inexpensive, can be deployed rapidly and can quickly identify areas where exhaled breath is building up in indoor spaces. The Environmental Study demonstrates that new approaches to CO_2 monitoring can be considered, to allow rapid deployment and improvement. Long-term monitoring may not be the right solution for every building and may not always be feasible due to the cost and lack of expertise of the occupants. Our study demonstrates that useful lessons can be learned from a fast, temporary installation and from monitoring carried out in real-world conditions and at realistic occupancy levels.

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