V-KEMS Study Group Report

Recovery from the Pandemic: Hospitality & Leisure

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WARNING: this report contains preliminary findings that have not been peer reviewed. The findings are intended to provoke further study and policy discussion and should not be treated as definitive scientific advice in response to the COVID-19 pandemic.

Whilst we expect these principles to help others formulate coherent and consistent guidelines, time has prevented any quantitative study of their effectiveness. This could be undertaken, but would require real data and time to build more detailed simulation tools. Thus, we are not able to make specific recommendations from the principles, e.g. we cannot infer that it is safe to do X if you follow principle Y.

Additionally, this report has been assembled in a short time frame, we have made every effort to ensure references and links are present. Where this is not the case, we apologise for the unintentional oversight.

Contents

1 Executive Summary

The UK hospitality and leisure industry as a whole has met some unprecedented challenges over the course of the pandemic, and will continue to do so as the nation recovers. On behalf of the Virtual Forum for Knowledge Exchange in the Mathematical Sciences (V-KEMS), the Newton Gateway to Mathematics convened Recovery from the Pandemic: Hospitality & Leisure, a Virtual Study Group, from 12th – 14th October 2021. This brought together mathematical scientists and other disciplines to solve challenges faced by the hospitality and leisure sector as a result of the COVID-19 pandemic.

With challenges presented by UK Hospitality, University of Cambridge Sports Centre, Royal Opera House, Shakespeare's Globe and Independent Cinema Office, we worked with Indigo Ltd, a consultancy for the UK cultural sector and Traveltech for Scotland, who work closely with the Scottish tourism sector, amongst others to develop the problems that were tackled during the study group with the interest of using mathematics as a tool to help solve the particular challenges hotels, restaurants and leisure facilities, such as cinemas, theatres and gyms, are facing as a result of the pandemic. Three issues were presented and then explored:

- Ventilation of Indoor Facilities
- Audience/Customer Risk Perception
- Scheduling/Resource Management

Over the study group, potential solutions were developed and these were presented on the final day. Those stakeholders who presented their challenge were provided with a short tailored report after the event. A potential collaboration between one of the challenge stakeholders and a study group participant is being discussed to enable further work as a follow up to the study group.

2 Background

The hospitality and leisure industry has faced many challenges as a result of the pandemic. These include staff shortages and supply chain problems as a result of the 'pingdemic' and the end of government furlough scheme, customer no shows due to positive testing, a decline in customer confidence and a change in cancellation time windows to meet customer expectations, new ventilation requirements for indoor spaces, ever changing restrictions on international travel and increased traffic at touristic locations. Unlike in previous study groups where the main focus was on modelling the spread of the infection, the theme of this event focused on the recovery from the pandemic and dealing with the operational difficulties and economic implications which have arisen.

2.1 Aims and Objectives

This study group brought mathematical scientists and other disciplines together to solve end user defined challenges with the aim of mitigating the impact of COVID-19 on the hospitality and leisure sector. With challenges presented by UK Hospitality, University of Cambridge Sports Centre, Royal Opera House, Shakespeare's Globe and Independent Cinema Office, we worked with Indigo Ltd, a consultancy for the UK cultural sector and Traveltech for Scotland, who work closely with the Scottish tourism sector, amongst others to develop the problems that were tackled during the study group. In particular, the study group addressed the following three areas of concern:

- Ventilation of indoor facilities - ensuring that adequate ventilation systems are in place for a wide variety of buildings/rooms.
- Audience/customer risk perception - understanding how the perception of risk as changed as a result of the pandemic.
- Scheduling/resource management - how to operate businesses based on limited resources and uncertain demand.

3 Challenge 1 : Ventilation

Cambridge University Sports Centre, the Independent Cinema Office and UK Hospitality provided challenges surrounding ventilation, which are summarised in the following section.

3.1 Problems

Cambridge University Sports Centre: Ensuring effective ventilation to reduce transmission of airborne viruses across all of the University Sports' indoor spaces.

The Cambridge University Sports Centre operates the University Sports facilities and conducts oversight of University Sports Clubs. It has three main sites: the University Sports Centre (indoor sports and gym), Fenner's Cricket and Tennis Ground (including indoor cricket school), and Wilberforce Road Sports Ground (Athletics and Hockey). All of the sites have some indoor space, with the indoor space at the sports grounds generally focused on function rooms and changing areas. The centre hosts approximately 60 sports clubs.

There are a wide variety of spaces, some mechanically ventilated and controlled by building management systems (BMS) and some naturally ventilated by using purpose provided openings (PPO), with a wide variety of (sporting and non-sporting) activities taking place and a wide variety of attendance levels. There are also variable conditions with the BMS' operating differently in response to the varying indoor environment and outdoor weather conditions. The control of the BMS is restricted to the Facilities Management (FM) team, so users do not have direct control of building settings, such as temperature set-points or ventilation. Therefore, they have to submit requests to the FM team for changes to be made. There is currently limited understanding of building operation and a lack of knowledge about things that can be done to improve the ventilation to mitigate the COVID airborne transmission disease.

The desired outcome is that Cambridge University Sports Centre want to have effective controls and measures to ensure that all of their spaces meet ventilation standards, and that these be sustainable in the long-term.

Independent Cinema Office: Identifying suitable guidance to be given to independent cinemas to ensure that they have adequate ventilation provision in their venues.

The independent cinemas have different building structures such as historical and modern buildings, with auditoria of different sizes. The ventilation systems in place also vary from cinema to cinema, and in general one of the following is in place:

1. Mechanical ventilation
2. Natural ventilation
3. No/unknown ventilation system

It would be beneficial for the Independent Cinema Office to understand what kind of guidance could be given to clients to support them in identifying whether they have adequate ventilation provision in their venues.

UK Hospitality: Provide general ventilation guidance for hospitality venues.

There are many forms of ventilation in place across the hospitality sector, from opening windows to mechanical devices, each with a different cost and effectiveness.

In the following section, we outline some scenarios from previous studies that may be relevant to the problem stakeholders.

3.2 Scenarios

Previous studies have shown that ancillary spaces to the main venues (e.g. canteens, cafes, bars etc.) are often overcrowded and not sufficiently ventilated. It is suggested that venues take extra care in those locations and segregate people into smaller groups and increase the air flow whenever possible to reduce airborne virus transmission risk. As shown in Figure 1, average CO_2 levels are high in a bar area zone marked "PT10" as this space was often overcrowded and not sufficiently ventilated. In comparison, auditorium zones PT2-PT8, PT16-PT19 and PT22-PT27 had good ventilation, as indicated on the graph.

If there is an activity on stage involving physical effort (e.g. singing, shouting etc.), it is advised to leave some space between the stage and the spectators in the first few rows.

An example of an auditorium with high occupancy but good ventilation is shown in Figure 2.

In the following section, we highlight the relevant ventilation guidance which can be used to inform venue operators.

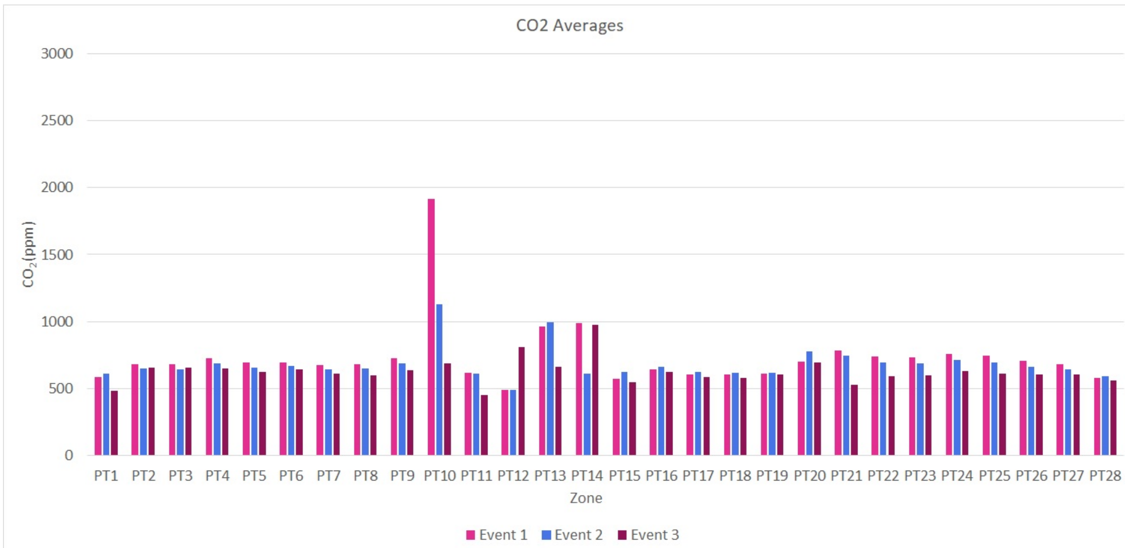

Figure 1: Comparison of bar and auditorium spaces in a theatre.

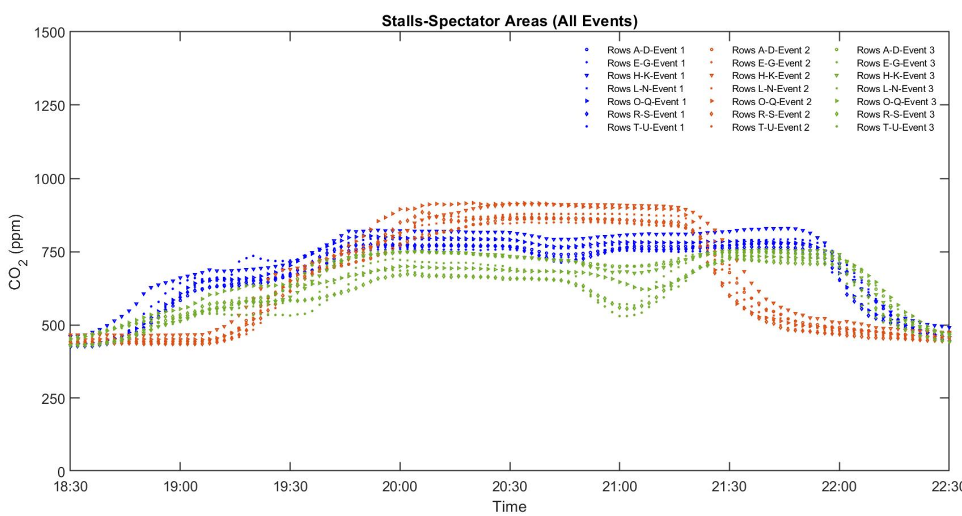

Figure 2: An example of an auditorium with high occupancy but good ventilation.

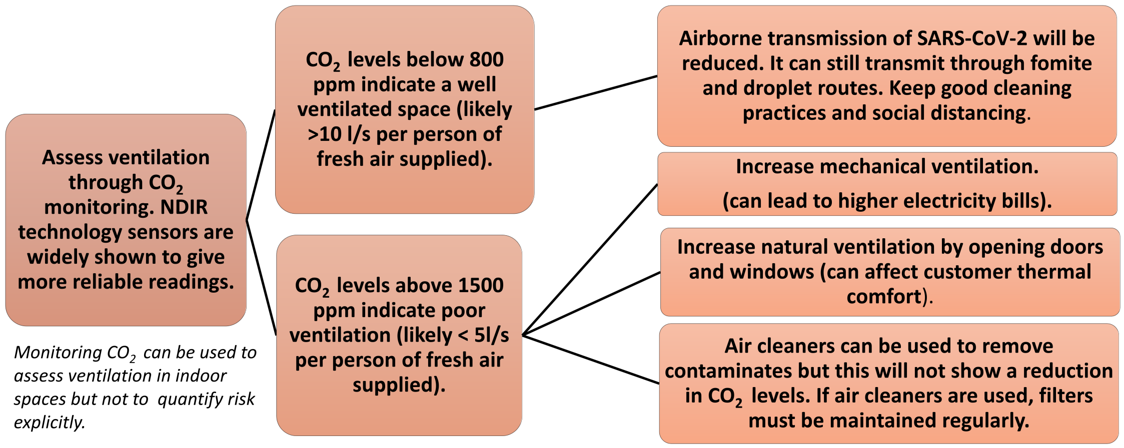

Figure 3: Step-by-step guidance for assessing ventilation in spaces using CO_2 monitors.

3.3 Guidance from literature

Ventilation is a key mitigation tool for aerosol airborne transmission of all respiratory viruses, including SARS-CoV-2. Mitigating infection risks from droplet and fomite transmission should include mask wearing, social distancing, and regular cleaning schedules. Measuring CO_2 levels is a useful tool to evaluate ventilation in a space. However, it is not a proxy for risk of airborne transmission.

Figure 3 outlines some basic steps to assess ventilation in spaces using CO_2 monitors. In this section, we draw on the literature to give some more detailed guidance.

3.3.1 Ventilation operation suggestions and CO_2 thresholds guidelines [13, 4, 5]

- A space with consistent CO_2 value < 800ppm (absolute value) is a well ventilated space (this does not mean that it is COVID-19 risk free).
- A space with sustained high CO_2 values (>1500ppm) is likely to indicate overcrowding or poor ventilation and mitigating actions are likely to be required.
- Based on current evidence, ventilation rates recommended in current UK building standards and guidance are considered adequate in most settings. The general recommendation is a supply of outdoor air of around 10 l/s per person, equivalent to approximately 800-1000ppm CO_2. In cases of regular supply of fresh air below 5 l/s per person, which is expected to lead to >1500 ppm CO_2, it is recommended that mitigating interventions

Category	Expectation of indoor environmental quality	CO_2 above outdoors (ppm)*
I	High	550
II	Medium	800
III	Moderate	1350
IV	Low	1350

Table 1: Recommended UK CO_2 values in pre-pandemic guidance. An adaptation from [12], which states CO_2 values for ventilation related to occupant comfort pre-pandemic. *assuming CO_2 emission of 20 l/hr/person.

(i.e. reducing occupancy density and/or increasing fresh air flow rates) should be introduced to reduce the infection risks. In spaces where aerosol generation could be higher (e.g. due to intense exercise, continuous talking, or a high chance of infectors being present) or where occupancy in the space lasts for a long time (e.g. a full working day), higher ventilation rates to maintain CO_2 concentrations below 800 ppm are recommended.

- ***The room air should not be recirculated unless absolutely necessary (e.g. the thermal comfort of the occupants can not be satisfied without re-circulation).***
- Ventilation should be provided at all times during the year and not only when the outside weather conditions are favourable.
- In winter, a balance between airborne infection risk, energy demand, and thermal comfort can be achieved by modulating the output of the supply air flow rates. But the supply air flow rates should not be lower than suggested values (mostly 8 – 10 l/s per person) at anytime during the year.
- If the space is naturally ventilated, opening the windows will provide fresh air. In winter, the openings do not need be opened as wide as they are in summer, but nevertheless they should be opened. Operating all the windows with reduced opening angle will help with mixing in the domain. However if both low and high level openings exist in the space, high level openings should be opened first. Low level openings should be opened following the high level openings only if it is required (i.e. the CO_2 targets are not reached and cold draughts will not cause thermal discomfort for occupants).
- In winter, natural ventilation can introduce larger air flow rates to spaces even with smaller openings. Therefore, operating the windows with smaller opening angles would serve the purpose. The benefits can be improved further if the space is purged even for a short time (e.g. a few minutes) during unoccupied time (e.g. between the meetings or performances).

- Demand control function of ventilation systems (i.e. reducing the ventilation flow rates according to the occupant density) should be disabled if the thermal comfort requirements could be met without the demand control function. Reducing the ventilation system CO_2 threshold values will bypass the demand control and will aid with providing larger fresh air flow rates.
- If the mechanical ventilation system has a rotary heat recovery unit, it is advisable to turn it off if the thermal comfort requirements of the occupants can be met without using the heat recovery unit. If the heat recovery is achieved by a plate or twin coil unit heat exchanger, it may remain operational. In both cases, suitable checks should be performed by a qualified person to make sure that the supply air is not contaminated by the recirculated air because of a leakage in the heat exchanger unit.
- If there are zones within the building that cannot be ventilated by fresh outside air (e.g. basement and storage spaces), people's access to such places should be limited, especially if they will spend more than 30 minutes there.
- If a space in the building has split type air-conditioner units but does not have any means of ventilation, they should only be used for a short period of time. Similarly, if there is no obvious ventilation in a room or zone, building users should be discouraged from using that space.
- Mechanical ventilation systems can be supported by natural ventilation by opening windows and providing extra fresh air into the space when the thermal comfort of the occupants is not compromised to unacceptable levels.
- The air in spaces with unavoidable transient occupancy such as corridors and staircases should be purged regularly.
- The furniture in spaces can be relocated (e.g. moving desks to further away from fresh air supplies) in heating seasons to keep the occupants away from the cold draughts. Also, dress codes can be more flexible, so people can wear warmer clothes indoors. These would help occupants to tolerate higher fresh air flow rates with lower temperatures and would help with achieving a balance between transmission risks, energy efficiency, and thermal comfort. It is also a possibility that disturbed thermal comfort might lead to shutting off the ventilation system completely which is undesirable for both infection risk and indoor air quality.
- If the toilet blocks in the buildings are ventilated with either natural ventilation (e.g. a window) or mechanical ventilation (e.g. a fan), the windows or fans should remain open or operational throughout the day. However, if the toilet blocks have both windows and extractor fans, the windows should be closed when the extractor fans are operating.

- If the space is ventilated using natural ventilation, the windows should be opened at least 15 minutes prior to occupants' arrival. If the space is ventilated using mechanical ventilation, the ventilation system should be in operation (i.e. supplying air) an hour before the occupants arrive to the building and it should cease the supply of air an hour after occupants leave the building.
- If CO_2 monitoring is employed, the following guidelines are recommended. The table in Figure 4 from [4] gives an indication of the suitability of CO_2 monitoring in different settings.

Selecting CO_2 sensors [4, 5]

- CO_2 monitoring with visual displays is more likely to lead to improved ventilation, as evidence suggests.
- CO_2 sensors employing nondispersive infrared (NDIR) technology are widely shown to give more reliable readings.
- It is often more appropriate to measure CO_2 concentrations relative to the background level rather than the absolute value in order to manage differences in sensor calibration offset.

Locating CO_2 sensors [4]

- Locating CO_2 sensors effectively is important, as it will define the conclusions drawn about the ventilation within a room. Sensors should be placed at breathing height, away from windows, doors, ventilation openings and not close to individuals. Based on simulated data, at locations near the walls, where CO_2 sensors are typically located, the range of variation within the interior of the room can be almost fully represented. Values that are particularly low (<500ppm) or high (>1500ppm) can be checked by moving the position of the monitor before taking action.

Reading CO_2 measurements [4]

- Appropriate averaging CO_2 periods (e.g. hourly or daily) should be used based on the purpose of the CO_2 monitoring, rather than instantaneous readings; a short duration higher value may result from temporary higher occupancy or occupant proximity to the sensor and is not likely to indicate poor ventilation. Shorter duration averaging may be

Table 2: Suitability of CO_2 monitoring in different types of spaces

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

Figure 4: Source: [4]

appropriate for managing ventilation where short-term actions (e.g. opening a window) are used to improve the balance between purging of indoor pollutants and thermal comfort. For settings in which occupants typically reside for shorter durations, average concentrations determined over shorter time periods could be considered.

- A useful measure of the spaces as a whole can be given by presenting both average values and maximum values.

Assigning the responsibility [4]

- Behavioural impacts play a major role in the effectiveness of managing ventilation through CO_2 monitoring. Unclear roles and responsibilities are often a barrier. We would recommend assigning the oversight and operation of the CO_2 monitoring to (a) dedicated person(s) that understand the background (reading the literature [1, 13, 14, 3, 4, 5, 6, 9, 10, 11] will be helpful in that).

Building good habits [4]

- Providing training and resources to develop habits and routines that will bring lasting behaviours towards improved ventilation. For example, checking the monitor/ventilating the room when first entering it / leaving it on during breaks / when the device prompts attention.

Exposure Time

- The overall cumulative exposure risk of an event depends on how much time people spend in the higher risk areas; for example, if a spectator at an outdoor football match spends the majority of their time at an indoor restaurant within the stadium they will have been at higher risk [3]. Similarly, toilets at different venues can have high CO_2 levels but time spent in those spaces is low; hence the risk is dependant both on ventilation and exposure time.

- Based on time spent in a space and CO_2 levels, exposure was presented in Figure 5 in terms of relative risk of being in a well-ventilated office space for 6 hours (Findings from [3]).

- Air cleaning technologies should be used if ventilation standards cannot be met [14, 11].

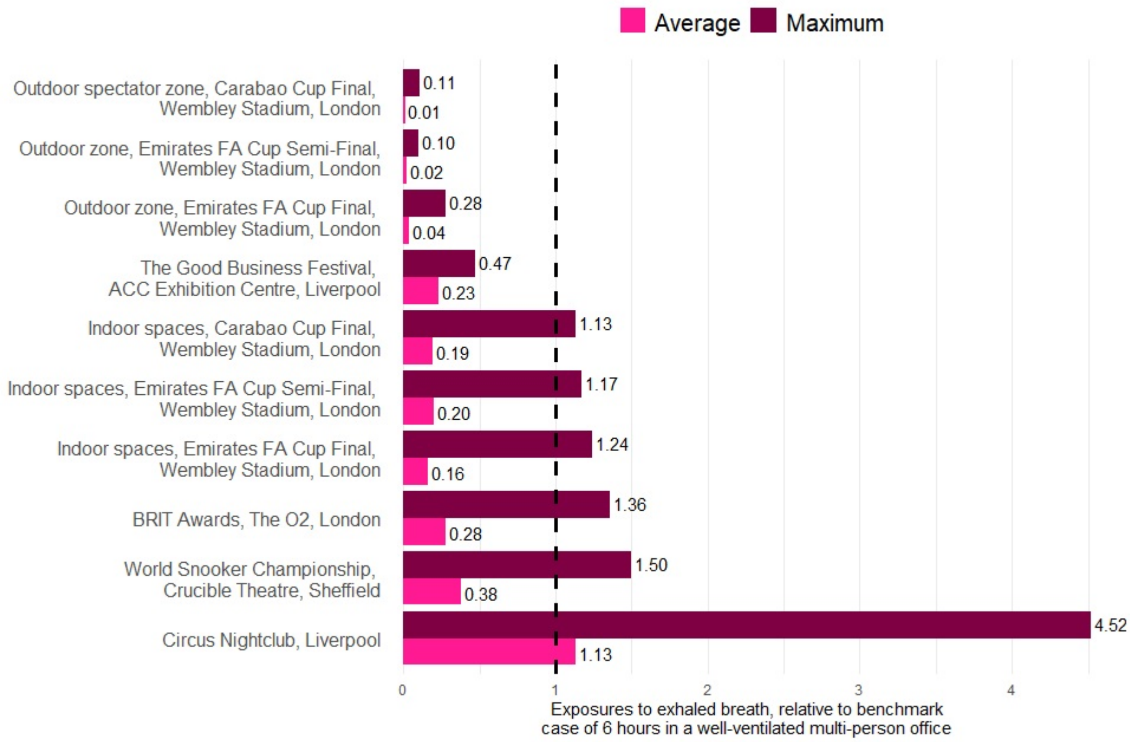

Figure 5: Source: [3]

- In-room air cleaners can be used when heating, ventilation, and air conditioning (HVAC) equipment does not meet recommendations for ventilation and filtration, removal of contaminants near a source is needed or when higher risk activities occur.
- To assess whether air cleaning technologies are an appropriate measure for a space, building operators are advised to refer to the relevant Chartered Institution of Building Services Engineers (CIBSE) Guidance [14]. The Relative Exposure Index calculator (see [15]) can be used to assess the relative exposure index of a space by introducing basic inputs and comparing the performance with and without air cleaners.

Maintenance

- Ensure that maintenance checks of the mechanical systems take place at the recommended frequency by trained staff, as usually the issues relate to technical defects. For example, changing filters, checking the quality of filters for misplacement or holes, etc. can have a direct impact on the air quality supplied in the space.

In the following section, we show how and where CO_2 sensors can be installed in both audito-

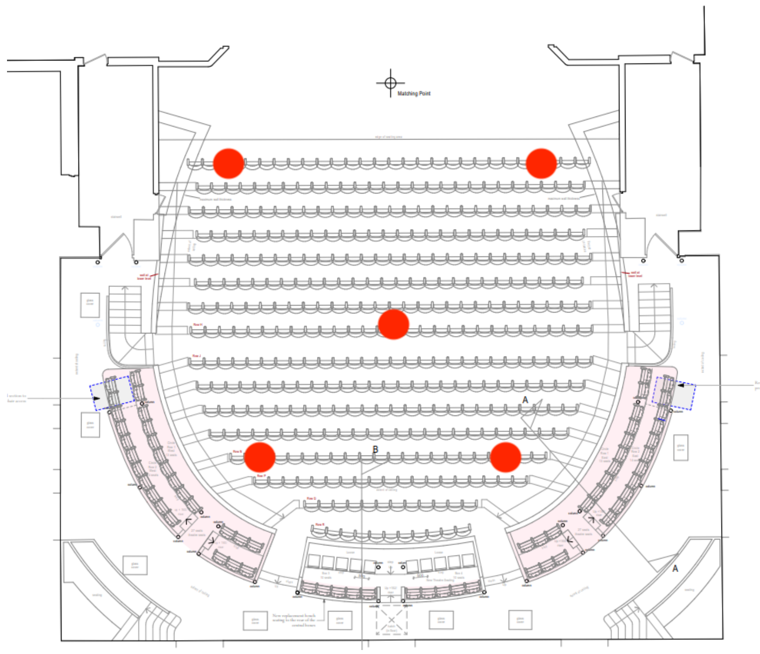

Figure 6: Installation example in the lower circle of an auditorium.

ria and sports facilities.

3.4 Auditorium & Sports Facilities Installations

Figures 6, 7 and 8 demonstrate how and where CO_2 monitors can be installed in an auditorium. Note that each auditorium will be different, and number of CO_2 sensors required will depend on each space. CO_2 sensors should be installed away from any mechanical vents and doors. Under seat placement is recommended in large auditoriums (see Figure 8). Walls can be appropriate in small auditoriums with CO_2 sensors placed at 2 to 2.5 m from the floor. When installing the sensors, command tape was used on walls and under auditorium seats, command tape was used with cable ties. Staff should be trained to observe and act on high CO_2 level scenarios.

Spaces with high occupancy over longer periods of time (1 hour) should be prioritised for CO_2 monitoring. An example of possible locations to install CO_2 monitors for the Ground Floor of the Cambridge University Sports Centre is given in Figure 9 where the proposed sensor locations are marked in red. Note that:

- At least 4 CO_2 sensors should be installed in a Sports hall, but 6-8 would provide better information depending on the size of the space.

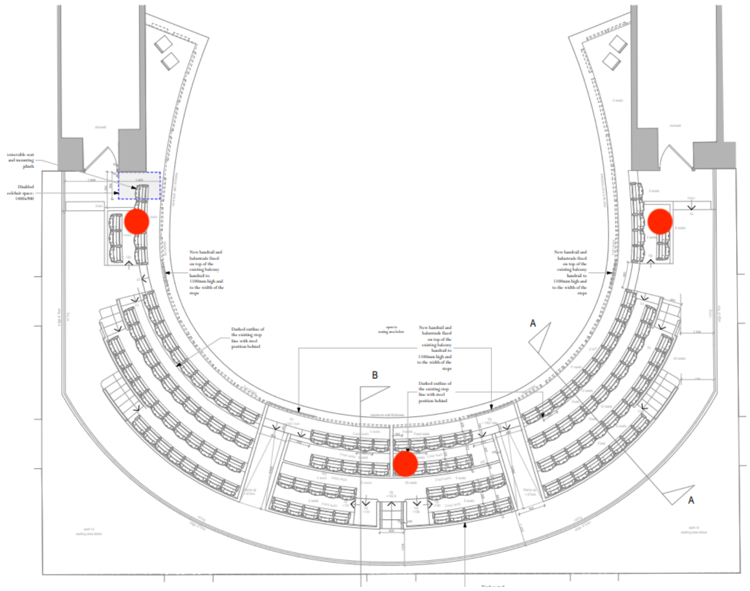

Figure 7: Installation example in the upper circle of an auditorium.

- Fitness suites should be monitored with at least 2 CO_2 sensors or more (depending on size). High aerobic exercise result in more aerosol production with potentially higher risk of airborne transmission.
- Squash courts can be monitored for ventilation but as only 2 people spend time there, other measures such as lateral flow tests before hand might be more appropriate.
- Changing rooms should be monitored if customers linger in the area.
- Conference rooms hosting long events should be monitored.
- Air Cleaners have proven effective in gym environments when combined with ventilation strategies [2].
- Toilets and corridors have short occupancy times hence should not be prioritised over other spaces.

Some further tips when installing CO_2 monitors are listed below.

- Install CO_2 sensors away from vents and windows/doors.
- Install CO_2 sensors at some distance from customers. Breathing onto a monitor can give high readings.
- Train staff to identify high readings and take action.

Figure 8: Installation example in auditorium.

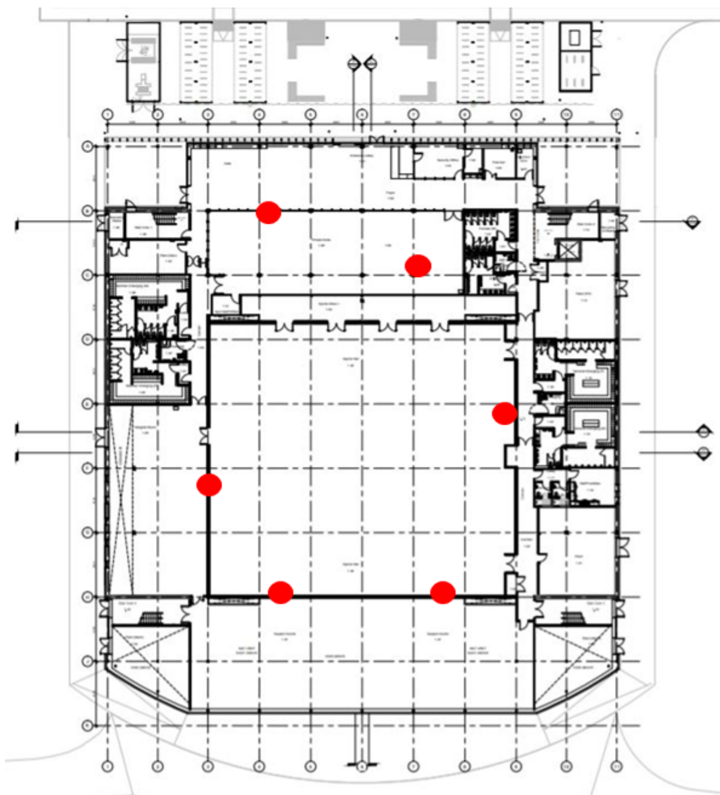

Figure 9: Installation example for Ground Floor of the Cambridge University Sports Centre, with the proposed sensor locations are marked in red.

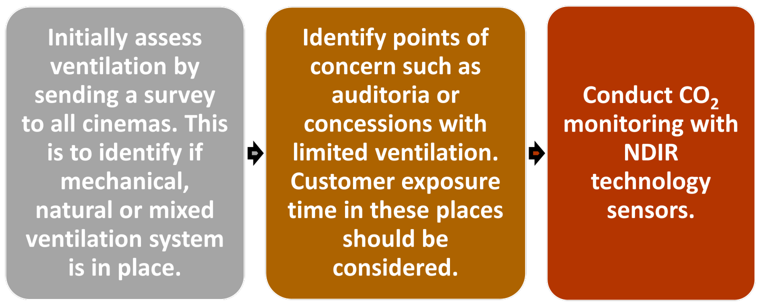

Figure 10: Step-by-step guidance for the Independent Cinema Office.

- CO_2 sensors should be placed on walls at about 2-2.5 m height.

In the following section, we outline some survey questions which can be used by the Independent Cinema Office to better understand the ventilation systems in place at different venues. Note that although the focus will be on the Independent Cinema Office, the questions can also be used by other bodies.

3.5 Survey Questions

The Independent Cinema Office has a large and varied stock of buildings which are ventilated by several different types of ventilation systems. Some of them have mechanical ventilation and some have natural ventilation, whilst others have limited knowledge of the ventilation provision. Therefore, as a first action, it would be critical to identify the venues with potential problems so that the efforts can be concentrated on those venues rather than visiting all of the venues individually.

The process that we recommend the Independent Cinema Office follows is outlined in Figure 10. Note that it is very important to consider exposure time to poor ventilation as the risk of infection is greater with longer exposure times (i.e., sitting in an auditorium for a duration of a movie).

The questions introduced below can be used to compile a survey and the Independent Cinema Office can distribute those surveys to identify the venues with potential ventilation problems. It is important to stress that the questions below are drafted for indicating the information required for identifying the venues with potential ventilation problems. The Independent Cinema Office might want to consider re-drafting the questions in appropriate format and processing through their ethical procedure before distributing to their members.

The following questions have been designed in consultation with the Independent Cinema Office, but could be appropriate to other similar venue operators:

Suggested questions for identifying venues with potential ventilation problems

1. Is the venue operational (i.e. currently accepting customers)?
2. How is the building ventilated?
   (a) Mechanically ventilated
   (b) Naturally ventilated (i.e. via the opening of windows, doors, and passive vents)
   (c) Mixed (i.e. both mechanical and natural) ventilation?
   (d) Don't know
3. Is a trained employee responsible for managing the operation of the ventilation system?
4. Are there reports of complaints regarding indoor air quality (e.g. bad odours or a smell of stale air) from customers or staff?
5. Is there a plan of action for when a staff member or customer complains about the indoor air quality or bad odours? If so, what is the plan?
6. Is there a plan of action for when a staff member or customer raises concerns regarding COVID-19 and the ventilation system? If so, what is the plan?
7. Are there specific locations where people congest (typically ancillary spaces to the main venues, e.g. canteen, cafe, foyer, or bar etc.)?
8. Do you agree to take part in a field study where a group of experts installs CO_2 monitors in your venue to assess the indoor air quality and adequacy of ventilation in the space?

Specifically for cinema venues, such as those members of the Independent Cinema Office, it would be interesting to know:

1. Were the cinema buildings constructed as purpose-built cinemas or were many built for a different purpose, such as theatres or halls, and later converted into cinemas?
2. If so, how have the changes affected ventilation?

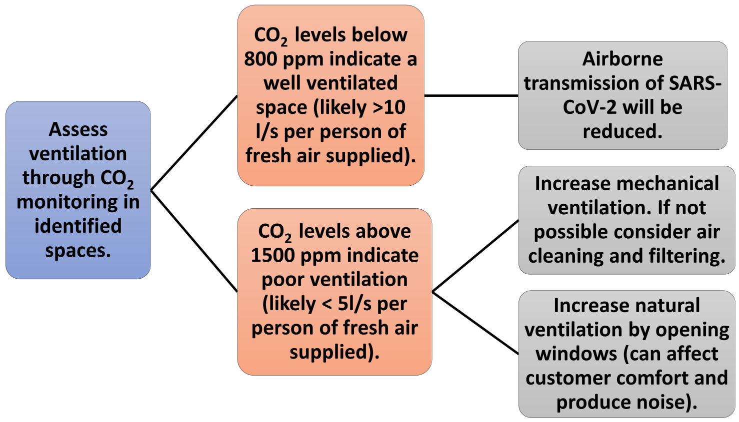

Figure 11: Guidance when assessing ventilation systems through CO_2 monitoring for the Independent Cinema Office.

When assessing ventilation systems through CO_2 monitoring, the Independent Cinema Office may find it useful to follow the guidance outlined in Figure 11.

In the following section, we highlight some key literature/documentation that the problem stakeholders can use to inform their decisions on what type of ventilation systems should be in place.

3.6 Useful Tools

There are a number of tools available for the assessment of airborne transmission risk and relative exposure to SARS-CoV-2. Some of these tools may require a good understanding of the scientific background, while others may be more simple. The tools should be used with caution when assessing large spaces, as they typically assume well-mixed conditions, which is unlikely to be the case in large spaces.

- The tool found in [8] estimates COVID-19 transmission risks based on room volume, ventilation rate etc. An introduction to the tool can be found in [7].
- The tool found in [15] can be used to calculate the COVID-19 Relative Exposure Index.
- The Fate and Transport of Indoor Microbiological Aerosols (FaTIMA) tool found in [18] allows for the determination of the indoor fate of microbiological aerosols associated with ventilation, filtration, deposition and inactivation mechanisms.
- The tool found in [16] can be used to estimate the effect of ventilation on COVID-19 airborne transmission.

- The tool found in [17] is a COVID-19 Multi-room and Recirculation Calculator for HVAC systems operational strategy assessment for reducing infection risk in buildings.

Note that a similar problem was investigated in a previous study group on Unlocking Higher Education Spaces for lecture theatres, see page 10 of [6].

In the following section, we summarise the work on Challenge 1: Ventilation and outline some areas for future work.

3.7 Summary & Future work

Within this section, we have provided general guidance on how to ventilate indoor spaces, highlighting key guidance and tools, and provided a list of survey questions that can be used to identify venues with potential ventilation problems.

The group that worked on this problem were part of the AIRBODS (Airborne Infection Reduction through Building Operation and Design for SARS-CoV-2) government-funded study. Depending on capacity, some future work with AIRBODS and the stakeholders may take place while considering the following.

It would be useful to gain an understanding of each of the buildings in question. Specifically, how they were intended to be used, how they are used now, how they were ventilated when first designed, how they are ventilated now, and if there have been any structural changes that could affect ventilation. AIRBODS colleagues could then advise to install CO_2 sensors in appropriate locations to monitor the effectiveness of the ventilation.

If architectural drawings (including floor plans, elevations, and photographs) can be provided, AIRBODS colleagues can help with understanding the buildings and identifying the possible locations for installation of sensors. This would give the approximate number of sensors needed, so budgeting for equipment could be planned.

If any ventilation related drawings (both mechanical and natural) and photographs (both interior and exterior) could be provided, AIRBODS colleagues could provide some specific insights regarding what could be done if CO_2 levels go above threshold values.

It would be useful if BMS data could be provided along with occupancy numbers if available. The air temperature, fresh air flow rates for each zone, the typical number of people in each zone the condition of re-circulation (on or off), heat recovery (on or off), and air conditioning information would be particularly relevant.

It would be useful if the challenge stakeholders could identify operable windows (or any other types of ventilation opening), their approximate dimensions (size of opening), and types (i.e. top-hung/side-hung etc.). This would help the AIRBODS colleagues to approximate potential supply air flow rates from the windows or other openings.

Whilst AIRBODS are unable to recommend specific equipment, they can identify examples of CO_2 monitoring equipment (brand and model) which was previously used and tested in the Events Research Program (ERP), for consideration if and when Cambridge University Sports Centre/Independent Cinema Office/UK Hospitality decide to purchase CO_2 loggers. Some sensors should be located in fixed positions within the breathing zone. Sensors that log data continuously and which can be accessed remotely via a dashboard are particularly useful. Doing so would allow instant notification when the CO_2 levels exceeds threshold values. Note: When selecting a system for long term monitoring, consideration should be given for the regular calibration of sensors.

If the Independent Cinema Office could provide examples of a variety of cinema spaces and more information, AIRBODS colleagues can then provide more detailed insights and suggestions.

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4 Challenge 2: Risk Perception

Shakespeare's Globe and The Royal Opera House provided challenges surrounding audience risk perception, which are summarised in the following section.

4.1 Problems

General issues: how are people's (i) attendance (ii) likelihood of cancellation, dependent on

- Distance
- Age
- When they book relative to when the event is.
- Repeat visits

Both Shakespeare's Globe and The Royal Opera House provided anonymised data. Can we use the data to draw correlations between these attributes, and assess risk perception?

4.2 The Royal Opera House

The Royal Opera House (ROH) is interested in how their audience demographic has changed after the events of 2020-2021. In particular, they are interested in the following questions:

1. Who has stopped coming?
2. Why have they stopped coming?
3. What can be done about it?

We addressed the first question by comparing the attributes of people who booked tickets prior to the imposition of lockdown in 2020 and after a full season has resumed in Autumn 2021. We observe that the pandemic had a very varied impact on the willingness of audience members to return to the opera house depending on their age and location. As the demographic composition of audiences vary from show to show, we show that different productions may be sensitive to different changes in the audience demographic after lockdown.

4.2.1 The Data

We were given anonymised bookings dating from 2018 till 11 October 2021. We were given the following data attached to each booking:

- Age of the person making the booking, in bins of 5 years;
- First half of the postcode of the billing address;
- Production, type (opera/ballet) and the season of the production;
- Stage (Main stage/Linbury Theatre);
- Date of booking;
- Date and time of the performance;
- Number of tickets booked;
- Total amount paid.

4.2.2 Analysis

Data selection and Pre-Processing

We compared the nine evening performances of the *Die Zauberflöte* in 2019 and the nine evening performances 2021 and focused on the location and age of the people making the bookings. We chose *Die Zauberflöte* as a point of reference as the data recorded a full run and it was not a new production. We did not have pre-pandemic data in the dataset to assess the demographic shifts for audience attending *Rigoletto* and *Jenůfa*.

We excluded the two daytime performances in the 2021 run (there were no daytime performances in the 2019 run) in the comparative analysis to eliminate the factor of the time of the performance in influencing the audience demographic.

As we only had limited time to analyse the data, we primarily focused on characterising bookings with the first two attributes. We used these two features as they are characteristics of audience members that are less dependent on circumstances that can change from performance to performance. For example, the number of tickets and the total amount paid is dependent on the ticket availability and the social life of that audience member at the particular moment the person made the booking. We defer discussions on how these features might be

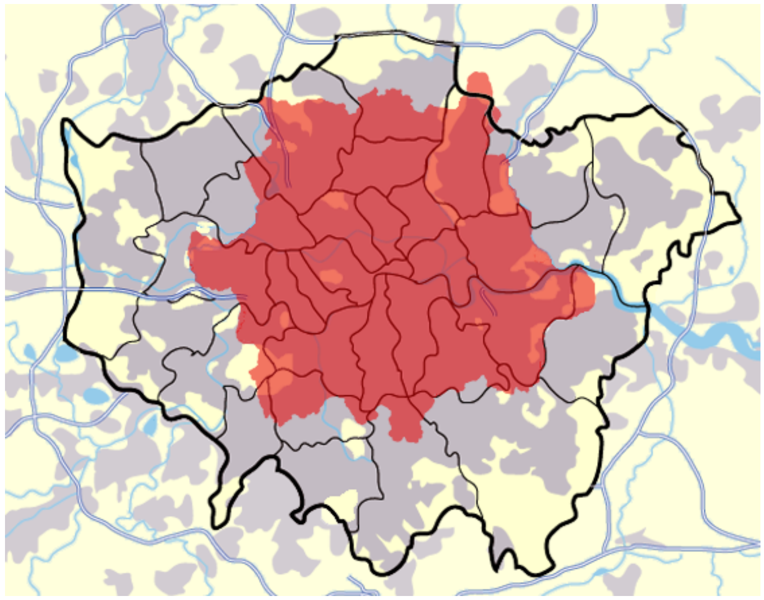

Figure 12: Inner London and Outer London Postcode Areas (source: [1])

used to characterise audience members with more sophisticated models in our discussion on future work.

We simplified the geographical data by classifying postcodes as either belonging to inner London, outer London, other UK, or non-UK, where the distinction between inner London and outer London is decided according to the London postal district designations (see Figure 12 and [1]).

Graphical summaries

Figures 13, 14, 15, 16 and 17 are graphical summaries of our findings.

Who has stopped coming?

We observed a significant decline in bookings from international audiences and those age 40+ outside London, while inner London audience attendance has stayed constant with no change in the age distribution. In fact, we saw an increase of audience members aged <30 attending these performances.

Who will stop coming?

We also examined the audience demographic variation across different productions pre-pandemic as a basis to predict which upcoming productions are likely to be impacted by the demographic shift post-lockdown (generalising from what we observe from Die Zauberflöte performances). For example, the reduction in international audiences are more likely to have a significant

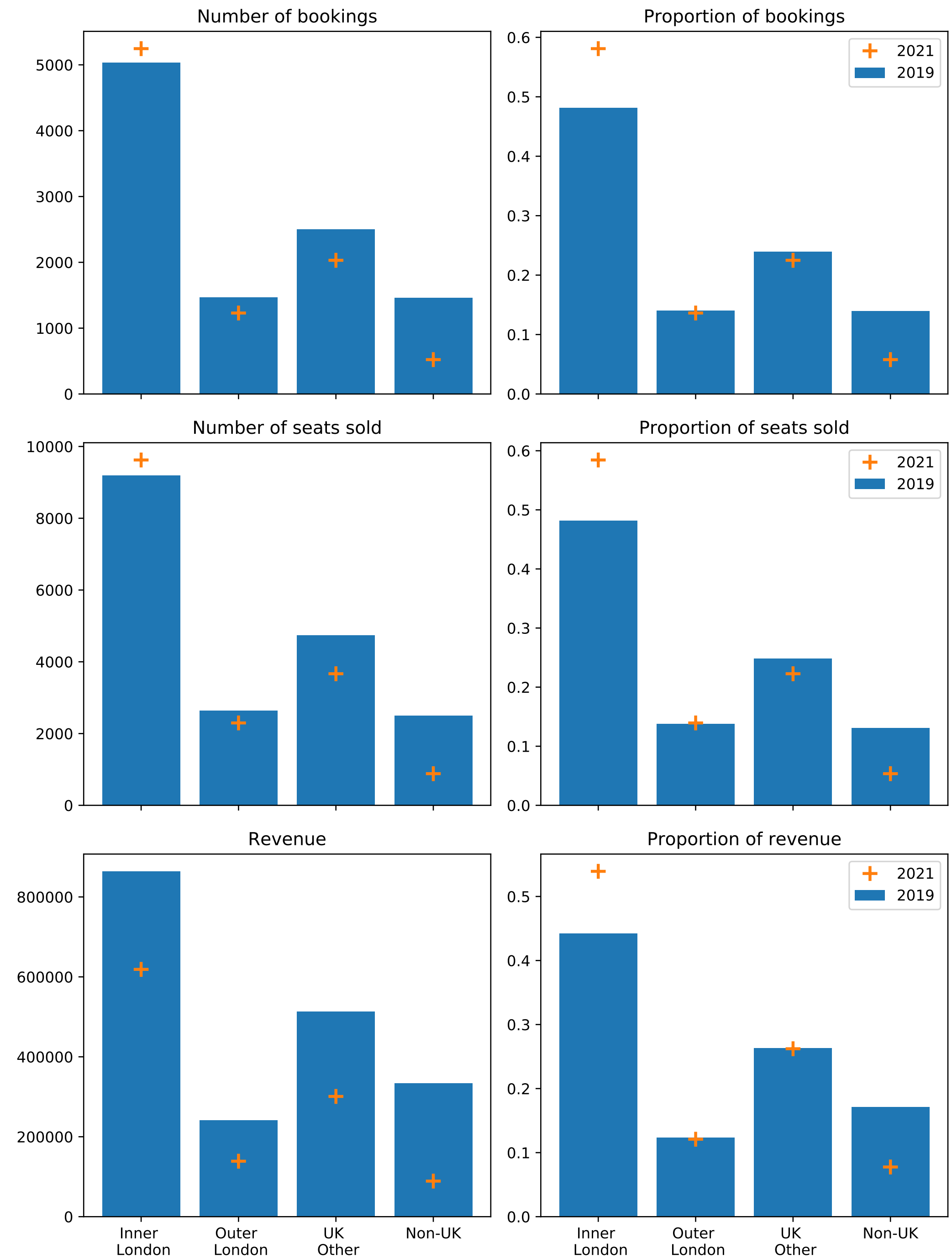

Figure 13: Pre and post lockdown geographical distribution of bookings, seats sold, and revenue across evening performances of Die Zauberflöte. The pre-lockdown run in Autumn 2019 consists of nine evening performances. The post-lockdown run in Autumn 2021 consists of nine evening performances, one performance in the afternoon and one performance in the morning; only the evening performances are included in this summary.

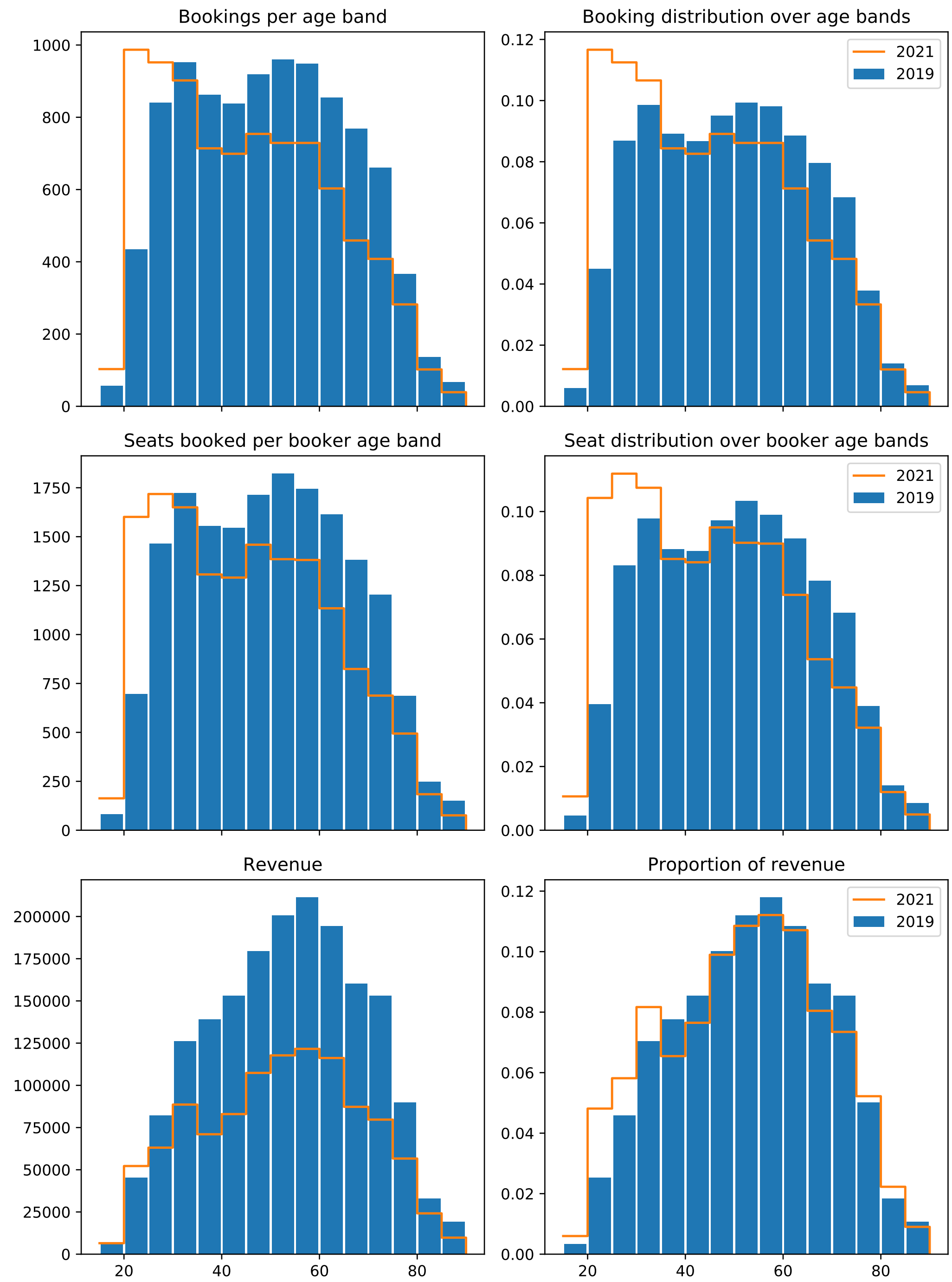

Figure 14: Pre and post lockdown age band distribution of bookings, seats sold, and revenue across evening performances of Die Zauberflöte. The pre-lockdown run in Autumn 2019 consists of nine evening performances. The post-lockdown run in Autumn 2021 consists of nine evening performances, one performance in the afternoon and one performance in the morning; only the evening performances are included in this summary.

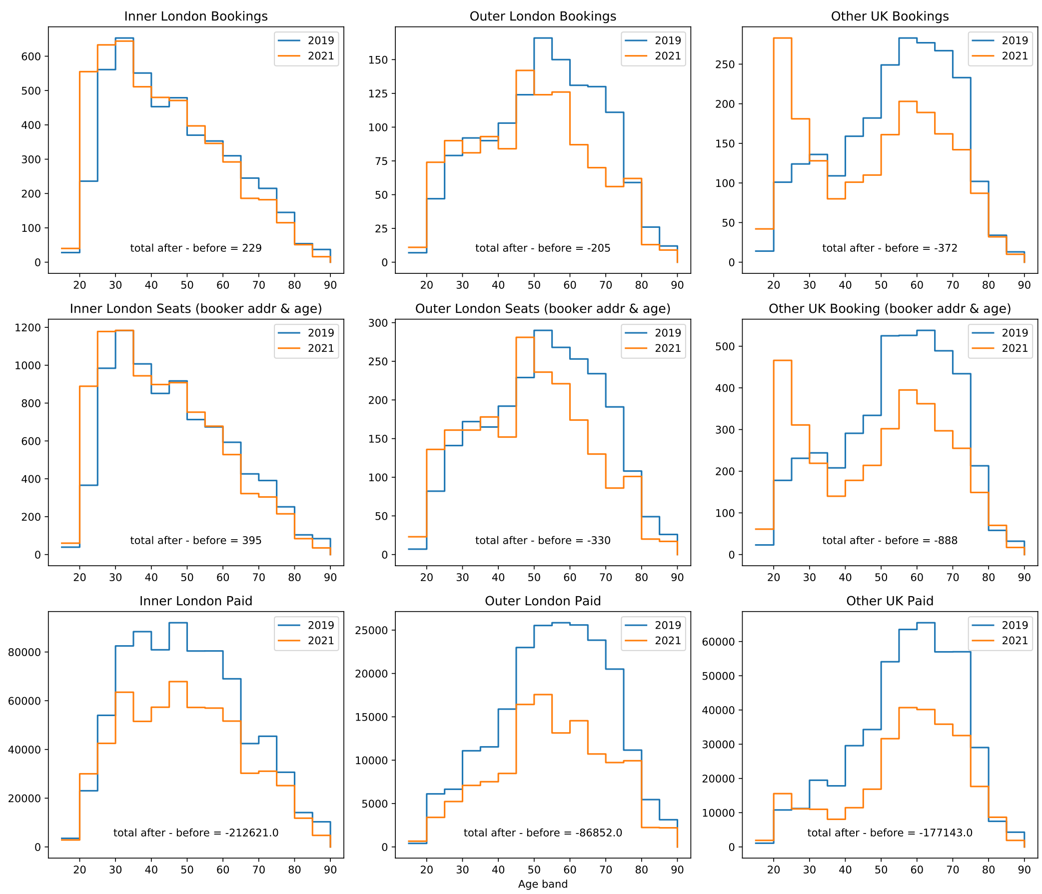

Figure 15: The number of bookings stratified along the age band and the location.

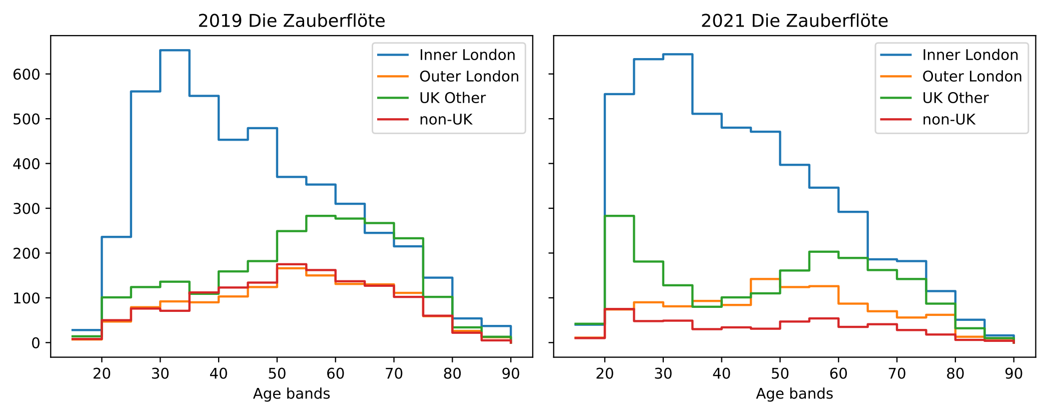

Figure 16: The number of bookings stratified along the age band and the location for Die Zauberflöte before and after the pandemic.

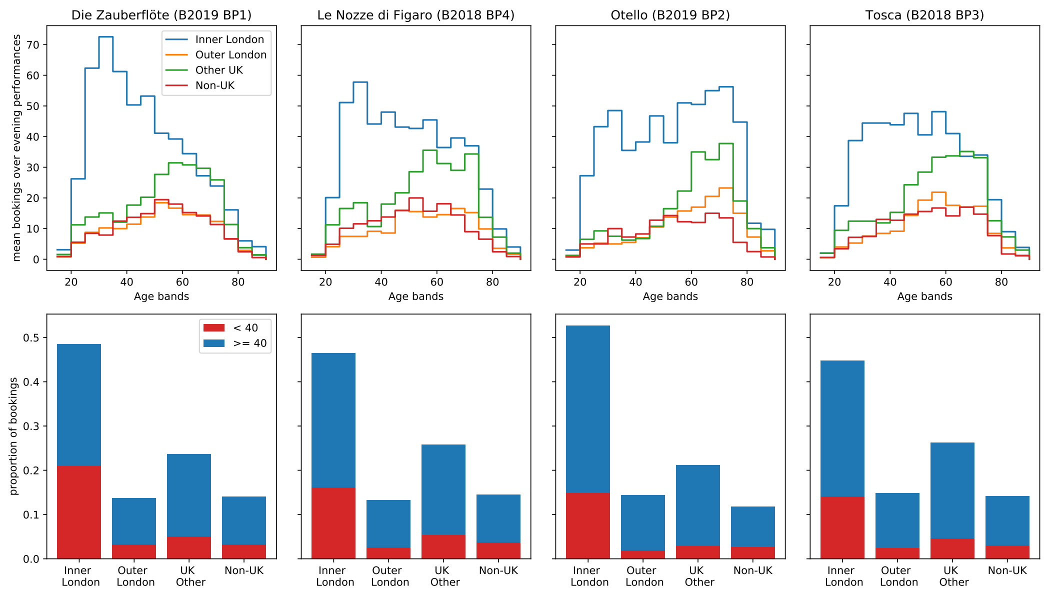

Figure 17: Projection for upcoming productions. Note that these productions have significant dependence on non-UK attendance and more dependence on older audiences than Die Zauberflöte.

impact on standard repertory productions such as Le Nozze di Figaro, and less so on Peter Grimes as Britten operas tend to be dominated by UK audiences.

Relevant results from the Indigo Audience Tracker

Indigo Ltd is a consultancy for the UK cultural sector, who worked with two other prominent consultancies (Baker Richards and One Further) to develop the Culture Restart Toolkit, a series of national surveys freely available for cultural organisations to use. They provided data from their Audience Tracker survey to give further insights into customer risk perception across the sector.

- The Royal Opera House collected 381 responses (out of a total of 45,450) for the Indigo Audience Tracker survey from May 18 to June 11 2021.
- 20.7% (79/381) people claimed that 'I was reluctant to travel to cultural events and venues'.
- 28.1% (107/381) people claimed that 'I was trying to avoid interacting with crowds of people'.
- 95.1% (362/381) of the participants are regular customers ('I attended/visited cultural events/venues pre COVID-19 4 or more times per year).
- 192 people answered the confidence question: an average rating of 2.78 was given when

asked to rate how confident they feel about attending/visiting cultural events/venues (5 very confident, -5 not very confident).

4.2.3 Discussion and Recommendations

Why have they stopped coming?

The cause of changes in the audience demographic is difficult to infer from the bookings data alone. In future work, the integration of the data from Indigo Ltd into the analysis may help to address this.

As there is no significant change in the age distribution among inner London audiences, we postulate that the perceived risk of coming to see an opera is no greater than other day-to-day activities (e.g. taking the Tube) for London residents interested in opera.

The difference in attendance due to geographic variation may not only be due to the perceived risk of going to the opera itself, but also the perceived infection risk of traveling and being in London, which is a far more crowded place than towns and villages which those 40+ outside inner London are likely to reside. Decline in audiences outside of inner London may also be due to competition with arts institutions local to their home addresses, and people moving out of London during the pandemic. Decline in international audiences is likely due to difficulties and reluctance to travel due to COVID travel restrictions imposed by governments.

What can we do?

Due to time constraints, we did not get a chance to fully engage with this part of the challenge. However, we note that the reasons for audience loss can be attributed to external factors (such as risk perception of London as a whole and international travel restrictions) that are out of ROH's control.

Despite stable numbers of audiences coming from inner London, ROH's net contribution to revenue has fallen. We have not investigated why that is the case, but note that ROH expected a drop in revenue yield, and as a result, launched audience development initiatives to fill the house, introduced young first time attenders through Young ROH reboot, and also extended their thank the NHS programme. Some work may be done on adjusting seating availability and pricing to shore up the revenue from the local audience base or attract audiences from out-side London.

4.2.4 Caveats

- As the ROH has only recently resumed full capacity performances, we are unable to comment on whether the demographic shift we observe (in particular the uptick in age <30 audiences) is due to pent up audience appetite that may dissipate over the coming months. On the other hand, this may be a sign that increased online content and engagement over the pandemic may have drawn in younger audiences, but more observations and surveys over the coming months are necessary to verify this claim.
- As the age distribution of Die Zauberflöte audiences is dissimilar to other operas (e.g. heavily skewed young, even compared to other Mozart operas e.g. Figaro), our observations may not generalise to other productions.
- We have only considered evening performances in our analysis for consistency. Unlike the run in 2019 which consisted entirely of evening performances, there are two extra non-evening productions of Die Zauberflöte 2021. Thus, the decline in audiences from outer London and beyond may be partially accounted for their ability to opt for the Saturday afternoon performance on offer. Indeed, we do see a relatively higher proportion of audience beyond inner London at that performance.
- We did not have enough time to compute confidence intervals that account for the variance in attendance from night to night. These confidence intervals will help us ascertain whether our observations are meaningful 'signals' that can be distinguished from the variability in attendance from night to night.

4.3 Shakespeare's Globe

Shakespeare's Globe hoped that more frequent and earlier communications would help customers to understand how they are mitigating risks and so help to shape their risk perception but cannot be sure how effective this has been. In particular, they are interested in addressing the following question: What can we learn about how and when our audience's perception of risks shaped?

Shakespeare's Globe shared anonymised bookings data that could be used to understand audience risk perception. This included data from there 2021 summer and 2019 summer season with the date, price, performance information and if/when a ticket is returned, distance of the customer to the venue (Globe, Inner London, Outer London, Non London) and some demographic data.

It would be beneficial to understand how well attending once predicts that a customer will return versus attending only once. The customer ID can be used to work out how many times customers return. The hypothesis is that once a customer has visited and felt safe, they are likely to return. It would be beneficial to refine by whether it is the first, second, third, ... visit, to look at typical waiting times between consecutive returns, and compare these to pre–COVID-19 and post–COVID-19 findings.

4.3.1 Analysis

Customer Retention

Figure 18 shows the proportion of people who visited/cancelled or exchanged tickets for the Globe n times for both 2019 and 2021 across four geographical categories (Globe, Inner London, Outer London, Non London). From this we can see that the majority of customers of both 2019 and 2021 visit the Globe once. The distribution of customer's visit times is stable across geographic categories. Furthermore, we notice that customers from the Globe addresses behave differently to the others and the proportion of customers visiting once goes down significantly from 2019 to 2021 with an increase in repeated visiting times.

The distribution of number of customer interactions is very similar between 2019 and 2021. However, when we filter by interactions where the customer did not return their ticket (i.e., attended), Figure 19 shows that the frequency of "1" visitors goes down, "2" visitors goes up, otherwise the distributions are the same. The possible explanation for this is that after visiting once, fear goes down, which results in a second visit, after which people return to their original patterns.

Visitor Geography

Figure 20 shows the number of bookings that were cancelled/exchanged or fulfilled across the four geographical locations. This shows that overall, there is a significant increase in the proportion of both attendance and cancellation from inner London from 2019 to 2021 due to the pandemic. The weights for Outer London and Non London remains roughly the same size before and after lockdown. The reduction from customers from the Globe addresses has been more pronounced in the cancellations than in the visits.

Visitor attendance across productions

Figures 21 and 22 show the that the visitor ratios are not hugely geographically affected but they are quite production affected. A shift in attendance increases towards Inner London

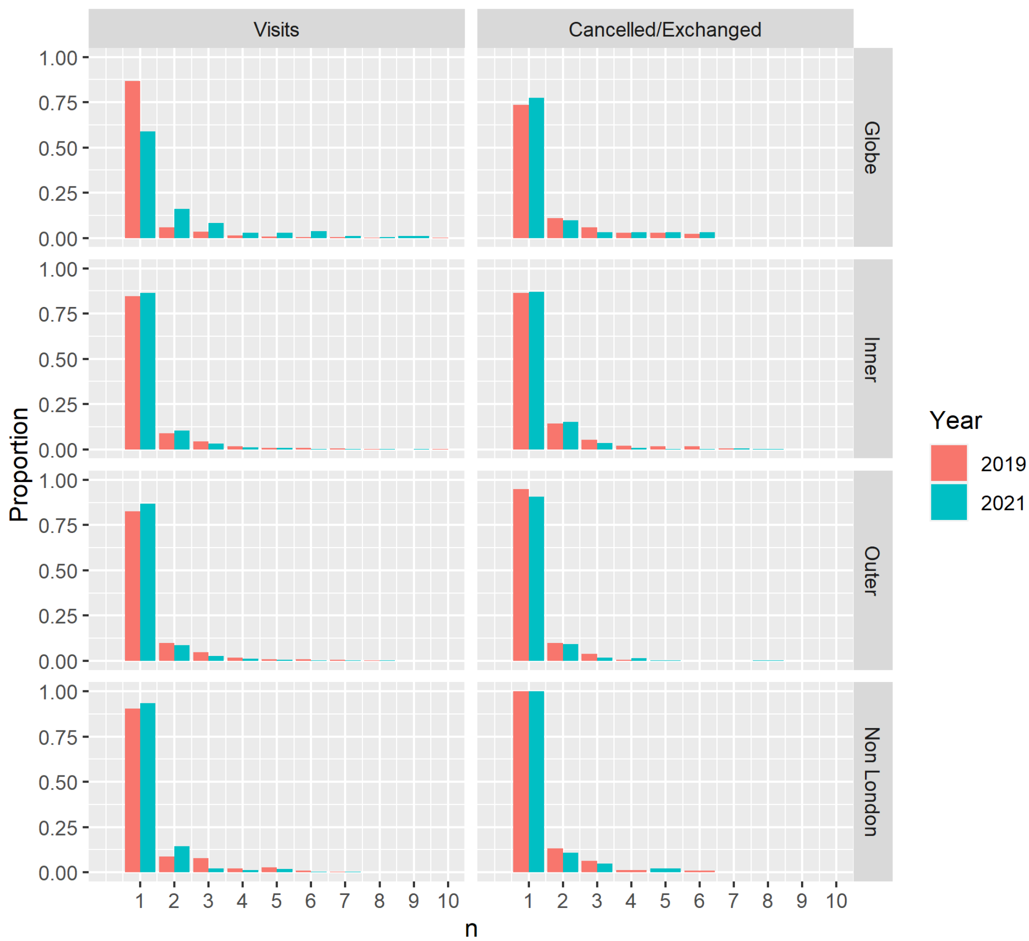

Figure 18: Proportion of proportion of people who visited/cancelled or exchanged tickets for the Globe n times for both 2019 and 2021 across four geographical categories (Globe, Inner London, Outer London, Non London).

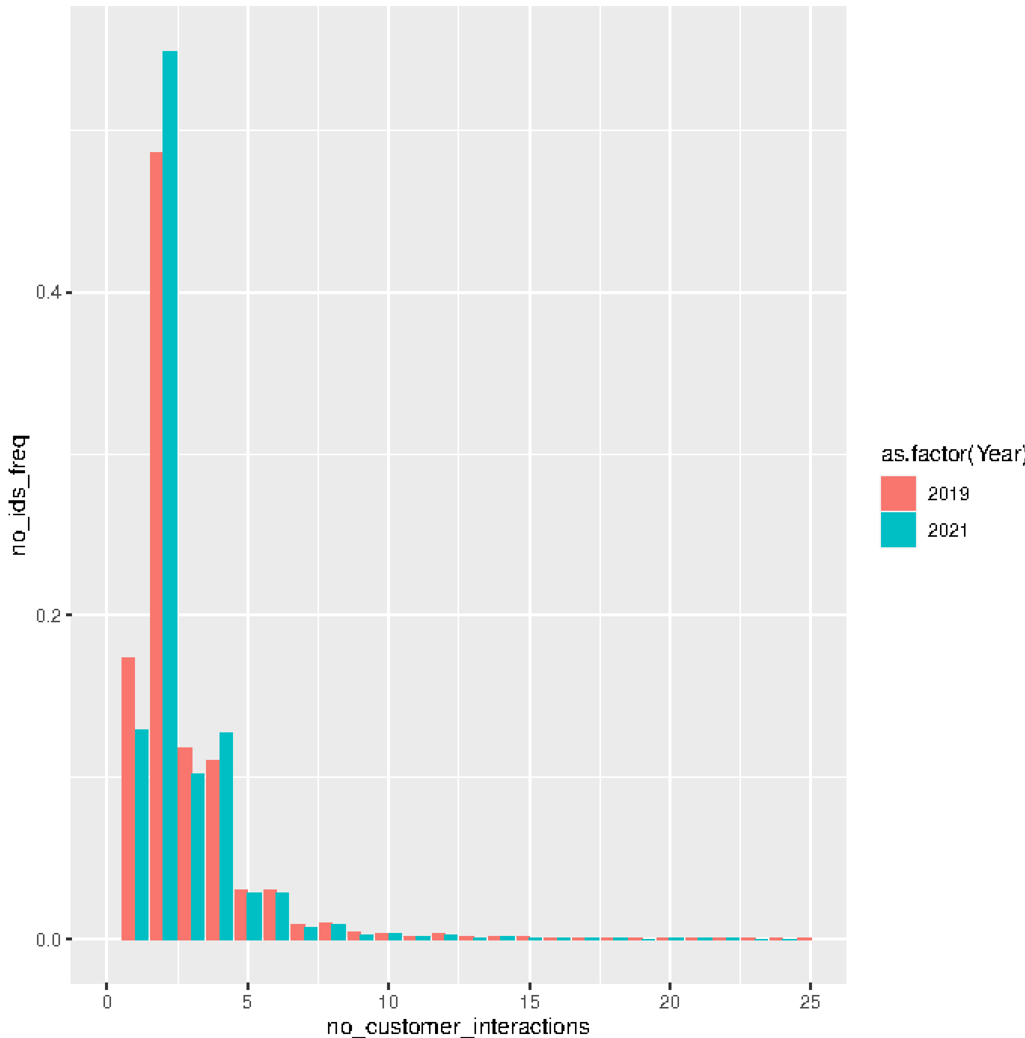

Figure 19: Distribution of visit numbers (for customers with < 400 visits).

and Outer London and decreases from the Globe addresses and Non London between 2019 and 2021. There are same variations in the performance percentages across different geographic categories - some productions with high visitor attendance could be advised going forward.

4.4 Summary & Future Work

Within this section, we have used the data provided by The Royal Opera House and Shakespeare's Globe to provide insights into customer risk perception.

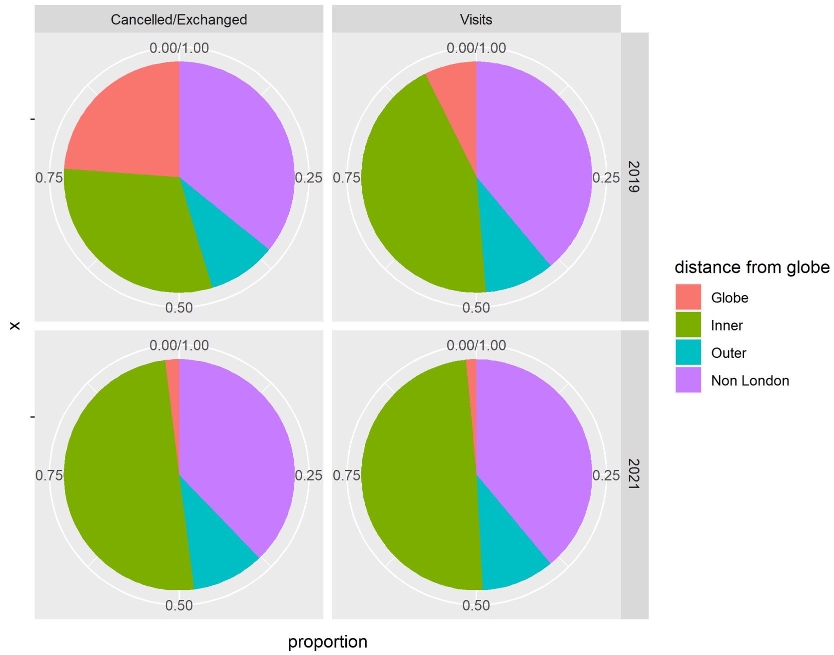

Figure 20: The number of bookings that were cancelled/exchanged or fulfilled across four geographical categories (Globe, Inner London, Outer London, Non London).

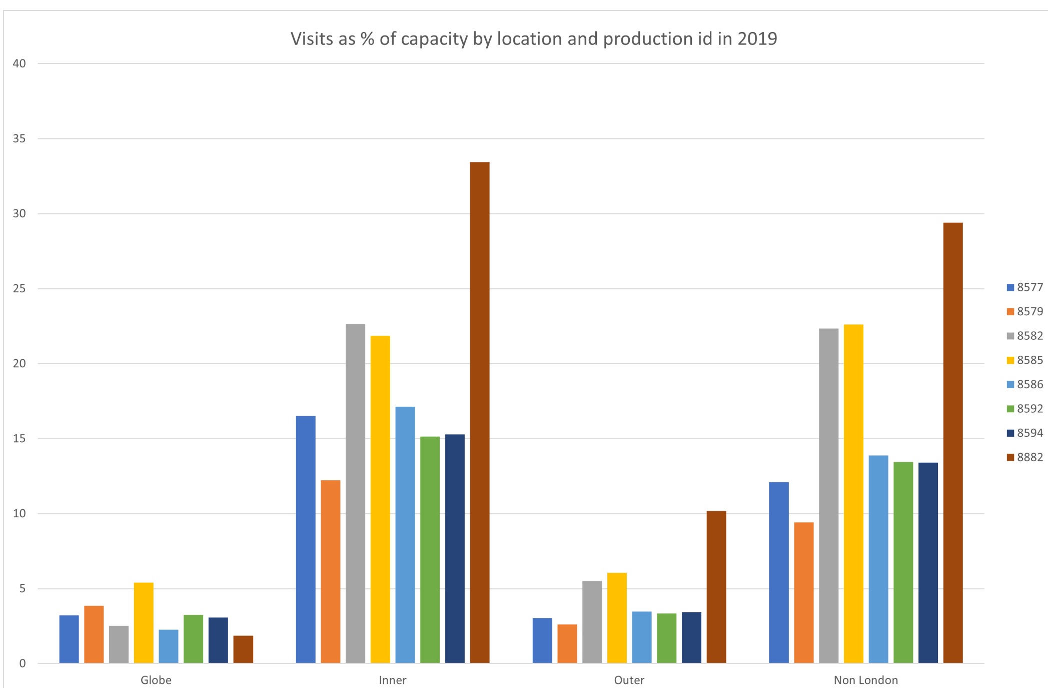

Figure 21: Visitor attendance across productions for 2019 across four geographical categories (Globe, Inner London, Outer London, Non London).

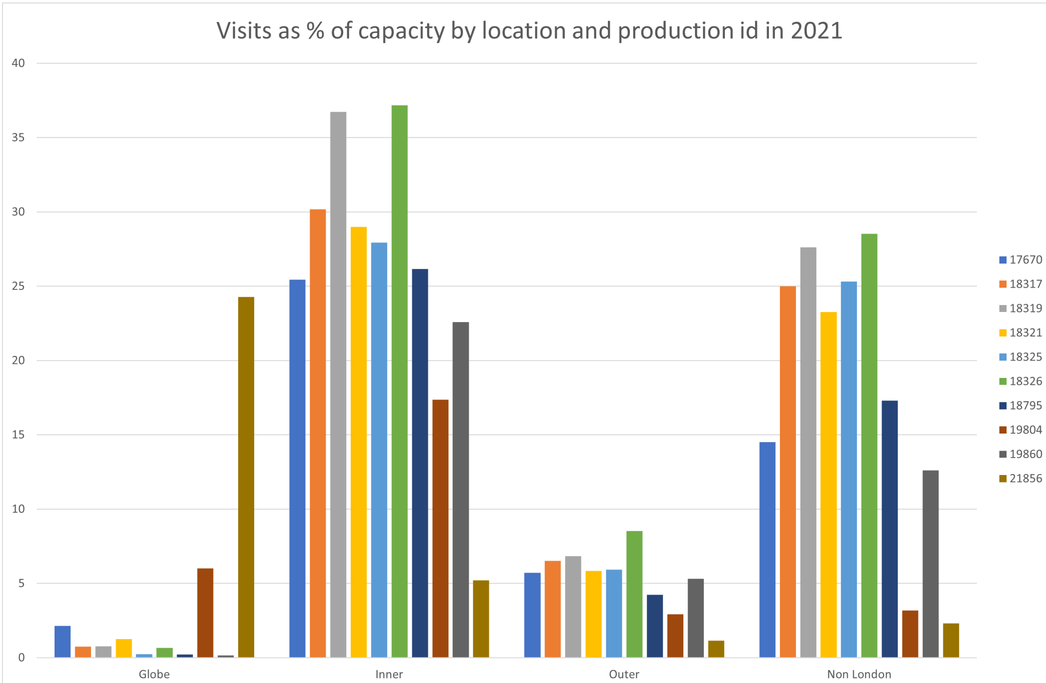

Figure 22: Visitor attendance across productions for 2021 across four geographical categories (Globe, Inner London, Outer London, Non London).

For The Royal Opera House, we focus on the Die Zauberflöte production and compare pre- and post-pandemic bookings. We find a significant decline in bookings from international audiences and those aged 40+ outside London, while inner London audience attendance has stayed constant with no change in the age distribution. Therefore, we postulate that the perceived risk of coming to see an opera is no greater than other day-to-day activities for London residents interested in opera.

For Shakespeare's Globe, we found that overall, there is a significant increase in the proportion of both attendance and cancellation from inner London from 2019 to 2021 due to the pandemic, but the distribution of customer's visit times is stable across geographic categories and the visitor ratios are not hugely geographically affected, although they are quite production affected. We find that there are same variations in the performance percentages across different geographic categories. Therefore, some productions with high visitor attendance could be advised going forward.

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5 Challenge 3 : Scheduling/Resource Management

Following the economic shock caused by COVID restrictions the hospitality industry is facing a challenging environment caused by staff shortages, supply chain problems and changes to consumer behaviour. However, measures introduced during COVID to facilitate contactless payment mean that even small hospitality businesses now have access to significant amounts of data. This section shows that by combining that data with optimisation techniques such as integer programming available in standard spreadsheet software, a single business can optimise profits while respecting scheduling constraints. Significant further benefits may be gained by multiple businesses working cooperatively.

5.1 Problems

The hospitality sector is facing a number of challenges. There are staff shortages and supply chain problems. These have exacerbated problems caused by the COVID epidemic in which the hospitality and leisure industry has taken a big economic hit. The current environment is still substantially different to the pre-COVID environment in that there appear to be certain customer sectors that have not returned to their usual spending patterns and in addition there are changes in customer behaviours such as an increase in the number of cancellations. Spend per customer also appears to be decreasing. Finally, the sector is concerned that there may be a future economic shock due to the possibility of further government restrictions over the winter. However, some of the changes introduced in the wake of the pandemic such as increased use of card and contactless payments means that many businesses have ready access to much more data than before. Thus, there is potential for combining this data with optimisation algorithms to to match resource (staff) to demand, both at the level of a single business and at the level of a consortium of businesses acting cooperatively.

5.2 Workings

5.2.1 A toy model

A toy decision support model can be used to illustrate how optimisation can assist in decision making and illustrate some of the trade-offs involved. This model also provides a starting point for models discussed subsequently, with elaborations of this initial idea. In this model we give a function providing the utility, u (essentially profit) which would be accrued if the business stays open for o hours with x_o tables operating given that x tables are occupied and y tables were booked but not claimed

$$u(x_0, o) = o\left[\underline{C}y + Cx - D\max\{x - x_0, 0\} - (P + Gx_0)\right] - (16 - o)K.$$

The utility function has terms relating to income

- $\underline{C}y$ booking fee collected from no shows, y,
- Cx income from customers, x, including the booking fee,

and also has terms relating to costs

- $P + Gx_0$ fixed and variable costs of being open with staffing levels for x_0 tables
- $D\max\{x - x_0, 0\}$ lost revenue and reputation cost (expressed as in financial terms) of turning customers away
- $(16 - o)K_i$ operating costs while closed (a maximum of 16 hours open is assumed).

5.2.2 Stochastic Optimisation

The model described in section 5.2.1 has a number of shortcomings. The first is that it assumes that the number of customers who will book and attend and book, but not show up (x and y respectively) are known in advance. In fact at best a range of possible values of these can be given. Thus, we must optimise subject to probability distributions of x and y which can in principle be determined from previous data or can be imposed to investigate various scenarios.

A utility function taking into account stochastic demand would take the form

$$\begin{aligned} u(x_0, o) = &\sum_{i=1}^{o}\left[\underline{C}y_i + C\left(x_i + \hat{x}_i\right) - D\max\{x_i + \hat{x}_i - x_0, 0\} - (P + Gx_0)\right] \\ &- \sum_{i=1}^{16-o} K_i \end{aligned}$$

This function includes a stochastic component to demand, $\hat{x}_i$: $\hat{x}_i < 0$, represents more no shows than anticipated, $\hat{x}_i > 0$ represents excessive walk ins. A Monte-Carlo algorithm, implemented in python code is used to optimise this function. For each hour of potential opening, the optimal staffing numbers are determined such that an ensemble average of $\hat{x}$ utility is maximised. The optimal opening hour is then determined by the maximum out of the utilities

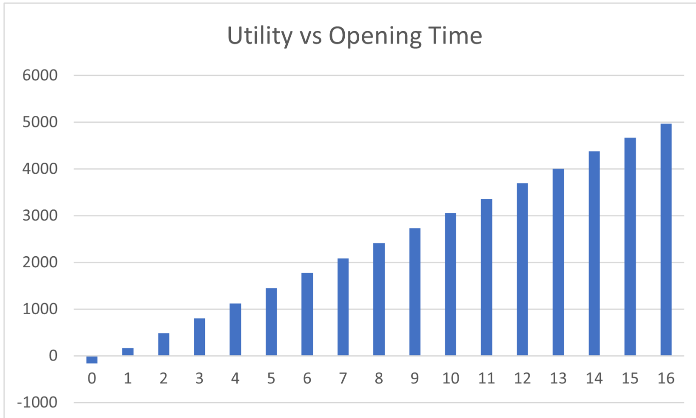


Figure 23: Utility vs opening time. For this example the parameters chosen favour the business remaining open for as long as possible.

calculated constraining the number of opening hours. This is shown in Figure 23. In this case, the parameters chosen favour staying open for the full 16 hours. However, other parameter values may favour more limited opening hours.

5.2.3 Integer Programming: Single Business

Further progress can be made by including ideas from the field of integer programming. This is a flexible framework which can also allow non-financial considerations to be included such as infection risk to be built into the model. Integer programming algorithms are available as part of many spreadsheet packages such as Microsoft Excel and Open Office Calc. An example implementation was created within Excel taking the perspective of a small business owner. No-shows in bookings, cancellations and walk-ins were implemented stochasticaly. An equivalent financial cost for infection risk was also built in. Excel's solver suite was used to maximise expected utility. Although valid for a single business owner acting independently, this model could also be used to predict the benefits of operating as part of a network. Key benefits of acting as part of a network would be less lost sales and reduced uncertainty: this framework would allow these benefits to be quantified.

The model optimises a utility function with terms representing income from

- Booking fee = (bookings - MIN (demand, bookings) × fee
- Service = MIN (demand, service capacity) × revenue per customer

and costs of

- Opening the restaurant, a fixed cost
- Running the service capacity = service capacity $\times$ variable cost
- Lost sales or reputation cost = MAX (demand-service capacity, 0) $\times$ lost sales or reputation cost
- Infection risk = f(MIN(demand, service capacity)/maximum capacity)

To calculate infection risk it is assumed that the crowding of people within the available space, i.e., the level of capacity utilization, has an increasing effect on the infection risk and this should be reflected in the choice of the function f.

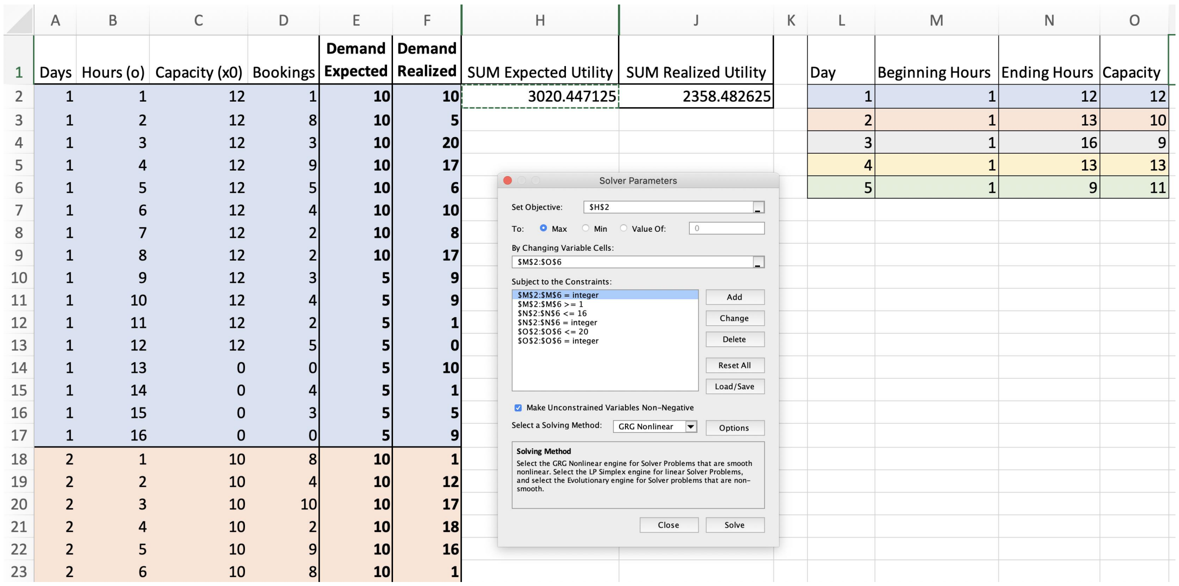
$$\begin{aligned} u(x_{0,m}, o_m) = \sum_{j=1}^{m}\sum_{i=1}^{o}\big((b_{j,i} - \min(d_{j,i}, b_{j,i}))\underline{C} + \min(d_{j,i}, x_{0,m})C \\ - (P + Gx_{0,m}) - \max(d_{j,i} - x_{0,m}, 0)L \\ - f(\min(d_{j,i}, x_{0,m})/x_R)\big) \end{aligned}$$

The optimal utility is calculated by optimising over the decision variables: the service capacity, $x_{0,m}$, of the restaurant on day m and the number of hours, o_m, the restaurant would be open on day m. This optimum is subject to constraints on the maximum service capacity and the maximum number of hours that the restaurant can remain open. The model requires as input statistical data on bookings and expected demand and financial data on revenues and costs per unit.

To test these ideas an example restaurant was simulated as shown in Figure 24. The restaurant has the following characteristics

- A maximum service capacity of 20 people
- Bookings vary between 1 and 10 per hour
- The expected demand is 10 people in the earlier times of the day, but drops to 5 people in later hours
- Customers arrive based on a uniformly distributed stochastic demand

The optimisation process determines the best integer values for ‘beginning hour’, ‘ending hour’, and ‘service capacity’ for the business each day and thus allows a business owner to identify the profits to be gained from the demand smoothing the app would provide.



	A	B	C	D	E	F	H	J
1	Days	Hours (o)	Capacity (x0)	Bookings	Demand Expected	Demand Realized	SUM Expected Utility	SUM Realized Utility
2	1	1	12	1	10	10	3020.447125	2358.482625
3	1	2	12	8	10	5		
4	1	3	12	3	10	20		
5	1	4	12	9	10	17		
6	1	5	12	5	10	6		
7	1	6	12	4	10	10		
8	1	7	12	2	10	8		
9	1	8	12	2	10	17		
10	1	9	12	3	5	9		
11	1	10	12	4	5	9		
12	1	11	12	2	5	1		
13	1	12	12	5	5	0		
14	1	13	0	0	5	10		
15	1	14	0	4	5	1		
16	1	15	0	3	5	5		
17	1	16	0	0	5	9		
18	2	1	10	8	10	1		
19	2	2	10	4	10	12		
20	2	3	10	10	10	17		
21	2	4	10	2	10	18		
22	2	5	10	9	10	16		
23	2	6	10	8	10	1		

	L	M	N	O
1	Day	Beginning Hours	Ending Hours	Capacity
2	1	1	12	12
3	2	1	13	10
4	3	1	16	9
5	4	1	13	13
6	5	1	9	11

Figure 24: Screenshot showing the single business integer optimisation model.

5.2.4 Integer Programming: Multiple Businesses

The integer programming approach can also be used to manage demand across several co-operating restaurants. A model was created with

- Deterministic demand
- Integer constraints for:
  - Staff availability/opening hours
  - Minimum numbers of customer (needed for viability)
  - Maximum number of customers

The model allocates custom to maximise the sum of fractions of target customer numbers.

To illustrate the benefits of cooperation, the model was first run as a greedy algorithm with each restaurant in the list taking the maximum number of customers possible until no customers remain. This represents a worst case non-cooperation scenario. Note that in reality restaurants would not know their position on the list and thus whether they would benefit. In this case, as shown in Figure 25, three out of five restaurants go out of business, despite there being 1100 total customers in a week. However, in the case of cooperation, shown in Figure 26, the same level of custom is enough to keep all restaurants financially viable.

M	T	W	R	F	S	U		Weekly Totals
5	5	5	5	5	5	5		700
12	12	12	4	0	0	0		400
0	0	0	0	0	0	0		0
0	0	0	0	0	0	0		0
0	0	0	0	0	0	0		0
220	220	220	140	100	100	100		1100

Figure 25: In a worst case scenario for uncooperative behaviour three out of five restaurants go out of business.

M	T	W	R	F	S	U		Weekly Totals
1	4	0	0	5	0	0		200
10	0	0	0	0	0	10		200
6	0	0	0	0	0	7		104
0	0	5	5	5	4	5		190
0	2	10	4	1	0	0		400
168	120	225	145	190	40	206		1094

Figure 26: In the case of cooperation all restaurants remain financially viable.

5.3 Summary & Future Work

In this section, we aim to address the issue of staff shortages highlighted by UK Hospitality. We begin by using a toy decision support model to illustrate how optimisation can assist in decision making and illustrate some of the trade-offs involved. We then use stochastic optimisation to account for stochastic demand and integer programming to further develop the model. We consider resource demand on both a single business level as well as at a multiple business level.

With more data becoming available there is increased potential to combine this data with optimisation algorithms to increase profits by better matching supply and demand. Modern spreadsheet programs have sophisticated optimisation techniques built in and can handle problems involving integer variables and constraints. These benefits can be realised by a single business working alone, however, further benefits can be gained through cooperation.

An idea for future work would be to develop an app that promotes cooperation. The app functionality could include:

- Aggregating useful information for customers such as price range, COVID-19 mitigation measures, rate of footfall so customer can avoid busy areas.
- Easy booking, with a booking deposit that goes to the restaurant should the customer cancel.
- If the restaurant needs to cancel, the booking deposit could be easily moved to another restaurant - similar restaurants can be recommended to the user in this case, in order to maintain goodwill and reduce inconvenience to the customer.
- Provide information about expected footfall to the restaurant owner so that they can staff accordingly.
- Providing this convenient service to the customer will lead to more return users.

On a restaurant-by-restaurant basis, our modelling showed that information such as what we hope this app would provide could allow the owner to staff according to predicted demand. Then, when implementing this optimisation and accounting for cooperation by, for example, reducing loss of goodwill, additional utility can be gained. However, it is important to consider the UK's competition law when developing such an app.

Our models rely on estimated parameter values, for example number of customers required per week for a business to be viable, and costs of opening. Providing these models with accurate parameter values would be vital in quantifying the true benefits of the app we suggest.

6 Conclusions

Over the study group, potential solutions were developed and these were presented on the final day. The outcomes are summarised in the following.

- Group 1: we have provided general guidance on how to ventilate indoor spaces, highlighting key guidance and tools, and provided a list of survey questions that can be used to identify venues with potential ventilation problems as well as guidance on the installation of CO2 monitors for Cambridge University Sports Centre and the Independent Cinema Office.

- Group 2: we have used data to provide insights into customer risk perception specific to The Royal Opera House and Shakespeare's Globe. We compared pre- and post-pandemic bookings data and use this to understand whether there has been a change in the groups of people attending performances.
  For The Royal Opera House, we focus on the Die Zauberflöte production and find a significant decline in bookings from international audiences and those aged 40+ outside London, while inner London audience attendance has stayed constant with no change in the age distribution.
  For Shakespeare's Globe, we found that overall, there is a significant increase in the proportion of both attendance and cancellation from inner London from 2019 to 2021 due to the pandemic, but the distribution of customer's visit times is stable across geographic categories and the visitor ratios are not hugely geographically affected, although they are quite production affected.

- Group 3: we address the issue of resource shortages using a toy decision support model, stochastic optimisation and integer programming to develop the model. We consider resource demand on both a single business level as well as at a multiple business level. Our modelling found that when restaurants work together to spread their load, small numbers of customers can ensure that all restaurants can stay open as long as a minimum threshold is met. However, if some restaurants are greedy, this can lead to closures due to lack of income

Next Steps:

A collaboration between the University of Oxford Mathematical Institute and The Royal Opera House was brought about in the follow up to this study group and a project is on the horizon.

A follow up event will be hosted by the Institute for Mathematical Innovation in the coming months to discuss and build on some of the outcomes of this study group.

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