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Impact of ventilation and avoidance measures on SARS-CoV-2 risk of infection in public indoor environments

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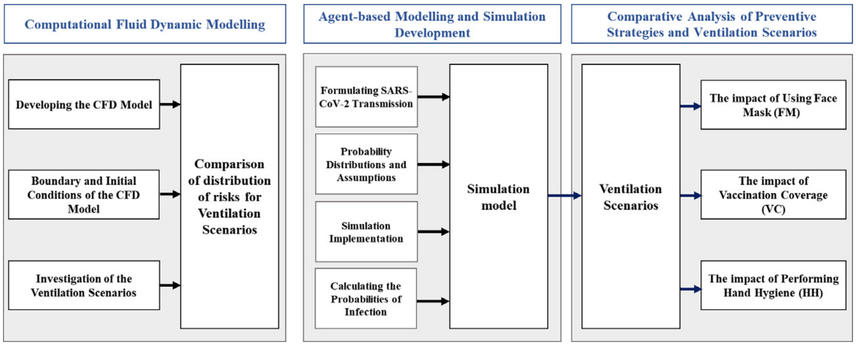
HIGHLIGHTS

- Delta variant requires the air change rate to be increased >1000 times compared to the original strain to prevent spread.
- Face coverings were the most effective and reliable form of preventative measure identified in simulations.
- Vaccinations had the potential to be highly effective given good compliance within the individual population.
- Indoor events with adherence to face coverings, have a minimal effect on the epidemic spread.

GRAPHICAL ABSTRACT



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ABSTRACT

Background: The literature includes many studies which individually assess the efficacy of protective measures against the spread of the SARS-CoV-2 virus. This study considers the high infection risk in public buildings and models the quality of the indoor environment, related safety measures, and their efficacy in preventing the spread of the SARS-CoV-2 virus.

Methods: Simulations are created that consider protective factors such as hand hygiene, face covering and engagement with Covid-19 vaccination programs in reducing the risk of infection in a university foyer. Furthermore, a computational fluid dynamics model is developed to simulate and analyse the university foyer under three ventilation regimes. The probability of transmission was measured across different scenarios.

Findings: Estimates suggest that the Delta variant requires the air change rate to be increased >1000 times compared to the original strain, which is practically not feasible. Consequently, appropriate hygiene practices, such as wearing masks, are essential to reducing secondary infections. A comparison of different protective factors in simulations found the overall burden of infections resulting from indoor contact depends on (i) face mask adherence, (ii) quality of the ventilation system, and (iii) other hygiene practices.

Interpretation: Relying on ventilation, whether natural, mechanical, or mixed, is not sufficient alone to mitigate the risk of aerosol infections. This is due to the internal configuration of the indoor space in terms of (i) size and number of windows, their location and opening frequency, as well as the position of the air extraction and supply inlets, which often induce hotspots with stagnating air, (ii) the excessive required air change rate. Hence, strict reliance on proper hygiene practices, namely adherence to face coverings and hand sanitising, are essential. Consequently, face mask adherence should be emphasized and promoted by policymakers for public health applications. Similar research may need to be conducted using a similar approach on the Omicron (B.1.1.529) variant.

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1. Introduction

In recent decades the evolution of viral diseases, such as SARS-CoV-1 (SARS), H1N1 (swine flu) and SARS-CoV-2, has highlighted how pathogens can quickly spread in indoor environments. A new form of coronavirus, SARS-CoV-2, was first reported in the Wuhan Province of China in December 2019 – and rapidly escalated to a worldwide pandemic by March 2020 (Dinleyici et al., 2021). The current COVID-19 pandemic has resulted in lockdowns worldwide to reduce contaminations. Since the fourteenth century, quarantines have been used as an effective solution for widespread disease (Tognotti, 2013). However, this is not always a viable socioeconomic or political solution in the modern world. Haug et al. predict that despite the long-lasting protection vaccines can provide and their role in reducing SARS-CoV-2 transmission, they alone cannot bring about the end of the pandemic. High levels of global population coverage are required to lower the transmission in the long term. To reduce the likelihood of spread, the incidences in which an infected individual encounters a susceptible one must be reduced, as well as risk reducing measures for each time, they are in contact (Haug et al., 2020; Skegg et al., 2021). Hence, better prevention methods need developing to allow a return to near pre-pandemic life despite the prevalence of pathogens, such as SAR-CoV-2. One possible solution is ensuring public indoor spaces have more robust ventilation systems and operational procedures to reduce viral transmission through aerosols. Delikhoon et al. (2021) reviewed recent literature on factors influencing airborne transmission of SARS-Cov-2 and the effects of negative pressure ventilation. They concluded that negative pressure ventilation, displacement ventilation, air conditioning systems, and non-invasive positive pressure ventilation are essential preventive measures against viral infection. Other possible solutions are mask-wearing, vaccinations, physical distancing, and hand hygiene. Premature de-escalation of preventative measures such as face coverage, social distancing and hand hygiene could be detrimental to transmission control. As such, this paper reviews existing research into the indoor transmission of disease to inform the correct ventilation configuration strategy as well as behavioural preventative measures, focusing on a university building case study. Universities are known for their potentially high infection risk due to individuals' social lifestyles and the use of public study spaces. This paper hypothesises that an adequately controlled indoor environment alongside other preventative measures including face covering, vaccination and hand hygiene can significantly reduce the risk of infections via aerosol transmission. Face coverings and physical distancing were some of the preliminary measures taken in a large number of countries to reduce the spread of SAR-CoV-2 at the start of the pandemic. Face masks work by blocking the exhalation of virus-containing aerosols in infected individuals, known as source control of infection (Brooks and Butler, 2021).

Furthermore, face masks offer protection for susceptible wearers by blocking larger droplets that could encounter exposed mucous membranes of the nose and mouth. In 2021, public health guidance for the use of face masks was relaxed across the UK before being re-implemented with the resurgence of a 'winter wave'. This paper investigates the extent of the role of ventilation in mitigating the risk of aerosol-induced infections in public indoor spaces and considers the efficacy of face mask usage with differing compliance to face-covering guidelines. These hypotheses are investigated through the creation of simulation models using Computational Fluid Dynamics (CFD) to assess the impact of different variables on the risk of transmission of SARS-CoV-2 in indoor environments.

The literature reports that transmission of diseases can occur through a variety of vectors, including aerosols (Fernstrom Michael, 2013; Khai, 2016; Kang et al., 2020). Interestingly, some research explores the correlation between levels of CO_2 in an indoor environment with the risk of transmission for an airborne pathogen (Fernstrom Michael, 2013; Khai, 2016; Kang et al., 2020). This can be calculated using the rebreathed rate of air, as it is assumed that the same air an infected person has breathed out must be breathed in by a susceptible person for contamination to take place.

The main vectors for indoor disease transmission are aerosol, droplet and contact (Fernstrom Michael, 2013; Khai, 2016; Kang et al., 2020). Guzman (2021) states that in terms of aerosols, the size (i.e., aerodynamic diameter) of bioaerosol particles carrying SARS-CoV-2 plays a determinant role in the propagation of the virus (Guzman, 2021). A SARS-CoV-2 carrier person provides a pathogenic bioaerosol load with submicron particles that remain suspended in the air for up to 3 h, and that can travel several meters before settling on surfaces (Guzman, 2021). These particles can potentially be inhaled by, and thus contaminate, a healthy person. Furthermore, the deposited bioaerosol creates contaminated surfaces, which if touched can act as a transmission vector to introduce the pathogen by mouth, nose or eyes and cause disease (Guzman, 2021). Direct contact is person-to-person infection through physical contact and can be mitigated using handwashing or sanitising (Khai, 2016; World Health Organization WHO, 2008; Lei et al., 2019; Tellier et al., 2019). To mitigate the risk of aerosol transmission, airflow must be controlled. Air changes per hour (ACH) is the number of times in an hour that the whole volume of air in a room is replaced by ventilated air, it influences the likelihood that suspended particles will settle onto surfaces and spread disease through direct contact. Therefore, by increasing the ACH, the risk of disease transmission can be reduced (Kohanski et al., 2020). This is done using HVAC (heating, ventilation, and air conditioning) systems. Studies have shown an association between decreased ventilation rates and increased infectious illness, but there are insufficient data to substantiate this claim (Adams et al., 2016; Luongo et al., 2016). ACH as a measure may not be representative unless taken over the whole year, and this is a limitation of some studies discussed in Luongo et al. (2016). The paper concludes that a positive causality cannot be established using only observational studies, but these are useful for exploring hypotheses.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) gives general guidance to cover different locations. Usually, for schools, a recommended ACH of 5–6 is given; however, ASHRAE recommends a higher ventilation rate of 6–12 ACH when dealing with viruses (Robertson, 2020). ACH is greatly affected by the HVAC system as well as the use of natural ventilation. This is discussed in Pirouz et al. (2021), as well as the way a human sneeze interacts with the air. The study simulates the aerosols and looks at how windows and dead zones can have an effect on their transport. Allen and Ibrahim (2021) explain how ventilation is essential in limiting the spread of SARS-CoV-2 and that previously most buildings were not designed for infection control. The link between air quality, pollution and SARS-CoV-2 is discussed in Ching and Kajino (2020), which notes that there is a correlation between deaths and air pollution, as well as air quality is improved in places that implemented a lockdown.

Lipinski et al. (2020) suggests that the type of flow produced by different types of ventilation, either laminar or turbulent, directly impacts the risk of disease transmission. Laminar flow, produced by displacement ventilation such as natural, can be more effective at removing diseases because layers of air rise to the ceiling to be removed without mixing. Conversely, recirculating systems can increase the risk of infection because turbulent flows mix clean and contaminated air, increasing transmission and allowing occupants to breathe contaminated air. These can result in a higher risk of transmission than in an unventilated room.

Other research discusses a possible correlation between carbon dioxide (CO_2) levels and the viral charge of aerosols in indoor environments (Seppanen et al., 1999; Mahyuddin Hazim, 2010; Rudnick, 2003a). Rudnick (2003a) discusses how the risk of airborne infection transmission could be estimated using CO_2 concentration. The rebreathed fraction is the fraction of inhaled air that has been previously exhaled by someone in the building and is found using CO_2 concentration as a marker. The Wells-Riley equation, used to compute the risk of airborne infection, assumes the concentration of suspended particles is at a steady-state level throughout exposure and that particles are airborne for long periods of time (Riley et al., 1978). This is not always the case, depending on particle size. Rudnick (2003a) provides a new formulation that provides an estimate of the "risk of indoor transmission of infection by the airborne route" without the need for the assumptions associated with the Wells-Riley eq. A variety of software is freely available to study disease transmission in indoor environments. Computational fluid dynamics (CFD) is the basis for most models involving the transmission of diseases (Grefenstette et al., 2013; Elmaghraby et al., 2018; Fariq et al., 2020; Peng et al., 2020; Elsayed, 2021; Robinson et al., 2021; Shi et al., 2021).

The known possible solutions effective in preventing SARS-CoV-2 transmission are vaccination, wearing face masks (FM), physical distancing, and hand hygiene. In a systematic review, Chu et al. (2020) investigated the effects of physical distance, face mask, and eye protection on virus transmission in healthcare and non-healthcare settings. Their finding supported physical distancing, face mask use, respirators, and eye protection in public. However, the degree to which these restrictions could be eased will be dependent on the effectiveness of the potential COVID-19 vaccines, which is variant sensitive (Chu et al., 2020; Poland et al., 2020; O'Donohue et al., 2021; Shen et al., 2021). To allow careful planning about what restrictions may need to be continued, research is required to project the effectiveness of indoor adjustment and wearing face masks alongside vaccination.

To encounter the Covid-19 pandemic, knowledge on the transmission of disease and prevention strategies in place is crucial to mitigate its impacts. Elveback et al. (1976) were quick to evaluate the effectiveness of intervention strategies, including the closure of schools and vaccination programs. There have been various strategies proposed to prevent the spread of transmission. Development of these strategies often includes using simulation models of the Covid-19 pandemic outbreak (Paleshi et al., 2017; O'Reilly et al., 2020). Some strategies to mitigate the effects of the Covid-19 pandemic include vaccination (Contreras and Priesemann, 2021; Phelan, 2020; Dodd et al., 2021), school closures (Lee, 2020; Armitage and Nellums, 2020; Burzynska and Contreras, 2020; Tupper and Colijn, 2021), face masks (MacIntyre and Wang, 2020; Howard et al., 2021a; Cheng et al., n.d.), quarantine (Bauch and Anand, 2020; Wong et al., 2021), workplace closure (Bauch, 2021; Zhang et al., 2021; Lei et al., 2018; Moritz et al., 2021), travel restriction (Rahman et al., 2020; Devi, 2020), physical distancing (MacIntyre and Wang, 2020; MacIntyre, 2020), and sanitation and hygiene (O'Reilly et al., 2020; Sampson et al., 2020; Lotfinejad et al., 2020).

To investigate the spread of SARS-CoV-2, various scenarios based on real-world data can be simulated. Agent-based modelling can be used to simulate the actions of individuals or agents and their interactions. The mathematical models that have been applied to the context of the SARS-CoV-2 spread have benefited from an agent-based simulation approach (Silva et al., 2020; Hinch et al., 2021). An agent-based simulation model was developed by Kerr et al. to describe a SARS-CoV-2 model (Kerr et al., 2021). Cuevas presented a simulation model to evaluate SARS-CoV-2 transmission risks in facilities (Cuevas, 2020). Almagor developed an agent-based model that simulates the spread of SARS-CoV-2 on an urban scale (Almagor and Picascia, 2020). Some agent-based models have been proposed to investigate the interrelation between the spread of the SARS-CoV-2 and intervention strategies (Kano et al., 2021; Hoertel et al., 2020; Alvarez Castro and Ford, 2021).

This paper considers the high infection risk in public buildings and aims to model and analyse the quality of the indoor environment, related safety measures, and their efficacy in preventing the spread of the SARS-CoV-2 virus. Following this introduction, Section 2 provides a summary of the methodology that underpins the research. Sections 3 and 4 report and discuss the results. Chapter 5 provides concluding remarks and directions for future research.

2. Methodology

This paper poses two research questions to be addressed with regards to the spread of SARS-CoV-2 in indoor environments:

1. What is the efficacy of the protective factors that lower the risk of SARS-CoV-2 infection via aerosols in indoor environments, focusing on face mask-wearing, vaccination coverage and hand hygiene?
2. To what extent different modes of ventilation, namely mechanical, and mixed, of indoor spaces can be controlled and optimised to minimize the risk of SARS-CoV-2 transmission via aerosols?

Given the aerosol-based dominant transmission mode of the SARS-COV-2 virus (Guzman, 2021; Ching and Kajino, 2020), the research required a fine-grained analysis of bioaerosol particle movements under complex and dynamically changing indoor conditions, governed by a wide range of factors, including (a) indoor space configuration in terms of position, size, and frequency of openings of windows; (b) level of reliance on mechanical systems, including operational strategy and position of the supply and extraction vents; (c) indoor occupancy and understanding of occupants' movement; and (d) indoor environmental conditions. Hence, to address the posited research questions, two simulation models were developed. A Computational Fluid Dynamics (CFD) model is used to provide a fine-grained understanding of bioaerosol particle movements under complex dynamic conditions, augmented with a Discrete Event Simulation model (DES) to model the dynamics of the overall indoor system as a series of events, including occupancy patterns, that change the system's state over time, as required by our complex case study. The location selected for the study is the Forum, a zone within the Queen's Buildings, with an area of 323 m^2, home to the Engineering Department of Cardiff University. It is an informal space where individuals and staff can gather; it is currently limited to 62 people due to the pandemic but previously held 200 people. There is a mixed ventilation strategy, with both mechanical and natural ventilation available. Natural ventilation involves 15 manually openable windows.

Multiple measures have been put in place to respond to the COVID-19 pandemic. Some apply to the university, and some are specific to the selected zone. In the Forum, hand hygiene rules state that each individual is responsible for cleaning their chair and table with spray provided before sitting anywhere. Furniture in the room is laid out with markings on the floor to ensure no one moves it. There are also hand sanitiser stations at each entrance to the Forum. These are effective measures but rely on individuals to follow them, which is a disadvantage that could undermine them. There has been some face-to-face teaching in the Forum where individuals can talk to lecturers. Lecturers are exempt from wearing a face-covering whilst teaching, so there will be times throughout the day when more viral particles could be released into the air if any lecturer were infected.

These measures have all been risk assessed; signs are in place as reminders, and instructional videos were made to demonstrate the best way to clean the area before starting work. All practicable steps have been taken to reduce the risk of transmission. However, all these measures are gradually being lifted, encouraged by high vaccination rates among the adult population. This brings with it the risk of exposing unvaccinated individuals to infection. This is discussed further in the latter sections.

2.1. Computational fluid dynamic modelling

This section discusses the computational fluid dynamic model to simulate and investigate airflow distribution over the Forum in four ventilation scenarios. The findings and analysis are then presented, including air velocity and its proposed impact on the spread of SARS-COV-2.

2.1.1. Developing the computational fluid dynamic model (CFD)

A Building Information Model (BIM) was developed, simplified to remove non-necessary features, and then imported into a CFD simulation environment; Extrusions were added to inlets and outlets to avoid airflow divergence and improve accuracy. Fig. 1(c and d) is the model once loaded into the CFD environment, with a key to the various materials used (Fig. 1 (f)). To allow the boundary condition of CO_2 being produced by the head volumes, a shell of particle board was modelled to separate their volumes from the room volume. Glass wool simulated the walls, floors, and ceilings, as it approximates insulated walls; steel was used for radiators, concrete for columns and wood for furniture.

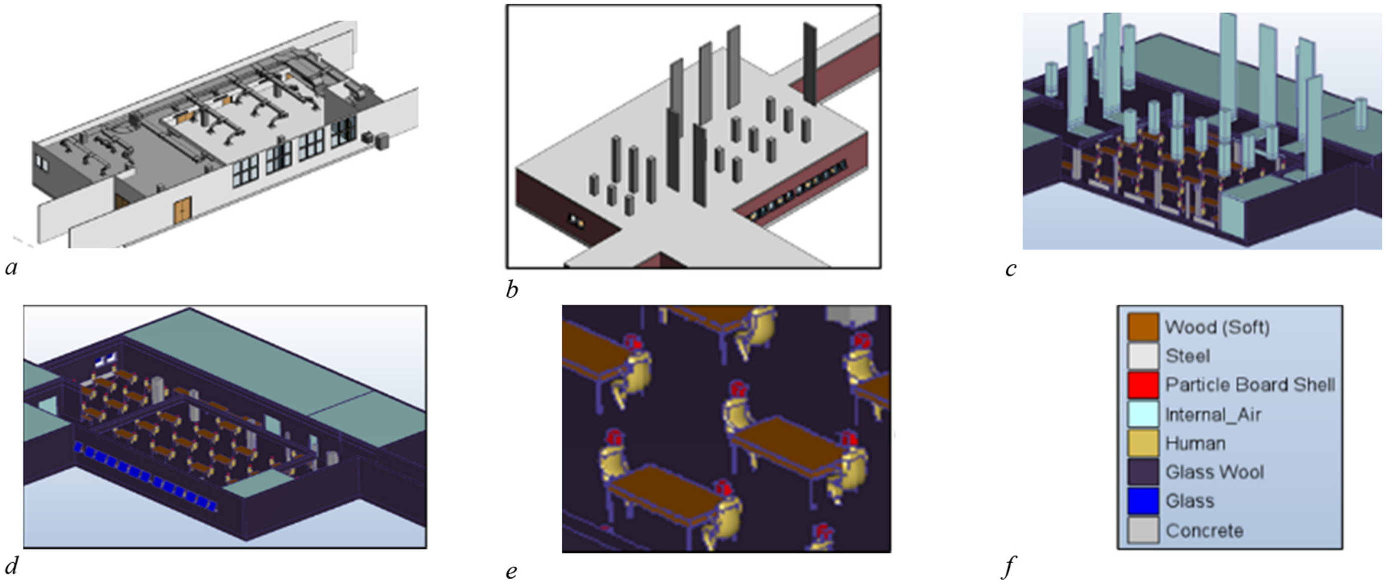

Fig. 1. Autodesk Revit models; a) original with mechanical ventilation, columns and doors included b) simplified, showing extrusions at inlets and outlets and extended corridors. Autodesk CFD models seen from above; c) mixed ventilation scenario; d) natural ventilation scenario; e) close-up of occupants at tables; f) key to each material.

2.1.2. Boundary and initial conditions

A variety of conditions were applied to the CFD simulation. These are set out below briefly, followed by an explanation. Table 1 explains the main assumptions, as well as the three scenarios investigated within the CFD models.

The volume flow rate was used to show flow to and from mechanical ventilation. For square air terminals (both supply and exhaust) this was $0{\cdot}09\text{m}^3$/s, and for rectangular (used for an exhaust only), this was $0{\cdot}168\text{m}^3$/s. A static gauge pressure of zero was applied to show air movement through the building for each internal door. For the natural ventilation, an average outdoors wind speed and direction were taken as 20 km/h from the east. When considering the height of the Forum above ground and the urban environment, the wind speed was converted to 1·986 m/s (Buxton, 2018). Scalars were used to simulate air mixing (scalar = 0) with CO_2 (scalar = 1) and represent possibly infected air (Rudnick, 2003b). The typical respiratory rate for a healthy adult at rest is 12–16 breaths per minute (Barrett et al., 2012). A value of 12 breaths per minute was chosen at 500 ml each, producing $0{\cdot}0001\text{m}^3$/s CO_2 per person. This was due to the dominant young age of the population involved. The air material density varied according to scalar, with values assumed: Air density $= 1{\cdot}2047 \times 10^{-6}$ g/mm^3 & CO_2 density $= 1{\cdot}773 \times 10^{-6}$ g/mm^3. For the mixed scenario, simulations were run for 62 and 200 people. The latter had the same boundary and initial conditions as the social distanced scenario, except for radiation and heat generation, which were excluded due to time constraints.

Table 1
Original (non-optimised) scenarios explained, and the major assumptions set out.

Type of ventilation	Scenario Number
Mixed – natural and mechanical	1
Just mechanical (winter)	2
Just natural (summer)	3
Assumptions	Scenarios where applicable
Simplified geometry for furniture and people, all doors are open.	All (1–3)
Each person is assigned 60 W heat generation, simulating body heat.	
External volume with dimensions 15 h × 310d × 500w (m) representing outside air (Autodesk 2021), with an x-direction velocity of −1·986 m/s simulating easterly wind.	
Gauge pressure of 0 Pa for all interior doors and at least one outlet; gauge pressure of -5 Pa for laboratory doors.	
Radiation applied to the seven radiators, with reference temperature of 20 °C and 0·9 emissivity as they are painted white.	
Scalars applied so that: 0 = Air, applied initially to all air volumes and as a boundary for inlets. 1 = CO_2, applied initially to all heads and as a boundary for exhaled breath. The coefficient of mixing is $0{\cdot}16\text{cm}^2$/s.	
Temperature conditions: 10 °C for the environment and external volume input. 17 °C for supply air and initial internal air. 35 °C as the exhaled breath boundary condition.	
To simulate occupants exhaling, a $0{\cdot}0001\text{m}^3$/s volume flow rate is applied to each face, equivalent to $0{\cdot}36\text{m}^3$ CO_2 produced per hour.	
Volume flow rate of $0{\cdot}09\text{m}^3$/s for square vents; $0{\cdot}168\text{m}^3$/s for rectangular vents for the supply and exhaust air.	1 & 2
Windows are fully open, constantly, with an outdoors air velocity of 1.986 m/s from the east.	1 & 3

2.1.3. Assumptions

Levels and dimensions were assumed from the Revit model unless measured on-site. Values for airflow through mechanical ventilation were taken from the floorplans. The windows have been modelled as open constantly, but in reality, this varies throughout the day and airflow from outside is likely overestimated. An assumed value for wind speed is another limitation of the model. The mechanical scenario is independent of wind speed, but the natural and mixed strategies would change if they varied. There are laboratories to the west of the Forum. Although the doors close automatically, there is the possibility of air transferring between the two spaces and infection. A pressure differential of 5 Pa was assumed between them and the public space, with the Forum at a higher pressure, to prevent contaminated air transfer (World Health Organization WHO, 2008) in line with findings from Delikhoon et al. (2021).

The results show that there are more stagnant areas – where air velocity < 0·1 m/s – with mechanical than with natural ventilation, suggesting it is less effective at removing air. On the other hand, although the natural scenario has higher velocities, there is an accumulation of CO_2 at lower levels, most significantly by the windows. This is a disadvantage of the natural ventilation scenario; air enters through the windows and seems to trap CO_2 in the area below them. Additional fans were included in the simulation to aid circulation in room areas with a higher risk of infectious particles settling. Fans were positioned to give optimal airflow to these stagnant areas, as well as to avoid being an obstacle for occupants. The other optimization used was the removal of tables (and therefore occupants) in stagnant areas, in this case the south corner.

Fig. 2 shows the results of air velocity, firstly the raw results and then the same data split into zones depending on the Forum's airflow speed. These zones are highlighted as a hatch on top of the original results diagram. The first line of panels for Fig. 2 is as follows: (a) mechanical ventilation, (b) mixed ventilation before optimization, (c) mixed ventilation with tables removed from the south area, (d) mixed ventilation with fans added, and (e) natural ventilation. The second line of panels shows the corresponding zoned diagram for each result above it, as well as a colour key for velocity magnitude, where the arrows show the direction of flow.

Table 2 shows the results of running the simulation with different types of ventilations, and their distribution of risks for each scenario are compared. Risk levels were obtained from Fig. 2, where panels (f) to (i) are panels (a) to (d) annotated with each area of risk, based on the speed of air within the room. Areas of each zone were found, and percentages calculated based on the proportion of the total Forum area taken up.

As set out earlier, the higher the ACH, the better the air circulation and the less likely infection is to spread. The volume of the Forum is 1041·4m^3, and the mechanical supply is 3888m^3/h. Natural supply has been estimated at 20,912m^3/h, giving a total of 24,800m^3/h. This means that mechanical ventilation only has 3·73 ACH; the recommended (when disregarding viruses) is between five and ten (Bhagat et al., 2020) so, logically, there are stagnant areas with this scenario. Natural ventilation partially solves this issue, with 20 ACH, although some stagnant areas remain. The value could be as high as 23·8 ACH for the mixed scenario. The natural value was found by assuming all windows are open entirely (24° to vertical) and that air enters through each side.

2.1.4. Prediction of ACH

It was possible to predict the ACH required as a function of the viral load, which varies for the original strain and the Delta variant. In the first case, $2{\cdot}27 \times 10^7$ was taken as the viral load emitted per hour per infected person (Ma et al., n.d.) and the Delta variant, which could be as much as 1260 times as infectious (Reardon, 2021), $2{\cdot}86 \times 10^{10}$ viruses per hour per person was taken. These values were used to predict how many air changes per hour are required to keep the viral load in the air at a safe level. Inhaling as few as 100 particles of SARS-CoV-2 could lead to infection (Ma et al., n.d.) and it was assumed that these particles would be equally spread around the Forum. These calculations assumed that one infected person was present in the Forum. The following equation is a calculation of the required ventilation rate as set out in the European Union (Bienfait et al., 1992).

$$Q_h = \frac{G}{C_i - C_0} \times \frac{1}{\epsilon_v}$$

Q_h = ventilation rate required for a healthy indoor environment (l/s).
G = pollution load of chemical (μg/s).
C_i = allowable concentration of chemical (μg/l).
C_0 = outdoor concentration of chemical at air intake (μg/l), assumed to be zero.
ϵ_v = ventilation effectiveness, assumed to be 0·9.

To find G, the viral load per hour was converted to μg/s; C_i as allowable concentration is:

$$C_i = \frac{\text{mass of virus}}{\text{volume of room}} \times \text{allowable viral load}$$

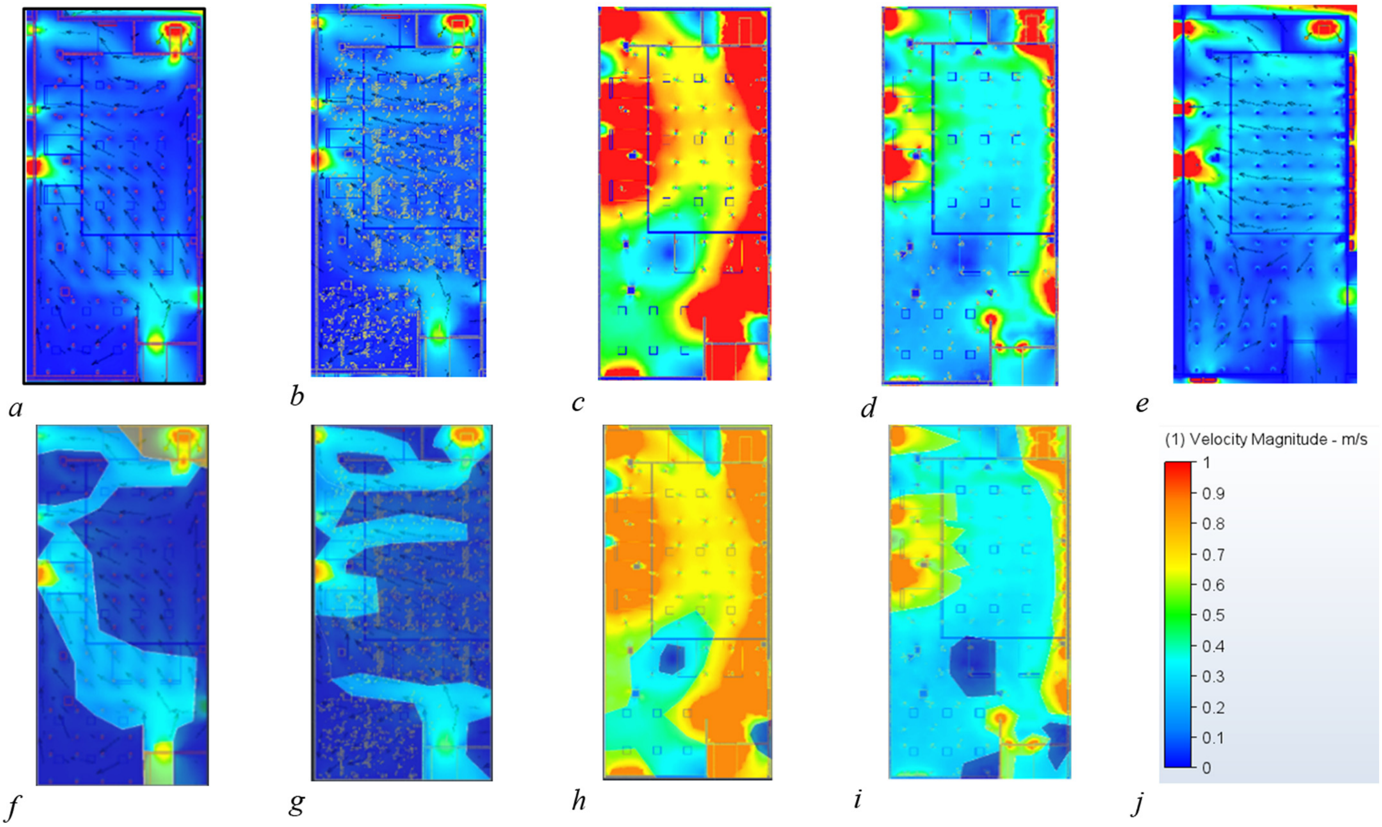

Fig. 2. CFD results and corresponding zoned diagrams, shows air flowing toward the laboratory doors and moving pass multiple people before exiting the room. All planes are on z-axis at head height (for those sitting down), final panel shows key to colours.

Table 2
Comparison of distributions of risks for different type of ventilations.

	Area of Forum (%) for each risk level		
Scenario	High risk ($v \leq 0{\cdot}1$ m/s)	Medium risk ($0{\cdot}1 < v \leq 0{\cdot}3$ m/s)	Low risk ($v > 0{\cdot}3$ m/s)
Mechanical (not optimised)	58·6	33·9	7·5
Mixed (not optimised)	62·9	35·2	1·9
Mixed (tables removed)	2·1	20·0	77·9
Mixed (fans added)	6·4	64·7	28·9

The mass of the virus was taken as $1{\cdot}0 \times 10^{-9}$ μg (Bar-On et al., 2020), the volume of the room is as set out above, and the viral load is the independent variable, as this will depend on the vaccination status occupants. Ventilation effectiveness was assumed to be 0·9 (Centers for Disease Control and Prevention, 2021). Required ACH was then calculated.

$$\text{Required ACH} = \frac{Q_h}{\text{volume of room}} \times \frac{3600}{1000}$$

The second term is simply a conversion factor to change Q_h into m^3/h. By combining the above equations, the below figures were created:

Fig. 3 (a) shows that for the original strain, the viral load can be reduced to 1,059,760 viruses present in the air, with the current set-up in the Forum. This gives approximately 1000 viruses per m^3 of air. Fig. 3 (b) shows that the required ACH for the Delta variant is 1260 times larger than that for the original strain.

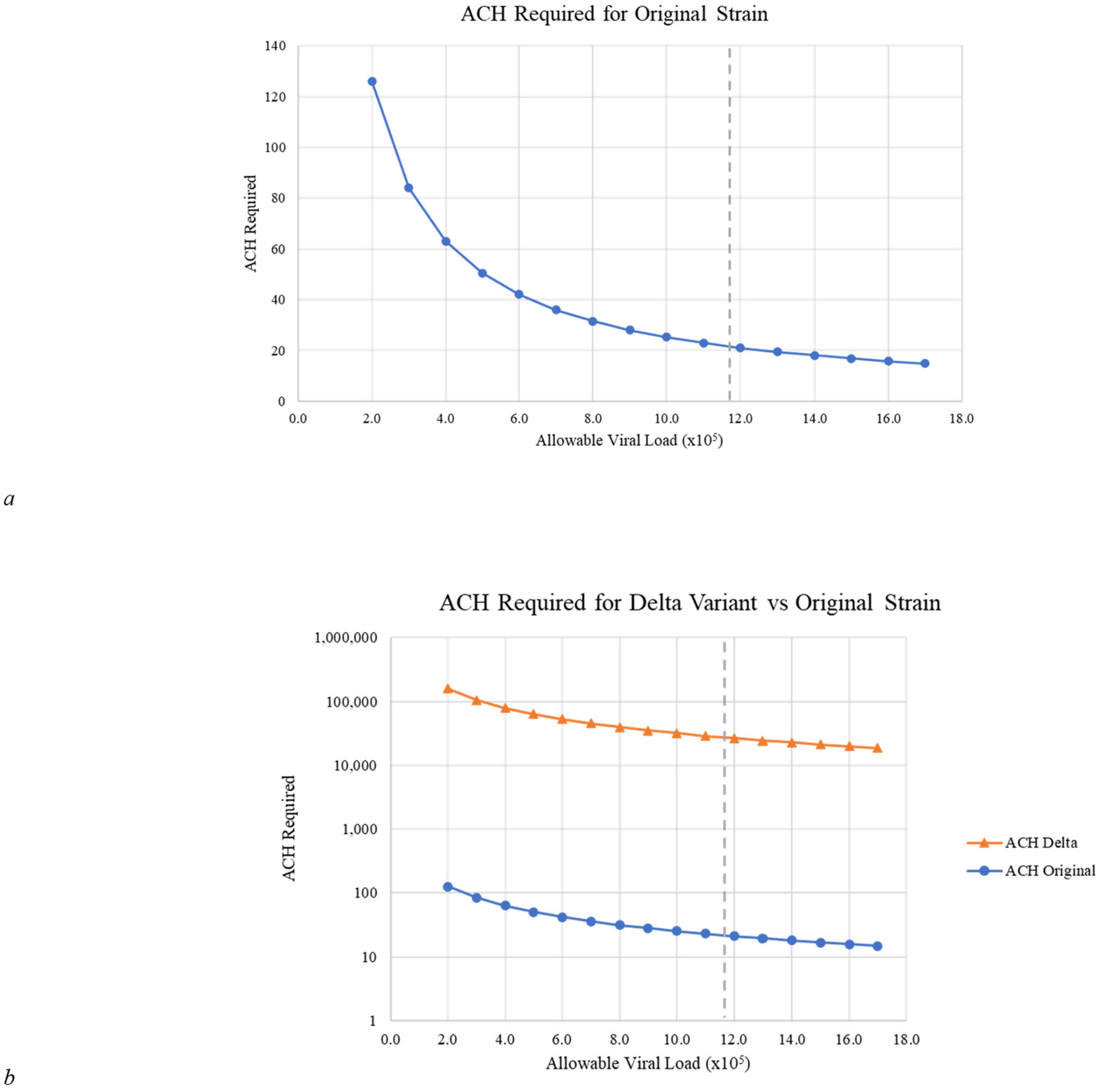

Fig. 3. (a) Graph of ACH required for original strain of SARS-CoV-2, shows that ACH decreases as the allowable viral load increases. (b) Comparison of ACH required for Delta variant with original strain, a logarithmic scale is used to show their proportionality.

2.2. Agent-based modelling and simulation development

This section presents the simulation model, which is used to analyse each ventilation scenario to evaluate the possible responses to infection in public indoor environments. Three types of ventilation are used in the simulation model, Mechanical ventilation with no optimisation (Ven I), Mixed ventilation with no optimisation (Ven II), Mixed ventilation with optimisation (fans added) (Ven III). Hereafter, wherever mentioned Ven I, Ven II and Ven III in the text, it refers to these abovementioned ventilations. The Discrete Event Simulation (DES) is explained, and the computations and assumptions are discussed.

2.2.1. Formulating SARS-CoV-2 transmission

Agent-Based Modelling is an efficient and effective way of modelling the spread of infectious diseases. In this type of simulation, everyone is given a specific behaviour and is denoted as an 'agent'. Agents behave and interact based on a set of rules. Each agent has their behaviour, location, movement pattern etc. An agent's attributes and, therefore, its behaviour may be subject to change. A probability determines its characteristics. By modelling agents and their interactions and using several scenarios, different patterns that contribute to or prevent the spread of disease can be found. These can lead to developing prevention strategies to be applied to the real world. To model the disease, spread, accurate data is required to estimate the parameters for such a simulation. While many factors can influence the model, a crucial parameter that must be accurately measured is the probability of disease transmission between two people.

Firstly, identifying parameters is needed to calculate the risk of acquiring an infection. One key parameter is the transmission probability between an infected individual to a susceptible or healthy individual. COVID-19 is thought to be transmitted between an infected individual and susceptible individual when they are within proximity. Governments and health organisations consider the 1·5-m to 2-m physical distancing. However, SARS-CoV-2 evidence is lacking for two meters distancing (Jones et al., 2020); in this study, a safe distance of two meters is considered.

The intensity of an infectious disease is often measured in epidemiological studies using reproduction numbers. The reproduction number often denoted at R_0 describes how many new infections are to be expected for every infected individual. Within a susceptible infective removed (SIR) model, the primary reproduction number is given by $R_0 = \beta_0/\gamma$, where β_0 is the initial transmission rate, and γ is the recovery rate. More commonly, adequate reproduction number, denoted by R_{et}, is used, which considers changes in immunity, travel policies and lockdowns over time as these all create variable transmissibility of disease. R_{et} measures the R number t periods from the onset. The classical SIR model, $R_{et} = (1 - c_t)\ \beta_t/\gamma$, is used, where c_t is the per capita number of infected cases at time t, and β_t is the transmission rate (Chudik et al., 2021). To estimate β_t, the number of positive cases for COVID-19 in Wales were used from November 2020 to February 2021, as by Chudik et al. (2021) and a percentage by using the population of Wales is created as provided by the Office for National Statistics. As the case study is focusing on a public space in a Welsh university, the β_t was estimated based on the case incidence in Wales. At the time of commencement of this study, there was no formal published figure for Wales. In this study, three different β_t were used, corresponding to the percentage of infected individuals entering the Forum. These values for the percentages of infected individuals in Wales were chosen based on two-month intervals as follows 1·7 %, 1·3 % and 0·4 % in this period.

The probability of this transmission in t minutes can be calculated as: $1 - e^{-\beta_t . t}$. In this model, a susceptible individual may contact an infected individual many times or with different infected individuals at different locations. It is also possible that more than one infected individual is closer to than two meters to a susceptible one. Consequently, the infection probability can be calculated for all contacts of infected individuals by $1 - e^{-\beta_t \sum_{t=1}^{n} t_i}$ where t_i is the time a susceptible individual contacts an infected one during the contact number i (Zargoush, 2019).

2.2.2. Simulation process

The Agent-Based simulation model method is used to define the characteristics and behaviours of agents who are individuals entering, having their seats, and walking in the Forum during their attendance. Each individual has some attributes that define their prevention behaviour toward infectious disease. Fig. 4 illustrates the simulation procedure during an individual's presence in the Forum.

At the beginning of the simulated session, individuals with different prevention attitudes entered the Forum, and there were some primary infected individuals. The rest are susceptible to infection. Each individual will be randomly allocated to a seat by using uniform distribution to select the row and column number of possible seats in the room. Their time in the Forum determines their chance of becoming ill or remaining healthy after the session. A susceptible individual might be seated near one infected individual or none at a distance of less than two meters. Because everyone is responsible for cleaning the chair and table with spray provided before sitting anywhere, there is an assumption that there is no contact with a contaminated surface around their table and seat and thus spread of infection is through airborne transmission.

During individuals' time in the Forum, they might interact with an infected individual sitting at the same table or walking in the Forum. This interaction time will be calculated and used to check the health status at the end of the session. Furthermore, each individual has protective behaviours that will affect their health at the end of the session, thus adding complexity to the simulation.

Note that a susceptible individual might contact infected individuals in different locations, as there are three zones in the Forum due to the ventilation condition. These three zones are categorised as high risk, medium risk, and low risk of acquiring the infection.

2.2.3. Probability distributions and assumptions

In the model, all individuals enter the system, and their related information is randomly generated using discrete distribution. Information is provided for each individual in this section includes their health status (infected or susceptible) and desire to have protective behaviour such as wearing a mask, using a hand sanitiser, and being vaccinated. After having all the needed information in the system, individuals are moved to their seats.

- Sixty-two individuals enter the Forum at the beginning of the simulation, with some infected.
- The initial health status of each individual is based on a discrete distribution with the probability of being infected in three categories: 1·3, 0·4 and 1·7 %.
- The seat is randomly assigned to the individuals.
- Each individual will have different protective approaches to avoid getting sick. The probability of each individual wearing a mask, using a hand sanitiser and being vaccinated is defined as a discrete distribution.
- Average spending time in the Forum is assumed to be a Triangular distribution with a minimum of 30, mode of 60, and a maximum number of 120 min.

2.2.4. Simulation implementation

To build the simulation model, the academic version of Arena simulation software 16.10.00001 is used. In order to achieve results with a minimal margin of error, a minimum number of iterations is determined for the model to be run. To do that, the formula $N = \left(\frac{Z.E}{E}\right)^2$ has been used.

N	Number of needed iterations
S = 1·5E-05	The standard deviation of a sample of 15 random iterations
Z = 1·96	For 95 % confidence interval (Normal Distribution)
E = 3E-06	Preferred margin for error

Therefore N $\cong$100, Consequently, 100 iterations were decided on to give a minimal margin of error. This model was tested by running some

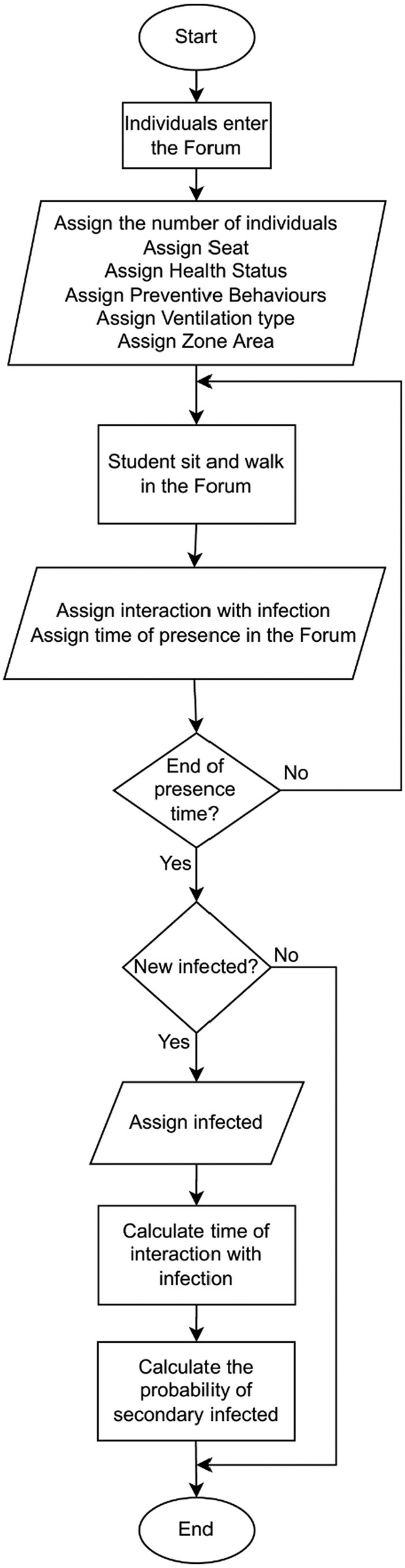

Fig. 4. Activities and preventive behaviours of individuals during their presence in the Forum.

scenarios 100 times vs 500 times to show consistency in the findings with this small margin of error.

2.2.5. Calculating the probabilities of infection

The final part of the model aims to determine each healthy individual's probability of becoming infected while contacting infectious individuals. Everyone may acquire infection based on time spent and contact with infected individuals. There are three zones of the high, medium, and low risks in the Forum for mechanical and mixed ventilation, and the probability of becoming infected in each zone is different. Therefore, the probability of contagion in each zone affects each individual's susceptibility. Everyone can take different actions to reduce their risk of transmitting or receiving the infection. The preventive behaviours of the individuals, i.e., wearing face masks, having vaccination coverage and hand sanitising, can affect the spread of the virus during their stay in the Forum. The prevention percentage of each behaviour is considered in calculating the probability of infection. The model then uses the time spent in the Forum for each individual to output the probability of newly infected cases.

3. Numerical results of comparative analysis of all preventive strategies

In this section, the simulation model is implemented for various scenarios to compare the effect of preventive behaviours on secondary cases. One is chosen as the base case scenario with no preventive strategy.

The results presented in Table 3 show the effect of prevention strategies in reducing the mean probability of secondary infected individuals for all rates of primary infected individuals.

3.1. Results of using face mask (FM)

Numerous studies show that face coverings have a significant effect on reducing the spread of airborne infectious diseases (Kai et al., 2020; Howard et al., 2021b; Yan et al., 2021; Driessche et al., 2021). Different types of face-covering have been suggested for use against disease transmission: the most known are N-95, N100, and surgical face masks (SFM). The name of N-95 and N-100 masks comes from their ability to block particles. N-95 and N-100 can filter 95 and 99·99 % of droplets and airborne particles. However, N100 is significantly more expensive than N-95 (Weiss et al., 2007). In this simulation, we assumed the use of the surgical face mask (SFM) to be used by all students entering the Forum, as is the policy requirement currently in all university buildings. This is also by far the most accessible type of face-covering by the public due to it being disposable and cheaper.

In this study, two different effectiveness of wearing surgical face masks (SFM) are used, firstly 56 % effectiveness and secondly, 67 % effectiveness which is discussed by Peeples (Peeples, 2020). The results of different proportions of wearing SFM with 56% percentage effectiveness for three types of ventilation and various primary infection rates have been shown in Table 3. Furthermore, the mean probability of secondary cases of the base case scenario has been added in this table for comparison. The same results for 67 % effectiveness of SFM are included in the supplementary appendix.

The results show that for 50 % of individuals wearing SFM, there is a 38 % reduction in the mean probability of secondary infected individuals, for 70 % wearing SFM, there is a 50 % reduction, and if 100 % of individuals are wearing SFM, there is a 69 % reduction of the mean probability of secondary infected individuals compared to the base case scenario. Furthermore, Ven III has the biggest reduction in the probability of secondary infected individuals using SFM.

3.2. Results of vaccination coverage (VC)

Vaccination status is one of the key preventative strategies against SARS-CoV-2. de Gier et al. (2021) reported on the effectiveness of

Table 3
The mean probability of secondary infected individuals for the base case scenarios and scenarios with various rates of wearing SFM with 56 % effectiveness, having been vaccinated VC, and performing HH for all types of ventilation and different rates of primary infected individuals.

Primary Infected Individuals	Scenario	Ven I	Ven II	Ven III
0·4 %	Base Case	2.55×10^{-5}	2.60×10^{-5}	1.89×10^{-5}
	SFM 50 %	1.57×10^{-5}	1.60×10^{-5}	1.18×10^{-5}
	SFM 70 %	1.26×10^{-5}	1.28×10^{-5}	9.49×10^{-6}
	SFM 90 %	9.96×10^{-6}	1.02×10^{-5}	7.52×10^{-6}
	SFM 100 %	8.01×10^{-6}	8.15×10^{-5}	5.94×10^{-6}
	VC 30 %	1.67×10^{-5}	1.70×10^{-5}	1.25×10^{-5}
	VC 50 %	1.24×10^{-5}	1.25×10^{-5}	9.14×10^{-6}
	VC 70 %	8.26×10^{-6}	8.42×10^{-6}	6.13×10^{-6}
	VC 90 %	5.80×10^{-6}	5.88×10^{-6}	4.25×10^{-6}
	HH 50 %	2.08×10^{-5}	2.12×10^{-5}	1.54×10^{-5}
	HH 70 %	1.87×10^{-5}	1.91×10^{-5}	1.39×10^{-5}
	HH 90 %	1.72×10^{-5}	1.75×10^{-5}	1.27×10^{-5}
	HH 100 %	1.59×10^{-5}	1.62×10^{-5}	1.18×10^{-5}
1.3 %	Base Case	5.06×10^{-5}	5.21×10^{-5}	3.90×10^{-5}
	SFM 50 %	2.84×10^{-5}	2.91×10^{-5}	2.18×10^{-5}
	SFM 70 %	2.23×10^{-5}	2.28×10^{-5}	1.72×10^{-5}
	SFM 90 %	1.78×10^{-5}	1.83×10^{-5}	1.37×10^{-5}
	FM 100 %	1.59×10^{-5}	1.63×10^{-5}	1.22×10^{-5}
	VC 30 %	3.24×10^{-5}	3.35×10^{-5}	2.52×10^{-5}
	VC 50 %	2.28×10^{-5}	2.35×10^{-5}	1.76×10^{-5}
	VC 70 %	1.47×10^{-5}	1.52×10^{-5}	1.14×10^{-5}
	VC 90 %	1.05×10^{-5}	1.08×10^{-5}	8.11×10^{-6}
	HH 50 %	3.97×10^{-5}	4.09×10^{-5}	3.07×10^{-5}
	HH 70 %	3.60×10^{-5}	3.71×10^{-5}	2.78×10^{-5}
	HH 90 %	3.28×10^{-5}	3.37×10^{-5}	2.53×10^{-5}
	HH 100 %	3.16×10^{-5}	3.25×10^{-5}	2.44×10^{-5}
1.7 %	Base Case	7.78×10^{-5}	7.97×10^{-5}	6.00×10^{-5}
	SFM 50 %	4.11×10^{-5}	4.19×10^{-5}	3.15×10^{-5}
	SFM 70 %	3.30×10^{-5}	3.37×10^{-5}	2.54×10^{-5}
	SFM 90 %	2.67×10^{-5}	2.74×10^{-5}	2.06×10^{-5}
	SFM 100 %	2.44×10^{-5}	2.50×10^{-5}	1.88×10^{-5}
	VC 30 %	4.88×10^{-5}	5.01×10^{-5}	3.81×10^{-5}
	VC 50 %	3.27×10^{-5}	3.36×10^{-5}	2.52×10^{-5}
	VC 70 %	2.20×10^{-5}	2.26×10^{-5}	1.69×10^{-5}
	VC 90 %	1.63×10^{-5}	1.67×10^{-5}	1.26×10^{-5}
	HH 50 %	6.03×10^{-5}	6.18×10^{-5}	4.66×10^{-5}
	HH 70 %	5.52×10^{-5}	5.66×10^{-5}	4.25×10^{-5}
	HH 90 %	5.06×10^{-5}	5.18×10^{-5}	3.90×10^{-5}
	HH 100 %	4.85×10^{-5}	4.97×10^{-5}	3.74×10^{-5}

vaccination against the spread for several scenarios. If an infected person was previously vaccinated, there was a 63 % reduction in risk of infection to a non-vaccinated individual. If the infected individual and the susceptible individual were both vaccinated, there was an additional reduction of transmission by 40 % on top of the protection the vaccine already provided the healthy individual (Chudik et al., 2021). It is essential to know that a vaccinated person is susceptible or infected. This simulation model leads to several scenarios being formed. Different probabilities of acquiring infection are assumed: either the infected individual having been vaccinated or not versus a susceptible individual having been vaccinated or not. The results of the impact of percentage variation of vaccination analysis for three types of ventilation have been shown in Table 3. Furthermore, the mean probability of secondary cases of the base case scenario has been included in this table to demonstrate the effectiveness of VC.

The results highlight that vaccination coverage reduces the risk of transmission in any type of ventilation. The results show that for 30 % of individuals vaccinated, there is a 34 % reduction of the mean probability of secondary infected individuals, for 50 % VC there is a 52 % reduction, and if 70 % of individuals are vaccinated, there is a 68 % reduction of the mean probability of secondary infected individuals compared to the base case scenario. Furthermore, the lowest transmission risk is seen in ventilation type III with high vaccination coverage.

3.3. Results of performing hand hygiene (HH)

Hand sanitising, including hand washing and using alcohol-based sanitizers, is a simple and inexpensive way to reduce risk of infection through contamination. Al-Ansary et al. (2020) claimed a 16 % reduction in the number of participants with acute respiratory infections, and Aiello et al. (2008) reported a 21 % effectiveness against the spread of respiratory illnesses. In this model, the effectiveness of hand sanitising against the spread of SARS-CoV-2 is chosen as 21 % effectiveness.

In this analysis, the model is run assuming that a proportion of 50 to 100 % of the individuals using alcohol-based hand sanitizers offered in the Forum for three types of ventilation. The results reveal that the larger the number of individuals performing HH, the lower the mean probability of secondary infected individuals. The results show that for 50 % of individuals performing HH, there is an 18% reduction of the mean probability of secondary infected individuals, for 70 % performing HH there is a 27 % reduction, and if 100 % of individuals are performing HH, there is a 38 % reduction of the mean probability of secondary infected individuals compared to the base case scenario. Furthermore, for ventilation type III the risk of transmission is the lowest.

3.4. Summary of the results: the impact of SFM, VC, and HH

In this section, the impact of various percentages of wearing a surgical face mask with 56 % effectiveness, VC and performing HH on the probability of secondary cases are illustrated in Fig. 5. The results show that more

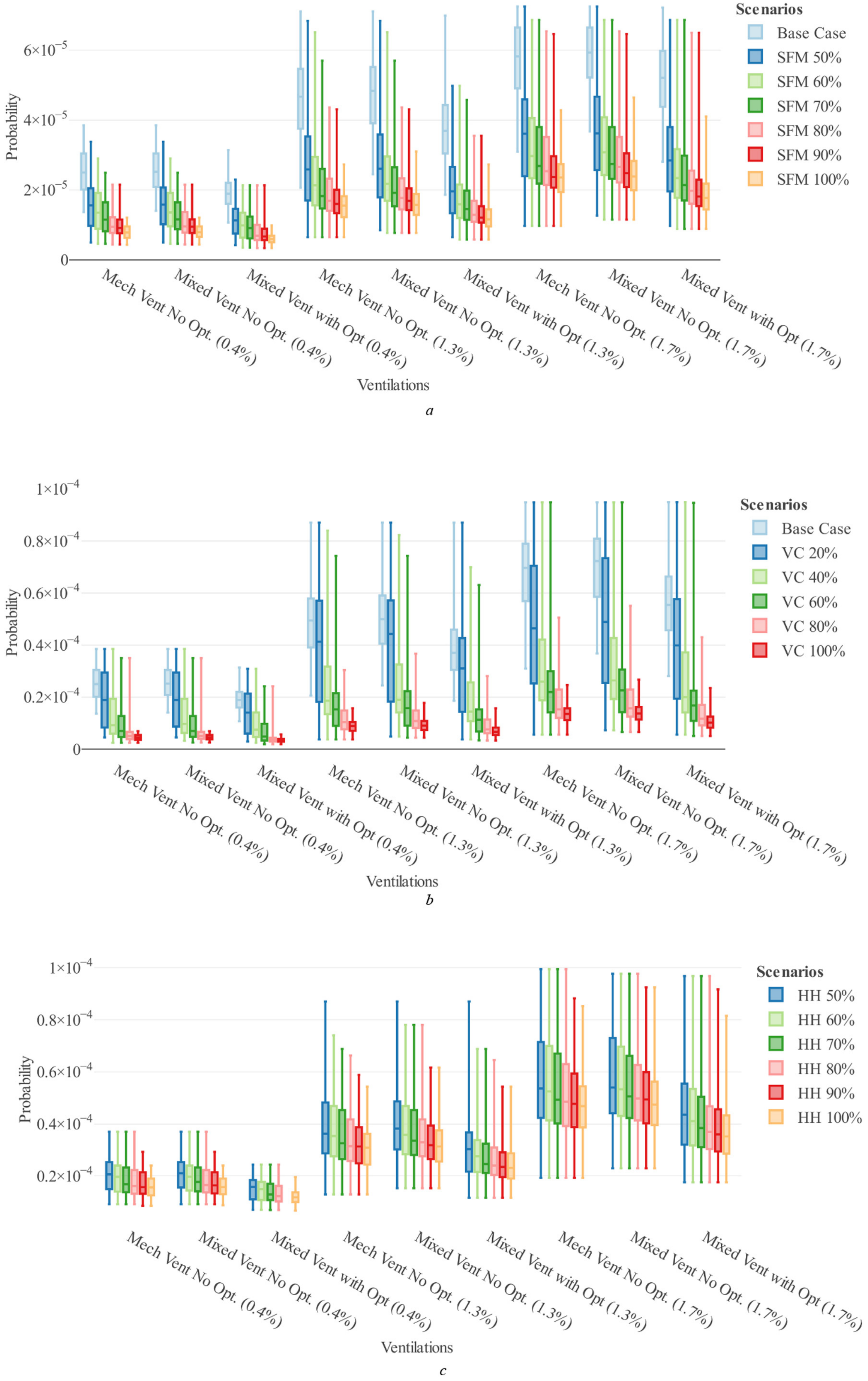

Fig. 5. Effect of different rates of wearing surgical face masks (a), vaccination coverage (b), and performing hand hygiene (c) on the probability of secondary infected cases for three types of ventilation with different rates of primary infected individuals.

engagement with SFM, VC and performing HH result in lower probabilities of secondary infected individuals. Furthermore, these figures show the difference between the result of the base case scenarios with different rates of applying preventive strategies in various ventilations. Similar figures for 67 % effectiveness of SFM and other scenarios can be found in the supplementary appendix.

3.5. Results of combination of different percentage of individuals wearing SFM, performing HH and VC

In this analysis, the model is run for various percentages of preventive behaviours for all types of ventilation. The results shown in Table 4 reveal the mean probability of secondary cases with different rates of infected individuals arriving at the Forum while 50 to 90 % of them wearing SFM, 50 to 90 % performing HH and while having different proportions of vaccination coverage from 10 % to 70 % for three types of ventilation.

The results reveal that when 50 % of the individuals are wearing SFM, 50 % are performing HH, and 10 % have VC, the probability of secondary infected individuals decreases to 56 % compared to the base case scenario. If 90 % of individuals are wearing SFM, 90 % are performing HH, and 70 % are vaccinated, there is a 91 % reduction in the mean probability of secondary infected individuals compared to the base case scenario. Furthermore, ventilation type III has the lowest risk of transmission compared to other ventilation types.

4. Discussion

While many studies in the literature consider SARS-CoV-2 transmission, there has been a need for better validation of transmission risks between a susceptible and infected individual. The models' parameters are based on existing literature findings; however, validating these parameters with primary empirical data is very difficult. Without such validation, the efficacy of prevention strategies is estimated (Kaiser et al., 2021). Validation of agent-based epidemiological models are known to be challenging (Yang and Atkinson, 2008). More reliable data on SARS-CoV-2 transmission could prove valuable in producing consistently accurate models, but unfortunately, are scarce. As such, transmission models can be validated against agent-based simulations. As with previous agent-based simulations (Yin et al., 2022; Zhou et al., 2021; Ying and O'Clery, 2021; Li and Giabbanelli, 2021), the result of this model is validated.

4.1. Research question 1: protective factors

Since the start of the pandemic, several public health measures have been put in place to reduce the risk of SARS-CoV-2 transmission. Due to the nature of aerosol-transmitted infections, indoor environments provide a greater challenge due to the lower rates of air turnover. Physical distancing, face coverings, hand hygiene and most recently, vaccination programs have been measures taken by most authorities to control the transmission of SARS-CoV-2. As shown in Section 3, by considering the results depicted in Table 3 for the base case scenarios and other scenarios with different proportions of wearing SFM, the mean probability of secondary infected individuals in Ven III is the lowest. Furthermore, for scenarios with various rates of compliance with SFM, better compliance by individuals was associated with a greater reduction in the mean probability of secondary infected individuals for all rates of primary infected individuals. Likewise, these results highlight the effectiveness of VC and the importance of suitable ventilation in reducing the risk of transmission. Moreover, the results reveal the importance of performing HH and ventilation types in reducing the risk of transmission. Altogether, containing each of these protective variables all showed a reduction in the probability of secondary infections. Simulations with all preventative measures highlight the ability to greatly reduce the risk of transmission if all measures are taken together. Adherence to face coverings remains the largest protective factor for secondary infections in the indoor environment, as shown in Fig. 5(a). With the use of surgical face masks in over 50 % of the individuals, there was a reduction in probability of secondary infections up to 68·6 %.

Simulations for the effect of vaccination highlighted a key aspect of the vaccination program. A reduction of up to 66 % in the probability of secondary infections can be seen, only with a vaccination compliance rate of 60 %. However, its effects on lowering the transmission of SARS-CoV-2 are significantly diminished with a lower vaccination rate. Whilst these are effects seen on a population level for individuals in the Forum, individually, SARS-CoV-2 vaccinations aim to reduce the disease burden on the body and reduce the severe consequences of infection including acute respiratory distress syndrome (ARDS) (Parasher, 2021).

The combination of the abovementioned protective factors, as well as hand hygiene, had the potential to reduce the risk of secondary infections by 93·6 % in the simulations. While vaccination rates are dependent on individual compliance and capacity of vaccination programs, face-covering mandating and, to a lesser extent, hand hygiene practices can be implemented by policymakers for the use of indoor environments such as the Forum.

4.2. Research question 2: ventilation optimization

As shown in Section 2.1, simulations produced results figures for each scenario. It was assumed that any area where air velocity < 0·1 m/s is stagnant, these are the darker blue areas, as shown by Fig. 2. They are dangerous for disease transmission, as any suspended droplets or aerosols will stay in that location and could settle onto surfaces or infect humans directly. Although this ACH value is high, it demonstrates the upper limit of the Forum's ventilation capacity. If weather conditions are favourable, natural ventilation can be used to mitigate the risk of disease transmission. ASHRAE recommends six to 12 ACH (Robertson, 2020) when including viruses. However, calculations set out below suggest this range should be much more significant when SARS-CoV-2 is present. Ma et al. (n.d.) found that “SARS-CoV-2 levels in exhaled breath could reach 105-107 copies/m^3”, showing that in the transmission of this disease, a vital role is played by exhaled breath. The air within the Forum is not recycled, so it

Table 4
The mean probability of secondary infected individuals with various rates of wearing SFM and performing HH with different proportions of VC for all types of ventilation and different rates of primary infected individuals.

Type of Ventilation	Primary Infected 1.3 %					Primary Infected 0.4 %					Primary Infected 1.7 %				
	Base Case	VC10% FM50% HH50%	VC30% FM70% HH80%	VC60% FM80% HH90%	VC70% FM90% HH90%	Base Case	VC10% FM50% HH50%	VC30% FM70% HH80%	VC60% FM80% HH90%	VC70% FM90% HH90%	Base Case	VC10% FM50% HH50%	VC30% FM70% HH80%	VC60% FM80% HH90%	VC70% FM90% HH90%
Ven I Mechanical Ven No Optimisation	5.06×10^{-5}	2.06×10^{-5}	1.06×10^{-5}	4.65×10^{-6}	3.38×10^{-6}	2.55×10^{-5}	1.10×10^{-5}	6.08×10^{-6}	3.07×10^{-6}	2.07×10^{-6}	7.78×10^{-5}	2.95×10^{-5}	1.53×10^{-5}	6.81×10^{-6}	4.98×10^{-6}
Ven II Mixed Ven No Optimisation	5.21×10^{-5}	2.12×10^{-5}	1.08×10^{-5}	4.77×10^{-6}	3.50×10^{-6}	2.60×10^{-5}	1.13×10^{-5}	6.20×10^{-6}	3.13×10^{-6}	2.13×10^{-6}	7.97×10^{-5}	3.01×10^{-5}	1.56×10^{-5}	7.00×10^{-6}	5.13×10^{-6}
Ven III Mixed Ven with Optimisation	3.90×10^{-5}	1.58×10^{-5}	8.20×10^{-6}	3.58×10^{-6}	2.62×10^{-6}	1.89×10^{-5}	8.26×10^{-6}	4.58×10^{-6}	2.30×10^{-6}	1.57×10^{-6}	6.00×10^{-5}	2.26×10^{-5}	1.19×10^{-5}	5.29×10^{-6}	3.86×10^{-6}

can be inferred that the number of viruses in the room will be drastically decreased by fully refreshing the air.

Fig. 3(a) shows that for the original strain, the viral load can be reduced to 1,059,760 viruses present in the air, with the current set-up in the Forum. This gives approximately 1000 viruses per m^3 of air, so it is not ideal, but if combined with an optimised ventilation system could be effective against the transmission of the disease. Fig. 3(b) shows that the required ACH for the Delta variant is 1260 times larger than that for the original strain, so it is impractical to design a system against it. Therefore, when the Forum is at total capacity, CO_2 from nearby people surrounds other individuals, whereas in the social distanced layout, this was limited, and the risk from infected air was mainly if the droplets settled on surfaces which could then transmit disease.

4.3. Limitations and future research

This study uses simulation models to assess the impact of preventative measures on the safety of individuals in an indoor environment. As such, some limitations are related to the input data for simulations. For example, many studies report a range of efficacy against SARS-CoV-2 transmission rather than one constant number. These ranges compound when many inputs are used and can make the data challenging to interpret. Another limitation is that the current data is used for the SARS-CoV-2 delta variant. With a rise in the number of cases of the Omicron-B variant, this study should be expanded upon to account for the reported change in infectivity. Furthermore, whilst face coverings are an essential protective factor in indoor environments, the way in which they are worn, and the type of mask worn greatly affects their efficacy. Lee et al. (2020) report the required steps to correctly put on and dispose of a face mask but found that hygiene protocols were not followed in most of the community population. Furthermore, while this study considers surgical face masks, many may use reusable fabric masks, which may not be able to prevent the spread of smaller droplets compared with the triple-layered, waterproof surgical face masks (Howard et al., 2021c).

For the CFD model, the effect of temperature could be investigated further in future work, as this can affect both the survival and transport of pathogens in the air. The link between CO_2 levels and viral load in the air should be further studied as this could lead to CO_2 monitoring to warn of likely risks in indoor environments as is now the new advice for education settings from the Welsh Government (2021). Finally, while our research is fully based on an analytical approach, our proposed CFD model may require calibration. The authors are in the process of deploying environmental sensors in the “Forum”, the unit of analysis used in this research, to acquire time-series data about a wide range of governing variables to calibrate our CFD model, including the selected boundary conditions. The results will be reported in a follow-on publication.

5. Conclusion

The findings of this study are two-fold. They address preventative measures for individuals as well as ventilation for building management. Several protective measures have been identified and assessed in their role in reducing secondary infections in a public indoor space, namely the Forum. Face coverings were the most effective and reliable form of preventative measure identified in simulations, while vaccinations had the potential to be highly effective given good compliance within the individual population. With further developments of the pandemic and the identification of a new Omicron-B variant, the efficacy of the current vaccination program needs reassessing with preliminary suggestions that timely ‘booster’ vaccinations are required for adequate protection against the new variant. Individuals, who form many users of the Forum, with no underlying health problems who fall into the 18 to 30-year-old age categories, will be lower in the adult vaccination priority list as per the UK vaccination program. Consequently, in the immediate to near future, face coverings will offer the most effective protection against the transmission of secondary infections for individuals using the Forum. Other practices such as hand hygiene and maintaining a physical distance of over two metres should also be mandated.

Furthermore, the ventilation of the Forum was investigated, and stagnant areas have been identified where air travels at <0·1 m/s. These pose risks for disease transmission, and so possible solutions have been recommended. Carbon dioxide and temperature distribution have also been simulated and correlated with the air velocities. For the natural ventilation simulation, there are areas where the CO_2 concentrations are high and air velocities are low. Solutions for both problems have been suggested. Namely using mechanical ventilation as well as natural, and rearranging furniture if necessary. Where the use of natural ventilation leads to CO_2 accumulating in some parts of the Forum, these areas will require either the use of mixed ventilation, or the reconfiguration of the existing mechanical supply and exhaust vents.

The expected number of infected people has been predicted using the incidence rate within Cardiff. This was used to find that ACH should be 1260 times higher when the Delta variant is prominent when compared to the original strain. Ranges were also given for the level of restrictions based on incidence rates.

Overall, the burden of infections on the pandemic because of indoor environment usage is largely dependent on the hygiene practices mandated, as well as the adequate ventilation in common spaces. Also, each indoor space is unique as involving a distinct configuration in terms of number, area, and position of doors and windows, the position of the mechanical air extraction and supply inlets, and occupancy schedules. Many hygiene practices are subject to individual compliance as well as fatigue from repeated and prolonged exposure to the pandemic (Lee et al., 2020). This study recommends that policymakers and public health officials continue to promote the use of face coverings in indoor public spaces and ensure building regulators that adequate ventilation is in place for the number of individuals in these spaces.

Credit authorship contribution statement

Yacine Rezgui conceived the study, designed, and led the research in his capacity of Principal Investigator on the EPSRC EP/T019514/1 project.

Ali Ghoroghi led the agent-based simulation work and authoring of the paper. Ali Ghoroghi has verified the underlying data.

Ruth Wallace carried out experiments and data analysis. The authors read and approved the final manuscript.

All authors have had full access to all data at all points of the research process and accept responsibility to submit for publication.

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Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Professor Yacine Rezgui reports financial support was provided by Engineering and Physical Sciences Research Council.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.156518.

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