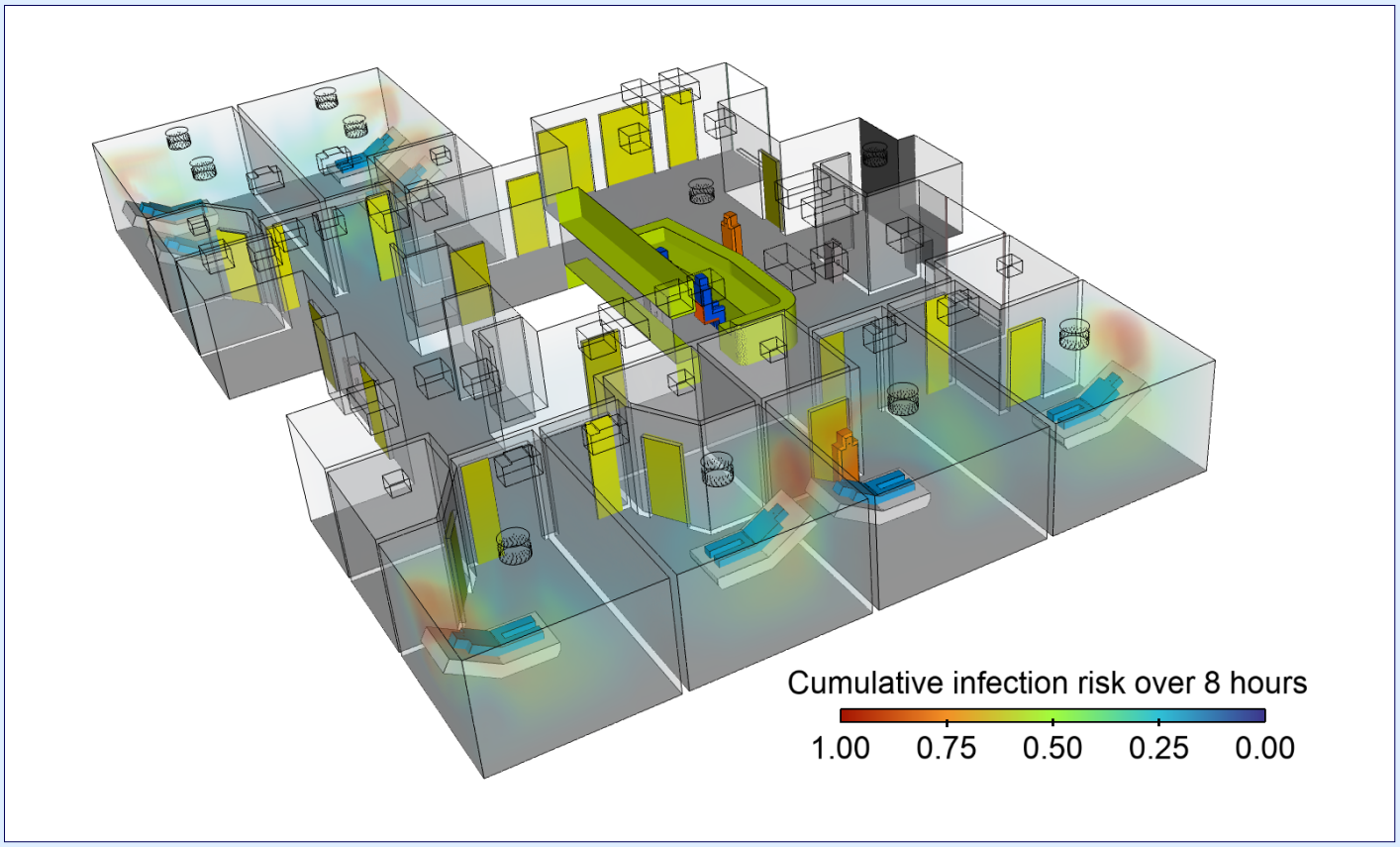
Digitisation for Safe Workplaces

Victorian Higher Education State Investment Fund

Unclassified Final Project Report

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Executive Summary

This project aimed to develop an understanding of what controls the risk of airborne pathogen spread in workplaces, and the effectiveness of various strategies to mitigate this risk. The basic premise of the study was that a major transmission mode is via the transport of pathogenic aerosols expelled by infectious occupant/s in the workplace, such that the infection risk to others can be determined from cumulative exposure to the spatiotemporally varying concentration of these aerosols. The study concentrated on interactions between physical factors, i.e. building layout and the heating, ventilation, and air conditioning (HVAC) system and its operational settings, along with human factors, i.e. the position & movement of a workplace's occupants. The study used sensors to characterise workplace airflow, particulate concentrations, indoor climate conditions, and human movement for five anonymised Victorian workplaces. These measurements formed inputs to computational fluid dynamics (CFD) models of airflow and aerosol transport within these five workplaces. The predictions of aerosol transport were used to compute a spatial 'cumulative infection risk map' for susceptible occupants in each workplace based upon viral & epidemiological data for one of two of the dominant COVID-19 variants at the commence of this study in July 2021, i.e. the Delta & Omicron variants. However, these results are still relevant (in terms of relative risk) to other variants and airborne pathogens. Based upon these workplace models, the efficacy of various potential risk mitigation strategies was assessed, ranging from simpler interventions such as local usage of air purifiers and the donning of PPE, to major alterations to HVAC layout & settings, building design, and usage.
As mentioned above, this project involved detailed Case Studies undertaken at five different workplace types: (i) an open-plan office, (ii) a factory 'paint' room, (iii) a section of a hospital ward, (iv) a lecture theatre, and (v) a scientific research laboratory. Continuous sensing of particulates, indoor climate, and human movement patterns was undertaken for two weeks at each workplace, as well as one-off measurements of airflows through HVAC ducting. The spread of airborne aerosols was then calculated using a CFD model tailored for each workplace that incorporated assumed locations of infectious & susceptible occupants. The infection risk was calculated as a cumulative value based on exposure for the likely period of the occupant at their location, e.g. an

It's established that COVID-19 is spread by aerosols. This study has developed an understanding of the interconnection between workplace layout & air conditioning systems to determine the risk of transmission and propose mitigation strategies.

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eight-hour work shift or a two-hour lecture. The predicted risks were therefore based on measured data for each workplace's HVAC system & settings, building layout & human factors, and continuous autonomous sensing throughout their workplace. The computational models were then used to predict the cumulative infection risk maps to uninfected occupants in the presence of various risk mitigation strategies discussed with each workplace operator (industry partner). In some instances, simple mitigation strategies were implemented and their real-world impacts quantified.

For Case Study 1, the open-plan office, the presence of slow crossflow ventilation led to significant cumulative infection risk to occupants in the open-plan region but increasing airflow or introducing correctly placed air purifiers significantly reduced risk. For Case Study 2, the factory paint room, its high ventilation rate combined with the low residence time of occupants in the room led to a generally low infection risk, which masking further minimised. For Case Study 3, the hospital ward section, the major conclusion was that the HVAC system design should not promote airborne pathogen movement from high-risk to low-risk areas, particularly if low-risk areas feature a high occupancy rate. For Case Study 4, the lecture theatre, despite the high air exchange rate, risks could still be locally high if crossflow ventilation is present, as this causes transmission of aerosol from an infected occupant to their neighbours, and/or when local air 'recirculation cells' occur. Lastly for Case Study 5, the research laboratory, the dense positioning of vents can produce local circulatory air cells that limit risk from being transmitted between cells, and thus between workstations if they are co-located/ aligned with the circulatory cells.

Based on the above five Case Studies, a series of recommendations are proposed in section 1. To summarise these, 'displacement ventilation' rather than 'mixing ventilation' HVAC systems are recommended, but the relative placement and orientation of HVAC outlet vents must be tailored for each workplace to optimise infection risk reduction. Locally placed air purifiers can reduce risk in low-ventilation-rate environments provided they are correctly selected, placed, and oriented. Social distancing of two metres and the use of fitted surgical and N95 masks significantly reduce cumulative infection risk. Finally, workplace layout analysis should be undertaken to optimise seating/ workstation plans to best reduce the cumulative infection risk to occupants.

"...'displacement ventilation' rather than 'mixing ventilation' HVAC systems are recommended, but the relative placement and orientation of HVAC outlet vents must be tailored for each workplace to optimise infection risk reduction."

- Professor Ivan Cole,
project Lead Chief Investigator, RMIT University

Locally placed air purifiers can reduce risk in low-ventilation-rate environments provided they are correctly selected, placed, and oriented.



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1. Final Public Recommendations

1.1 Risk analysis – HVAC system

1. 'Displacement' ventilation systems (i.e. those that promote vertical flow with little lateral crossflow) are more recommended than 'mixing' ventilation systems (i.e. those that promote a high degree of air mixing & lateral flow) for airborne pathogen management in densely occupied workplaces.

    a. Simply increasing the HVAC system's air changes per hour (ACH) for the indoor space has different extents of benefits based on the effectiveness of the system's original design, i.e. there is more to pathogen management than the single-metric ACH (see section 1.6; Recommendation 8).

2. Relative placement & orientation of inlet & outlet vents is critical – avoid ventilation schemes that promote aerosol movement from areas with a high probability of an infected occupant to low probability (e.g. a hospital in-patient room to a nearby nurses' station).

    a. HVAC systems should be tailored for certain types of workplaces by increasing the number, position, orientation, and flowrate of exhaust (outlet) vents such that isolated, self-circulating regions occur with limited movement of air & aerosol between them.

    b. A high ACH does not always provide better ventilation or airflow. The position & orientation of the air vents can cause ventilation short-circuiting and/or 'bubble zones' with poor airflow where airborne pathogens can linger. The development of new measurement & evaluation guidelines may be needed (see section 1.6; Recommendation 8).

1.2 Risk analysis – HVAC system

3. Where ventilation rate is low, local air purifiers are recommended as they can significantly reduce risk if correctly selected, placed, and oriented.

    a. We do note that these aspects can be difficult to assess without specialist input, and there are challenges maintaining the positioning & flowrate setting of portable units in workplaces with multiple employees.

4. Where ventilation rate is low, local air purifiers are recommended as they can significantly reduce risk if correctly selected, placed, and oriented.

    a. The exception to the above is where the ventilation system is not effective throughout the space, i.e. although the ventilation rate is high, the flow is unevenly distributed, leading to low-flow regions and dead zones.

1.3 Control Measure – Social distancing

5. The highest risk always occurs quite close to the infected occupant/in-patient, thus physical distancing will significantly reduce risk (by a greater margin if the directions of air movement are considered during occupant placement). Each case is different, but two metres will reduce cumulative infection risk.

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1.4 Control Measure – PPE

6. Well-fitting masks, e.g. surgical masks & N95, significantly reduce infection risk, and in combination with the social distancing guidance, are quite effective.

    a. We do note limitations to people's compliance with mask recommendations in the long term.

1.5 Control Measure – Layout

7. Analysis of each specific workplace is recommended to optimise its layout (see section 1.6; Recommendation 8 for possible analysis methods). This is because:

    a. Partitions may have limited use for reducing infection risk as they depend extensively on the workspace's original design & current configuration.

    b. Seating/workstation/room occupancy plans (including deliberately empty workstations) can be modified. However, such changes interact with airflow patterns and may increase risk to certain occupants.

    c. Keeping internal doors closed can have a significant effect on infection risk, but keeping a clear (occupant-free) path from each likely infector to their nearest HVAC exhaust (outlet) vent will inhibit localised increases to infection risk around infectors from completely encompassing adjacent, frequently occupied areas.

1.6 Future Methods to Achieve Recommendations 1, 2, and 7

8. For large construction/renovation projects with the capacity to perform CFD analyses, such analyses – even if approximate – assist in clarifying airflows & potential deadspots, and thus minimise infection risk by informing local redesigns of occupancy layout, HVAC configuration, and/or architecture. For smaller workplace construction/renovation scenarios without the scope for CFD analyses, the relevant future HVAC & related building design standards could incorporate the above recommendations around ACH, airflow direction, and layout in a generalised sense to minimise cumulative infection risk. For existing workplaces without the possibility of near-term HVAC configuration and/or architectural changes, a modified in-place test of the existing HVAC system's efficacy would be beneficial, e.g. a residence time distribution measurement test could be performed to identify regions with low airflow. Identifying such a test would likely require a dedicated research effort.

9. Building air purifiers directly into the HVAC system during construction & renovation (instead of placing standalone units) is better due to improved simplicity & safety, but should be paired with an appropriate sterilisation schedule (not considered here).



…CFD analyses – even if approximate – would assist in clarifying airflows & potential deadspots, and thus minimising infection risk by informing local redesigns of occupancy layout, HVAC configuration, and/or architecture.

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2. Introduction

2.1 Project Aim

This project aimed to develop an understanding of what controls the risk of airborne pathogen spread in workplaces, and the effectiveness of various strategies to mitigate this risk. This process and risk prediction were addressed from a building and human activity viewpoint rather than from a medical or social perspective. Hence this project was primarily concerned with the spread of virus-laden pathogenic aerosols expelled by infected occupants in the workplace, and the impacts of both building factors (building layout, ventilation rates and vent placement, and workplace/activity type) and human factors (location, movement, and density of infectious and susceptible occupants). This report provides five detailed Case Studies of specific workplaces that consider the interconnectivity of these factors and their impact upon cumulative infection risk to airborne pathogens for these workplaces. The impact of potential risk mitigation strategies – selected through discussions with managers and health and safety professionals at each workplace – was considered for each workplace, including alterations to ventilation rates and schemes, and alterations to building occupancy and operational practices.

2.2 Project Activities

The five Case Studies considered in this project encompass the following workplace types:
1) An open-plan office
2) A 'paint room' within a factory
3) A section of a hospital ward
4) A scientific research laboratory
5) A lecture theatre

Given the presence of infected occupant/s in each of the above workplaces, the project aimed to determine the likely spread of pathogenic aerosols and the cumulative infection risk to uninfected (susceptible) building occupants. This risk was assessed as a function of the building layout, heating, ventilation, and air conditioning (HVAC) system, and human factors as outlined in section 2.1. This assessment was supported by experimental studies, continuous sensing for two weeks at each workplace between December 2021 to August 2022, sensor data analysis, and computational fluid dynamics (CFD) modelling for each workplace. Human movement, microclimate (relative humidity, barometric pressure, and temperature), and airborne contaminant (volatile organic compounds and particulates) data were all continuously measured over a study period of approximately two weeks at each workplace, as well as a one-off detailed characterisation of air flowrates through the HVAC ducts at each workplace. The measured human movement data and ventilation flow rates formed inputs to CFD models of airflow and aerosol transport within each workplace, and an infected occupant/s was assumed at various locations to determine the infection risk to susceptible occupants throughout the workplace. Analysis of particulate matter from sensors spread throughout the workplaces was then used to confirm the consistency of the risk predictions. After the above characterisation and confirmation processes, several risk mitigation strategies were considered for each workplace. The practical approach taken during this project to conduct

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the above is described in Figure 2-1. This workflow was designed to ensure that that only realistic scenarios were modelled, and only feasible mitigation procedures were investigated.

The use of Case Studies as the investigative mode for this project has advantages in that the results are closely tied to actual workplaces and realistic modes of usage, with potential mitigation approaches matched to the clients to ensure that the modelling is relevant. However, as aerosol transport is highly sensitive to local factors such as workplace layout and HVAC system design and settings, the cumulative infection risk maps for each Case Study are not readily generalisable to other workplaces. To overcome this limitation, a second set of analyses were conducted whereby each workplace's operating conditions were altered to widen the results' applicability by testing modifications that could not be readily implemented in practice, such as HVAC system refit or floorplan redesign. This combination of specific workplace Case Studies and extensions to them provides a greater degree of generality (and relevance) to the results presented here.

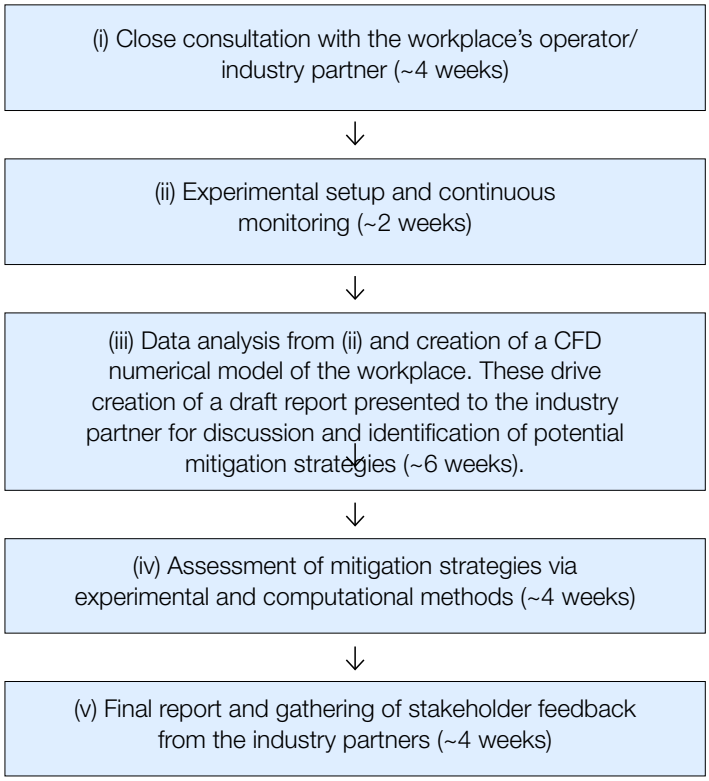


Figure 2-1: Project workflow for each Case Study, including interactions with industry partners, sensor measurements of each workplace, simulation of each workplace, and development and discussion of infection risk mitigation strategies

2.3 Background and Key Concepts

To assist the understanding of this report and its significance, a summary is now presented of some of the key concepts that regulate airborne pathogen transmission and aerosol transport in the workplace:

i. **How pathogens are transported by aerosols**

Aerosolised sputum droplets ejected from an infectious occupant during speaking, coughing, and sneezing can host pathogens such as COVID-19. These ejected droplets span sizes (i.e. diameters) from 0.1 to 1000 micron, and even submicron droplets can carry a few pathogen virions that (upon inhalation by a susceptible occupant) can cause infection. While droplets larger than ~20 microns rapidly fall to the floor under gravity, smaller droplets evaporate rapidly to form pathogenic desiccated aerosols with a median size of 6 microns. Due to their small size and low density, these desiccated aerosols remain suspended for long periods and are thus easily transported by ambient airflows within the workplace. These airflows are often complex and unsteady, and so the resultant distribution of aerosols – and thus the infection risk to susceptible occupants – can vary strongly in space and time.

ii. **Relation between airflow, aerosol transport, and infection risk**

As described above, the infection risk associated with pathogenic aerosols is highly variable both in space and time, resulting in localised hotspots of infection risk. In this project, 'cumulative infection risk maps' of this spatial risk distribution are presented, which were predicted using computational fluid dynamics (CFD) simulations of the heating, ventilation, and air-conditioning (HVAC) airflows and associated aerosol transport across the five workplaces studied. These airflow and aerosol transport models were developed using computer-aided design (CAD) models of the geometry, furniture, and human occupancy data for each workplace,

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coupled with onsite measurements of human movement (Qin et al., 2023) and HVAC airflows through vents, windows, and doors gaps. These five CFD models have been validated to some extent via laboratory experiments using particulate matter sensors and an artificial droplet generator. The aerosol distributions predicted from these CFD models were used to calculate 'risk maps' of the cumulative infection risk to occupants stationed for a period of time relevant to each workplace. This calculation made use of a novel extended version (Li et al., 2021) of a well-established/ conventional model for infection risk, namely that of Wells (1955) & Riley et al. (1978). This extended model quantifies the cumulative infection risk in terms of local aerosol concentration and exposure time and includes parameters such as sputum viral load and pathogen infectious dose. These parameters vary significantly with pathogen type, i.e. COVID-19 variant. Critically, these cumulative infection risk maps allowed the efficacy of various mitigation strategies to be virtually tested and the results discussed with each workplace's operator/industry partner.

iii. Air conditioning systems, positions of vents, and how they control airflow and thus aerosol transport

Aerosols, by definition, are small enough to be suspended in the air and thus require external forces to transport them (i.e. carried with air movements caused by people walking, doors opening and closing, air movement from external windows, and HVAC system flows). In most workplaces, on average it is the HVAC system that generates much of this flow to keep the air at the desired temperature and ensure sufficient fresh air is being continuously forced through the indoor workspace to keep CO_2 concentration and relative humidity at acceptable levels. There are regulatory requirements for the minimum number of air changes per hour (ACH) produced by HVAC airflows, which depend on the intended use of the workspace. Two HVAC variables are critical to aerosol transport and infection risk. They are the ACH value (the higher the better to minimise the residence time for which airborne pathogens stay within the space) and the positioning & velocity of the HVAC system's supply (inlet) and exhaust (outlet) ducting, which determine in which direction the flow occurs and how fast it is. In this report, both these factors along with human movement effects are accounted for in the cumulative infection risk maps, which are in turn based on detailed measurements taken in each workplace.

iv. Effect of human movement on aerosol transport

Human movement in the workplace can impact transport of aerosols, both directly via the airflows generated by people walking and moving, and indirectly via the opening and closing of doors and movement of bulky supplies and equipment. These airflows cause temporary localised disturbances to the background HVAC airflows that can significantly impact local aerosol transport and pathogen risk; for instance, occupants traversing a workplace can 'drag' aerosol particles behind them. Similarly, the opening and closing of a swinging door can pump aerosols through the door opening, i.e. down corridors and into/from rooms.

v. Human movement sensing, analysis, and effects on cumulative infection risk

To gather human movement data for each Case Study, an ethically approved study was designed in which anonymised volunteer participants at each of the five studied workplaces carried human movement sensors (Bluetooth low-energy tags) during the two-week study period. These recorded the predominant locations of each participant within their workplace. Advanced AI algorithms and fingerprinting techniques were then developed to refine and verify



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the location of each participant for subsequent analysis. Human movement paths then also determined from the evolution of participants' locations over time. These results were then incorporated into detailed CFD studies of the transport of aerosols in the five workplaces studies, resulting in the cumulative infection risk maps presented later in this report.

vi. Risk mitigation strategies

Several mitigation strategies were considered to manage the cumulative infection risk in the five workplaces studied. These include alterations to HVAC layout, systems and settings, introduction of local air purifiers, alterations in building use and occupancy levels, and the donning of personalised protective equipment (PPE) such as N95 masks worn by infected and/or susceptible occupants. The efficacy of these strategies was tested via the CFD models developed for the five workplaces studied, and candidate strategies were shortlisted in conjunction with the workplace operators. However, given the short timeframe of this phase of the project, only a limited number of these mitigation strategies could be implemented and tested for each workplace.

vii. $PM_{2.5}$ and CO_2 as proxies for pathogenic aerosolsk

Measured concentrations of particulates ≤ 2.5 micron in size (conventionally termed '$PM_{2.5}$') and CO_2 concentration were both considered as candidate proxies for pathogenic aerosols, under the assumption that these proxy airborne contaminants are transported through air in a similar way. In the former case, $PM_{2.5}$ particles are of similar size and density to desiccated pathogenic aerosols (median size 6 micron), and so share similar airborne transport characteristics. Both pathogenic aerosols and CO_2 are highly correlated with human activity and are therefore good indicators of ventilation rates, however CO_2 diffuses through air alongside being dispersed through the air, unlike desiccated aerosols. In this project, $PM_{2.5}$ was the final chosen proxy for pathogenic aerosols and was monitored to understand aerosol transport through the workplace. Further details are presented in section 3.3.

viii. Stakeholder feedback

Feedback was gathered from the workplace operators to understand the impact of airflow sensing and modelling on our industry partner organisations in terms of the issues, benefits, and short-term impacts of the risk mitigation strategies that were implemented. At the time of writing, feedback was available from three of the five organisational settings studied here and listed in section 2.2, namely the open-plan office, hospital ward section, and factory paint room. This information is summarised in section 9.



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2.4 Background and Key Concepts

The final public recommendations resulting from this report are based on five Case Studies of Victorian workplaces and their extension case studies. This work naturally therefore covers only a fraction of possible workplace types, and for those workplaces studied, a fraction of the types of ventilation systems, layouts, and human use patterns it's possible to find therein. As aerosol transport is highly case-specific, this report is therefore unable to make 'comparative recommendations' such as the ranking of one type of HVAC system against another. However, it can make relative recommendations derived from the Case Studies and extensions that have a broader applicability. These recommendations attempt to address the following questions:

- How well do conventional metrics (such as air changes per hour) characterise the risk of exposure to airborne pathogens?
- Which types of airflow patterns may or may not be useful to minimise exposure risk?
  - Which types of HVAC systems assist or restrict the generation of those flow patterns?
  - Which types of building layouts assist or restrict the generation of those flow patterns?
- How does the interaction between building layout and HVAC system configuration impact the transmission risk of airborne pathogens?
- How does human movement impact the risk of airborne pathogen transmission?
- For the different Case Studies investigated here, which mitigation strategies would be the most effective?

2.5 Limitations to this Report's Recommendations

The final public recommendations presented in section 1 are subject to several limitations; some of these are described in the Appendix (sections 13.1 & 13.2) and opportunities for future work related to these limitations are described in section 10. Many of these limitations are associated with the CFD model and its embedded model of infection risk. Firstly, while CFD is a well-established method in both the HVAC industry and research sectors for modelling HVAC flows and aerosol transport, the computational resolution required to properly resolve the aerosol plume at the scale of a real workplace is currently not feasible. As a result, the turbulent flow and transport models employed in this study (Reynolds Averaged Navier-Stokes or 'RANS') tend to disperse (or 'smear out') the predicted distribution of aerosol concentration, leading to overprediction of aerosol spread and underprediction of the magnitude of infection risk hotspots. Secondly, these calculations are based on the transport of desiccated aerosols of 6 microns in size, whereas in reality, readily transmissible aerosols typically span 0.1 to 20 microns in size. As the transport characteristics of aerosols are strongly dependent upon their size, the assumption of monosized aerosols tends to underpredict aerosol dispersion. It is currently unclear whether this effect is greater or smaller than the aforementioned 'smearing' effect associated with the RANS turbulence model used here. In either case, these errors are expected to be significantly smaller than those associated with the extended Well-Riley risk model, which is based upon clinical data that became publicly available in early 2022 for sputum viral loads and rates of infection for the COVID-19 Delta variant. These clinical data vary significantly between infectious individuals (i.e. 'super spreader' in-patients exhibit a much higher viral load), stage of infection, pathogen type (particularly COVID-19 variant), and the ventilation rate, previous exposure, vaccine status, and level of immunosuppression status of susceptible persons. As such, the risk values quoted throughout this report should be interpreted in terms of relative infection risk rather than absolute infection risk. This limitation however does not impact the findings presented here with respect to risk mitigation strategies.



3. Preamble to Case Studies

3.1 Sensor Monitoring of Five Workplaces

In each of the five workplaces studied during this project (listed in section 2.2), microclimatic, indoor air quality, and human movement data were monitored continuously and recorded at high frequency (relative to common industrial practice) by sensors distributed around each workplace by the project team (detailed in the Appendix section 13.3). The microclimatic parameters included relative humidity (RH) and temperature, and the air quality parameters included the concentrations of volatile organic contaminants and particulate matter (PM) at size classifications of ≤ 1 (i.e. 'PM_1'), ≤ 2.5 ('$PM_{2.5}$'), and ≤ 10 microns ('PM_{10}'). In addition, for each workplace, a one-off study of air movement was undertaken to measure the air flowrates passing through the HVAC system's vents. Finally, the human movement sensors captured how the anonymised occupants of each workplace moved within and utilised their workplace throughout the day. Note that this latter aspect was not undertaken by the project team for the scientific research laboratory (Case Study 4) or the lecture theatre (Case Study 5), which in the latter case was due to pre-existing anonymised human movement sensors being present in that workplace.

3.2 CFD Simulation and Calculation of the Risk of Infection

All CFD simulations described in this report employed the 'finite volume method' form of computational fluid dynamics as implemented within the industry standard CFD software package Ansys Fluent version 2021R2 (Ansys, Inc., Canonsburg, Pennsylvania, USA). All simulations were performed on workstation desktop PCs with a single CPU with 12 cores. These required varying computational runtimes to complete, depending partly on the size of the workplace and thus the number of finite volume computational cells required to mesh the workplace. These runtimes ranged from 12-24 hours (for steady-state simulations, i.e. most simulations described in this report) to seven days (transient CFD simulations) on these desktop PCs. For further implementation details, the reader is directed to the project-associated publication by Li et al., (2022). The main outputs from these simulations were the barometric gauge air pressure, air velocity, and COVID-19-containing aerosol concentration (dimensionless volume fraction) distributions throughout each workplace. In the latter case, this

…microclimatic, indoor air quality, and human movement data were monitored continuously and recorded at high frequency (relative to common industrial practice) by sensors distributed around each workplace by the project team.

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aerosol was ejected from an infected occupant and then propagated into the workplace by the ambient airflow driven by the HVAC system and human movement, thus dispersing to form a cloud of aerosol.
The cumulative risk of infection from COVID-19 was estimated from the aerosol concentration distribution described above. This 'postprocessing' method operated on the CFD simulation results using the method and assumptions outlined by Li et al., (2022) and calculated the cumulative risk of infection to a susceptible occupant caused by exposure to infected aerosol effect in their vicinity over their likely residency time at their workstation. This predictive risk model was developed during this project and accounts for a range of factors such as the COVID-19 variant being modelled, the immunisation level of the susceptible person, the type and filtration efficiency of the PPE being worn, and the time of exposure of the susceptible person to the local concentration of COVID-19-containing aerosol around them; see Li et al., (2022).

3.3 Particulates Measurements and their Interpretation

Clearly it is not possible to release COVID-19 containing aerosols into workplace environments, and it is difficult even to release and track non-pathogenic aerosols over a long period of time. To gain an experimental understanding of air mixing and a proxy for the movement of COVID-19 aerosols, and as discussed in section 3.3, the particulate matter ($PM_{2.5}$) concentration in ambient air was measured using up to eight sensors placed around each of the five workplaces studied. Signature peaks/spikes were noticed in these particulate concentration readings at nearby locations, and further peaks were noticed in other nearby particulate sensors at slightly later times but with smaller magnitude than the earliest peak. It seems reasonable to assume that (i) some initial release event led to signature peaks in $PM_{2.5}$ at one of the sensors, which was then recorded by other sensors in the vicinity (in terms of aerosol transport) of the particulate source, (ii) the time taken for this particulate-containing plume to reach adjacent sensors at the peak concentration recorded there reflects the local rate & spread/dispersion of airborne particles, and (iii) this process could be a guide to the dynamics of pathogenic aerosol flow in these workplaces. In this report, the relative magnitude of these peak values between each sensor and the first sensor to show the signature peak were calculated, the time lag between the peaks for each sensor vs. the first sensor to show the signature peak were calculated, and the correlation between the $PM_{2.5}$ profile shapes (including the signature peak and its decay) were calculated. These results allowed the estimation of dynamics of aerosol spread throughout the sensored workplaces, which allowed the estimation of relatively isolated regions of mixing/recirculated air within each workplace. This information helped to characterise the overall rate of air mixing throughout each workplace.

The predictive risk model developed here… accounts for… the COVID-19 variant being modelled, the immunisation level of the susceptible person, the type & filtration efficiency of the PPE being worn, and the time of exposure of the susceptible person.



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4. Case Study 1: Open-Plan Office

4.1 General Information and HVAC System Details

The open-plan office considered for Case Study 1 is part of a mid-storey in a city office block. Microclimate (temperature, humidity, pressure), air quality (CO_2 and particulates) and human movement data were monitored in this office over a two-week period during February 2022. The HVAC system was controlled centrally for the whole office block (where the air flowrate was based on building occupancy rates) and was operated in 'mixing ventilation' mode. The floorplan of this office is shown in Figure 4-1, including location of the wall and ceiling HVAC inlet and outlet vents, office workstations, as well as two additional meeting rooms in the southwest and northeast corners and a kitchen in the southwest corner. The kitchen is open but has a perforated wall separating it from open-plan area to the west. There were 33 workstations and a total of 30 employees working in the office, although occupancy did not exceed 50% during the monitoring period. Air flow measurements at the HVAC vents indicated approximately 3.0 air changes per hour (ACH) within this workplace during working hours, which is at the lower end of the recommended range for an office space. The inlet vents on the north wall supplied most of the input air, which flowed across the office to the outlet vents on the south and west walls. Alongside this predominant airflow, a small proportion of air flowed through the HVAC ceiling inlet and outlet vents.

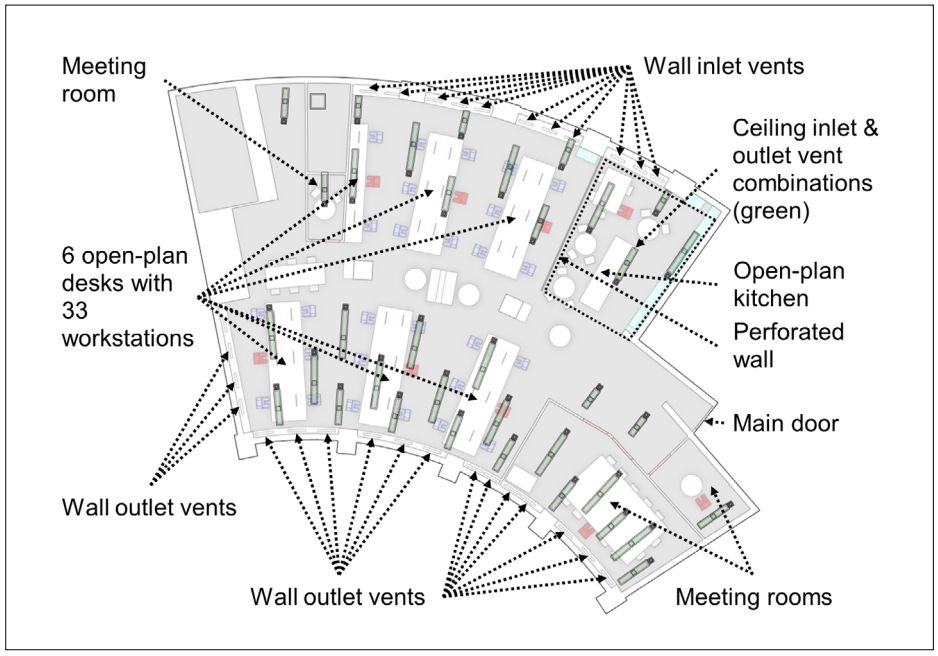


Figure 4-1 – Floorplan of the open-plan office studied during this project. Each combined ceiling inlet & outlet HVAC vent combination is shown as a green rectangle. The blue & red squares indicate the location of infectious & susceptible office occupants, respectively. The measured overall ACH value was 3.0 with the predominant airflow from the north wall (as depicted) to the south & west walls, and a small proportion of air flowing through the HVAC ceiling vents.

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4.2 Human Movement

13 out of 30 employees in this office agreed to take place in the human movement studies, with occupancy during the monitoring period not exceeding 50%. Further analysis of the sensor data demonstrated that the actual participation rate on any given day during the monitoring period was roughly one third. Figure 4-2 presents a 'heat map' showing the intensity (i.e. frequency) of the locations of monitored occupants during the two-week monitoring period.

The space utilisation of the monitored occupants was analysed and revealed that occupants tended to remain seated during their work shifts with only short trips to other locations, e.g. kitchen and meeting rooms. These short visits were to similar sites and occurred multiple times daily. The pathways used by occupants sitting in the same area during these short visits were generally similar. Thus, these pathways are critical in terms of predicting cumulative infection risk.

4.3 Aerosol Movement and COVID-19 Cumulative Infection Riskt

The CFD model constructed here for air (aerosol) flow around the open-plan office uses the office layout presented in Figure 4-1. The flowrates measured through the virtual HVAC inlets were as measured for this office. For simplicity, the HVAC outlets were modelled here as operating 'passively', i.e. simply maintaining atmospheric pressure, rather than active outlet vents via a fan-driven exhaust system. The airspeed distribution within the lab predicted under these conditions via CFD simulation is presented in Figure 4-3 at an elevation of 1.6 m corresponding to the average mouth height of a standing human being). This distribution demonstrates that airflow was predicted to be generally slow, i.e. ≤ 0.05 m/s, with further interrogation revealing that its orientation was generally from north to south.

Figure 4-4 presents the predicted steady-state aerosol concentration generated from a single occupant infected with the Delta variant at a central location close to the south wall of the office. The corresponding cumulative infection risk ('CIR') distribution for (i) a 6-hour exposure time to the infected occupant, (ii) all occupants modelled as wearing surgical masks with 75% filtration efficiency, and (iii) CIR calculated at an elevation of 1.6 m above the floor (average height of a standing human's mouth) is presented in Figure 4-5; note these three conditions are applicable to all CIR plots presented in this chapter. The CIR distribution in Figure 4-5 is strongly correlated with the steady-state aerosol distribution in Figure 4-3, which is expected as infection risk increases with the local concentration in the air of COVID-19-containing aerosol. Both aerosol and cumulative infection risk are widely spread across this office, and track with the slow and generally north-to-south airflow within the office. Spread also occurs in the east-west direction, but to a smaller extent.

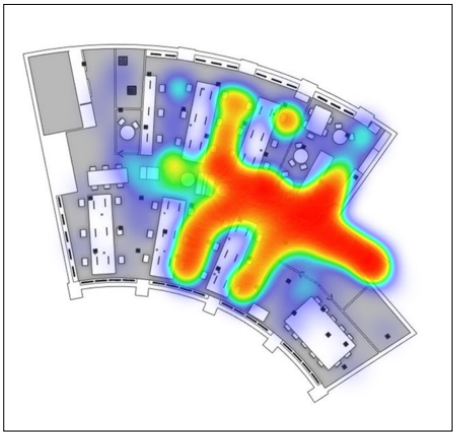


Figure 4-2 – 'Heat map' showing the two-dimensional distribution of relative frequency of monitored occupant locations around the open-plan office's floor during the two-week monitoring period.

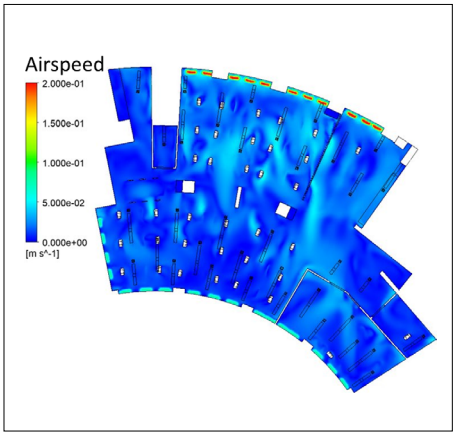


Figure 4-3 – Predicted airspeed distribution within the open-plan office at a human standing mouth height of 1.6 m and the measured ACH value of 3.0.

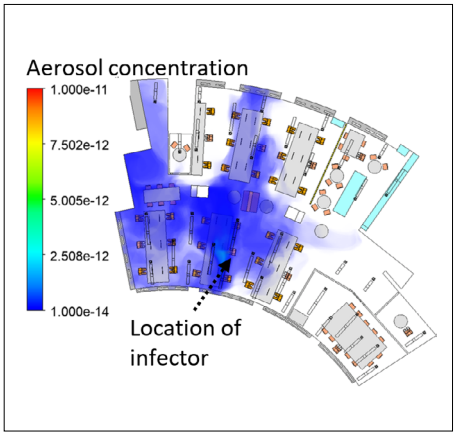


Figure 4-4 – Predicted aerosol concentration distribution at a human standing mouth height of 1.6 m during steady-state daytime exposure to a single occupant (infected with the Delta variant) who dons a surgical mask with the overall ACH being 3.0.

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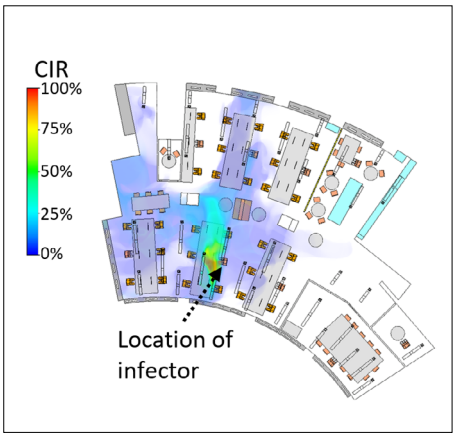


Figure 4-5 – Predicted cumulative infection risk (CIR) at an elevation of 1.6 m during steady-state daytime exposure to a single occupant (infected with the Delta variant) for six hours. All occupants don surgical masks with the overall ACH being 3.0.

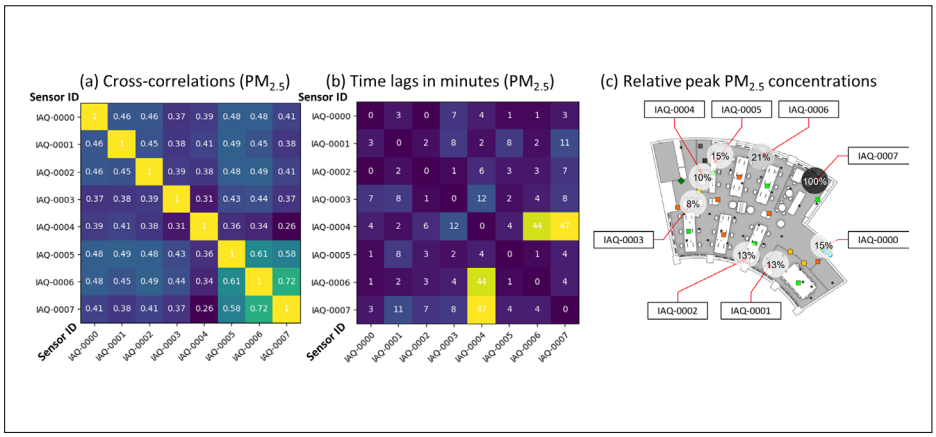


Figure 4-6 – (a) Cross-correlations, (b) time lags available to the nearest minute, and (c) relative magnitudes of the $PM_{2.5}$ concentration peaks measured in the open-plan office studied during this project. The circled values in (c) are concentrations divided by the largest peak value recorded and are thus dimensionless.

Given the above results, further simulations were undertaken with the infected occupant in a variety of other locations around the office and similar results were predicted, i.e. if the infected occupant was in the northern section of the office, the corresponding aerosol concentration and cumulative infection risk distributions were more widespread, again reflecting the slow, prevailing north-south airflow.

4.4 Particulates Measurements and their Interpretation

Eight sensors for airborne particulate matter, i.e. IAQ0000 to IAQ0007 in Figure 4-6(c), were installed into the office to track the $PM_{2.5}$ concentration distribution. As explained in detail in section 3.3, the correlation between signature peaks/spikes in the $PM_{2.5}$ profiles is presented in Figure 4-6 for an event around midday on 22nd February occurring within the kitchen (sensor IAQ-0007). The time of this peak correlated strongly with peaks registered at adjacent sensors IAQ-0005 and IAQ-0006 and occurred for these latter sensors only four minutes later. However, the magnitudes of these spikes at all seven other sensors were significantly reduced (10-20% of the source).

Analysis of several such events during the two-week monitoring period at this office showed the similar high correlation between spike timing at the eight $PM_{2.5}$ sensors, although the spike magnitudes varied as described above. Thus, these data imply that particulates travel reasonably quickly from their source to adjacent zones within this office albeit at reduced magnitudes, which is in broad agreement with the results from CFD modelling in section 4.2.

4.5 Risk Mitigation Strategies

From the trends in the CFD, sensor, and human movement data described in sections 4.2 - 4.4, respectively, and from critical discussions with the office managers, the following mitigation strategies were proposed:

i. Introduce partitions between workstations
ii. Increase the overall ventilation rate
iii. Use an array of locally placed (portable) air purifiers

i. Use of Desk Partitions

The CFD simulations described in section 4.2 were modified to include desk-to-ceiling partitions along either (i) the middle of the long, shared desks (north-south), or (ii) both north-south partitions and partitions between each occupant and their neighbours to left and right, i.e. east-west partitions. While both arrangements of partitions did constrain aerosol movement into the aisles, they did not limit spread effectively within the aisles, and thus did not limit cumulative infection risk effectively in this office. These results are therefore not presented for brevity. Note that the managers of this open-plan office also considered this type of intervention unfavourably.

ii. Increased HVAC Air Changes Per Hour

The ACH value measured for this office (3.0) was relatively low, though providing good energy efficiency. Further simulations were therefore conducted using ACH values ranging from the baseline existing value (3.0) to 6.0, at 8.0, and at 12.0, with a single infected occupant seated at a mid-seat in the northern section. Figure 4-7

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demonstrates that at the baseline ACH value of 3.0, the cumulative infection risk is predicted to be widespread. Substantive risk reduction requires much a higher ACH of 8.0 (Figure 4-8), which constrains risk to the immediate vicinity of the infected occupant. Increasing further to 12.0 then constrains this risk even more closely around the occupant; this result is not shown for brevity. While effective, this strategy was however difficult to implement as (i) the HVAC system was controlled centrally, and (ii) building managers do not prefer high ACH values due to both their energy costs and their negative effects on human comfort.

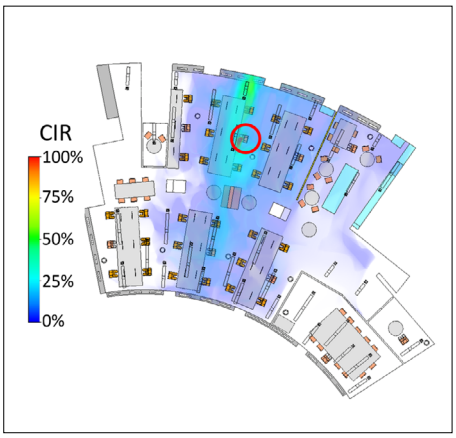


Figure 4-7 – Predicted cumulative infection risk (CIR) at an elevation of 1.6 m from a single occupant (infected with the Delta variant and circled in red) located towards the upper-left corner at an ACH value of 3.0 after six hours. All occupants don surgical masks.

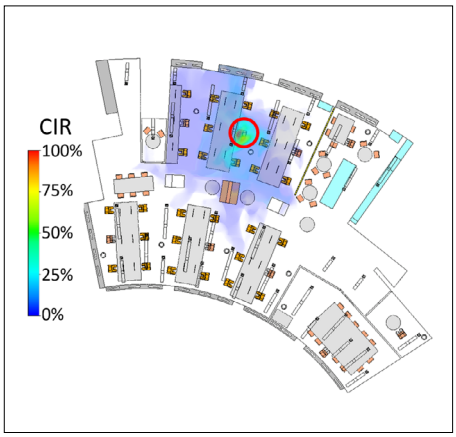


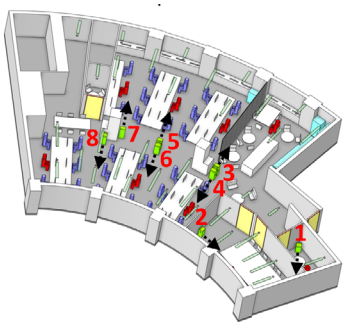
Figure 4-8 – Predicted cumulative infection risk (CIR) at an elevation of 1.6 m from a single occupant (infected with the Delta variant and circled in red) located towards the upper-left corner at an ACH value of 8.0 after six hours. All occupants don surgical masks.

iii. Introducing Locally Placed Air Purifiers

Air purifiers may be used to clean and direct air without the need for potentially difficult alterations to the HVAC system. This mitigation strategy was modelled using CFD prior to the workplace operator purchasing any purifiers by placing five virtual purifiers around the simulated office and assuming all occupants were unmasked and included five infected individuals. In terms of locations, one smaller purifier operating at 401 m³/hr was considered for placement in each of the two meeting rooms, and three larger purifiers each operating at 701 m³/hr were considered for placement in the open-plan area (Figure 4-9). Note that with all five purifiers active, the overall ACH value for the office increased from 3.0 to 8.0.

Figure 4-9 (with purifiers) vs. Figure 4-8 (no purifiers) demonstrates that for the common infected occupant placed in the upper left corner (as depicted), CIR after six hours was significantly reduced by the judicious selection, placement, and orientation of the five local air purifiers. Specifically, the proportion of the office's floor area with risk > 10% was reduced from 74% (without purifiers) to < 24% (with purifiers), though more generally, the effectiveness of this strategy will depend on the type and rating of the air purifiers, their position, and their number. Given these results, the industry partner moved ahead with purchasing five purifiers for this office. A follow-up period of monitoring the particulate matter ($PM_{2.5}$) was commissioned to monitor and confirm the efficacy of this mitigation strategy (Figure 4-10).

(a) Potential air purifiers positions (green boxes) with each position numbered (red). Black arrows show the orientation of each purifier's outlet vent, i.e. the direction of the purified airflow.



(b) CIR >10% for purifiers in positions 1, 2, 4, 5, 7



Figure 4-9 – (a) 3D CAD schematic showing the eight possible positions & orientations considered for the five air purifiers added to the open-plan office simulations. (b) Predicted cumulative infection risk (CIR) distribution at an elevation of 1.6 m for the CIR-optimised arrangement of five air purifiers. This assumes six hours' exposure to five (red-circled) occupants infected with the Delta variant, with all occupants donning surgical masks. For clarity, (b) shows only those regions with CIR > 10%. Note that with five purifiers active, the overall ACH value for this open-plan office increased from 3.0 to 8.0.

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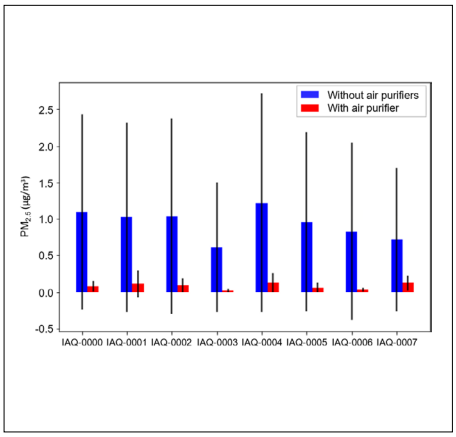


Figure 4-10 – Changes in measured airborne particulates concentration ($PM_{2.5}$) after introduction of five air purifiers into the open-plan office, which also increased the overall ACH from 3.0 to 8.0. Error bars indicate the standard deviation of $PM_{2.5}$ concentration over the monitoring period.

During the follow-up monitoring period, an event was recorded that triggered a strong particulate source in the kitchen. The maximum $PM_{2.5}$ value at sensor locations outside the kitchen was however always ≤ 5% of the peak recorded in the kitchen (compared with 21% without the purifiers). In absolute terms, the average $PM_{2.5}$ count with purifiers was also reduced to ≤ 10% of its value without purifiers (Figure 4-10). This confirms that locally placed air purifiers can be highly effective at reducing risk if selected, placed, and oriented carefully in the chosen workplace.

4.6 Summary

An open-plan office with an HVAC system set at a relatively low ACH value of 3.0 was examined. It was found that aerosol spread, and thus cumulative infection risk, was relatively widespread and was reinforced in this case by the airflow patterns established by the north-south prevailing airflow created by this office's orientation of HVAC inlet and outlet vents.

Computational model predictions demonstrate that cumulative infection risk may be mitigated by dramatically increasing the ACH, but a more practical solution appears to be the use of local air purifiers. However, the number, location, and orientation of these must be optimised to the specific workplace in which they are implemented

MAJOR FINDING: Low ventilation rates and mixing ventilation schemes may increase risk of pathogen transmission. Under these circumstances, correctly placed and aligned local air purifiers may be effective.

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5. Case Study 2: Factory Paint Room

5.1 General Information and HVAC System Details

This Case Study involved the monitoring & CFD simulation of a factory 'paint room' as illustrated in Figure 5-1. The paint room was monitored for two weeks during May 2022 and included automated painting units, workbenches, and drying racks.

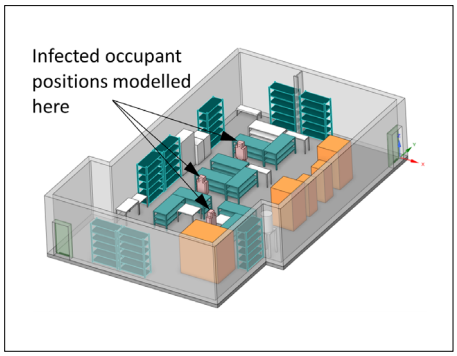


Figure 5-1 – 3D CAD schematic of the factory paint room studied during this project. The measured overall ACH value imposed by the HVAC system's ceiling vents was relatively high at 8.0.

The paint room had five HVAC inlet ducts and one outlet duct, all of which were located in the ceiling as shown in Figure 5-2, with dimensions 0.6 m × 0.6 m (inlets) and 0.6 m × 1.2 m (outlets). The incoming vents' airflow was measured as being larger than the outgoing vent's airflow, which means the room is at a slight positive pressure relative to atmospheric pressure and some air from the HVAC inlet vents escapes through the gaps around the room's doors. The ceiling vents provided a relatively high overall air change rate (ACH) value of 8.0, which was predicted to generate a moderate resulting airspeed distribution in Figure 5-3 of 0.05 - 0.2 m/s in the bulk of the room, with higher values around the ducts (up to 0.6 m/s). Figure 5-4 presents the air flow lines predicted for the paint room, which demonstrate (i) the strong directionality of the airflow coming from the inlet ducts, and (ii) that this combination of HVAC system and room layout tend to promote air recirculation zones rather than room-wide air mixing.

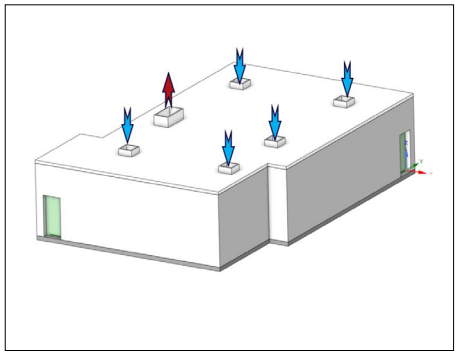


Figure 5-2 – 3D CAD schematic of the ceiling HVAC inlet and outlet vents for the factory paint room studied during this project. This arrangement and the measured overall ACH of 8.0 promoted local air recirculation zones rather than room-wide air mixing.

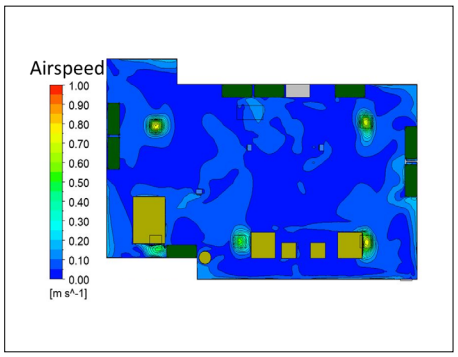


Figure 5-3 – Predicted airspeed distribution within the factory paint room at a human standing mouth height of 1.6 m and an overall ACH value of 3.0

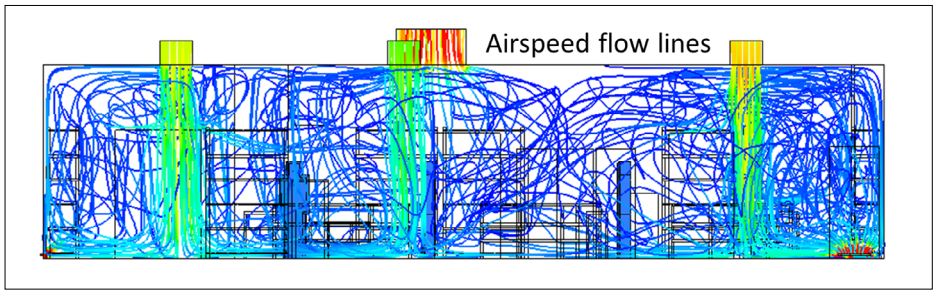


Figure 5-4 – Cross-section of the air flow pattern predicted within the factory paint room. Airflow follows the coloured flow lines, which indicate the local airspeed according to the same legend as used in Figure 5-3. Air from the HVAC inlets generally travels from these (green-dominated) ceiling inlets down towards the floor, then around 'recirculation cells' occupying different zones of the paint room, and then slowly between cells and then upwards into the (red-dominated) HVAC ceiling outlet. The modelled overall ACH value matched the measured value of 3.0.

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5.2 Human Movement

During the two-week monitoring period, the factory paint room normally did not have more than two occupants using it. Both agreed to be monitored. Figure 5-5 demonstrates that the occupancy time for occupants during each visit to the paint room was relatively short at ≤ 5 minutes except for two locations (both near painting machines) where it averaged 25 minutes.

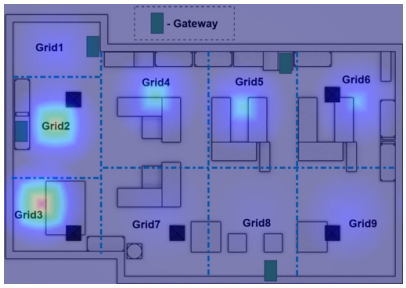


Figure 5-5 – 'Heat map' showing the two-dimensional distribution of relative frequency of monitored occupant locations around the factory paint room's floor during the two-week monitoring period. The red & purple ends of the colour spectrum indicate limiting values of 25 minutes (both near painting machines) and ≤ 5 minutes (everywhere else), respectively.

5.3 Aerosol Movement and COVID-19 Cumulative Infection Risk

Figure 5-6 presents two cumulative infection risk distributions predicted from CFD simulations of the factory paint room. Both assumed a single, stationary occupant infected with the Delta variant located slightly towards the 'lower-middle' wall of the paint room as depicted in Figure 5-6. Both also assumed a single susceptible occupant was present in the room and is standing with their mouth at the average human height (elevation) of 1.6 m. The two distributions differ only in the assumed exposure time, which bracket the lower extreme of a five-minute visit (suggested by the human monitoring data in Figure 5-5) and the upper extreme of a six-hour work shift. Both the infected occupant and any visitors are modelled as wearing surgical masks with 75% filtration efficiency.

Figures 5-6 and 5-7 predict that while the cumulative infection risk for six hours of exposure time is considerable in the infected occupant's vicinity, this high-risk region does not propagate across the whole paint room. The risk after 5 minutes' exposure was very low. This confined behaviour may be due to the air recirculation zones predicted to occur in the paint room (Figure 5-4). Thus, the paint room was found to present negligible infection risk to the susceptible occupant except in the immediate vicinity of the infected occupant.

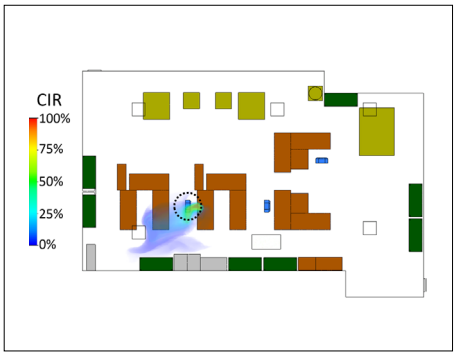


Figure 5-6 – Predicted cumulative infection risk (CIR) distribution at an elevation of 1.6 m after six hours' exposure to a single occupant (infected with the Delta variant and circled in black) with all occupants donning surgical masks with an overall ACH of 8.0

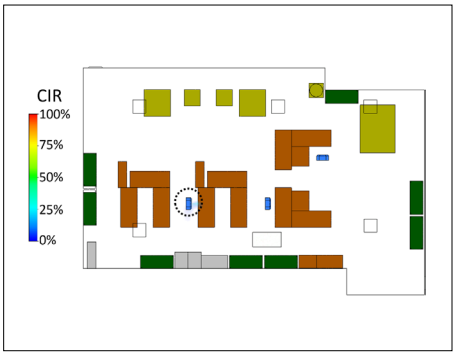


Figure 5-7 – Predicted cumulative infection risk (CIR) distribution at an elevation of 1.6 m after five minutes' exposure to a single occupant (infected with the Delta variant and circled in black) with all occupants donning surgical masks with an overall ACH of 8.0

5.4 Particulates Measurements and their Interpretation

Four particulates sensors were installed into the factory paint room during the two-week monitoring period. As explained in detail in section 3.3, the correlation between signature peaks/spikes in the $PM_{2.5}$ profiles was determined for the sensors in this network. The measurements for the sensors adjacent to the painting machines showed the highest spikes in $PM_{2.5}$ concentration, indicating that they are due to the opening of the machine. These spikes lasted approximately two hours, with the occupant in the vicinity of the painting machine being present for just 30-40 minutes, which presumably reflects the opening and unloading the machine. Thus, the spike in $PM_{2.5}$ took ~80 minutes to dissipate after closure of the painting machine. Figure 5-8 presents the $PM_{2.5}$ concentration relative to that measured for the closest sensor to the painting machine.

The scaled (dimensionless) $PM_{2.5}$ values in Figure 5-8 are all within 20% of the maximum spike value (100%), which indicates that the particulates were rapidly distributed over the entire paint room by ambient air currents prior to their removal by the HVAC system through the ceiling outlet vent. Thus, there is a contrast between the observed widespread dispersion of particulates measured by the sensors and the limited dispersion of aerosol predicted by the CFD model of the

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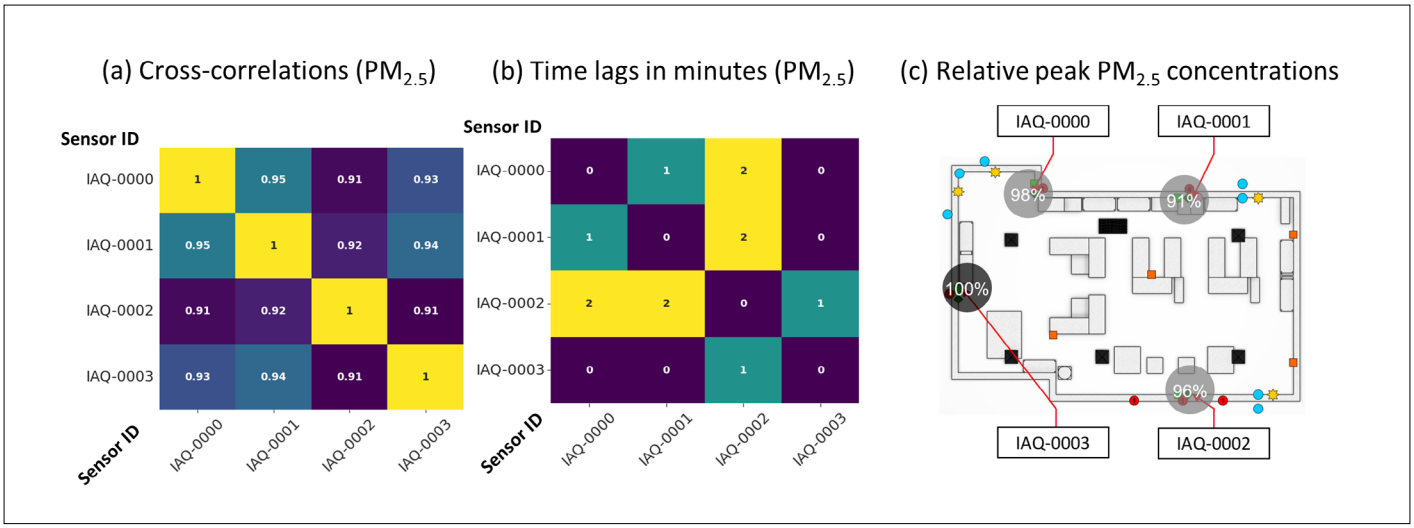


Figure 5-8 – (a) Cross-correlations, (b) time lags available to the nearest minute, and (c) relative magnitudes of the $PM_{2.5}$ concentration peaks measured in the factory paint room studied during this project. The circled values in (c) are concentrations divided by the largest peak value recorded and are thus dimensionless.

paint room. This disagreement is attributed here to the large amounts of particulates released by the painting machines, which are far greater than the small (in absolute terms) release rate of aerosol exhaled by COVID-19-infected humans.

5.5 Risk Mitigation Strategies

The results from the CFD modelling of the factory paint room (section 5.3), which integrate the duct placement and measured air flowrates through them (section 5.1), combined with the observed human movement data (section 5.2) predict that during operationally 'normal' days involving short visits by susceptible occupants, the combination of mask-wearing and social distancing is sufficient to render the paint room a low-infection-risk environment. The key contributors to this prediction are the low occupant residency time in this room, the placement of HVAC vents, and the high ACH value, which combine to ensure that the spread of cumulative infection risk is limited to a certain air recirculation zone. Thus, if occupants stay in separate parts of the room, the cumulative infection risk is predicted to be limited. The disagreement between these predicted results and those measured after emissions from the painting machines (section 5.4), which spread widely throughout the room, does however offer the following caution. High emissions of aerosol may be able to escape from their local air recirculation cell and spread throughout the room at significant concentrations before they are cleared by the HVAC system, which can take longer than an hour to occur.

5.6 Summary

In the factory paint room studied during this project, an HVAC system with a relatively high ACH value combined with the generally short visits by occupants to the room lead to the conclusion that mask wearing and social distancing should limit the cumulative infection risk to 'acceptable' levels.

MAJOR FINDING: The use of a high HVAC air exchange rate (ACH value) and PPE can minimise cumulative infection risk to a relatively low level, particularly when occupants' residence times at their workstations is limited.

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6. Case Study 3: Section of a Hospital Ward

6.1 General Information and HVAC System Details

This case study involved part of a hospital ward that includes a ward entrance area, nurses' station, six ward rooms (4 single rooms & 2 double occupancy rooms), common ward area including corridors, and various utility rooms as depicted in Figure 6-1. Air quality & human movement sensing were undertaken over a two-week period during March - April 2022. In terms of ward utilisation, this ward has – depending on epidemiology of COVID in the local community – functioned as either (i) a pandemic ward caring exclusively for in-patients with COVID-19, or (ii) as a general medical/surgical ward designated to care for in-patients without known COVID-19 infections. The pandemic ward scenario '(i)' was assessed here from the perspective of presenting a high infection transmission risk from infected in-patients to ward staff. The non-pandemic ward scenario '(ii)' was assessed for infection transmission risk from visitors (who were only later identified as being infected with COVID-19) to in-patients & staff.

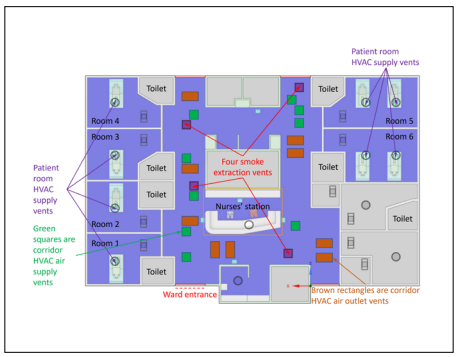


Figure 6-1 – Floorplan of the hospital ward section studied during this project

This section of the hospital ward employed a 'mixing' ventilation scheme in which supply air from the outside environment was supplied through ceiling inlet vents in the in-patient rooms and removed by ceiling outlet vents in the corridors of the common ward area. The air changes per hour (ACH) value was 6.0, which represents a 'moderate' ventilation rate. During the pandemic period, this airflow was supplemented by continuous activation of an emergency smoke extraction system in the ceiling cavity (comprised of separate fans and ducts) that vented to the building's exterior. This system was operated at a negative pressure of -2 Pa relative to the ward air pressure, which increased the ACH value to a relatively high value of 8.6. Regardless of operation of the smoke extraction system, the regular HVAC outlets in the ward section operated 'passively' to maintain atmospheric pressure. This arrangement of negative pressure in some areas of the ward section led to the generation of incoming airflows around the gaps in its external doors, with the hospital corridors outside these doors assumed as being at atmospheric pressure.

6.2 Human Movement

For this case study, more than 60% (22 participants) of nurses volunteered for monitoring of human movement during the monitoring period. The resulting 'heat map' of nurse location density is shown in Figure 6-2. A high nurse location density occurs near the nurses' station, as well as two lower-density 'hotspots' in other ward rooms. These results highlight the critical need to control the cumulative infection risk around the nurses' station.

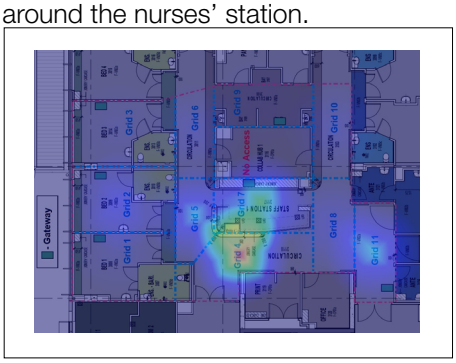


Figure 6-2 – Two-dimensional 'heat map' of monitored nurse location density around the hospital ward section over the two-week monitoring period

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6.3 Pandemic Ward Scenario – Aerosol Movement and Infection Risk

CFD modelling was used to predict airflow, aerosol transport, and cumulative infection risk to staff on the hospital ward. This used the layout & HVAC system information presented in section 6.1 and assumes the ward to be operating in pandemic mode, i.e. with all beds occupied with in-patients infected with the Omicron variant of COVID-19, which corresponds to the worst-case scenario for infection transmission risk to staff. Staff were modelled as always wearing surgical masks (with 75% filtration efficiency) and in-patients were modelled as either donning no masks, surgical masks, or N95 masks (95% filtration efficiency); however, we note wearing of masks by in-patients is impractical in some cases. An exposure time of eight hours was chosen to reflect a typical ward shift.

When in-patient mask wearing is a practical option, the mask type donned by in-patients is predicted to have a profound effect on cumulative infection risk to staff. If the infected in-patients wear N95 masks, the region of significant infection risk to staff is localised to each infected in-patient (Figure 6-3); note that the risk plot is presented at the average height (elevation) of a standing human's mouth (1.6 m), which is the case for all risk plots presented in this chapter. If the infected in-patients wear surgical masks, the region of significant infection risk to staff spreads to include parts of the corridors (Figure 6-4). If the infected in-patients do not wear masks, the region of significant infection risk includes most of the ward section including the nurse's station (Figure 6-5).

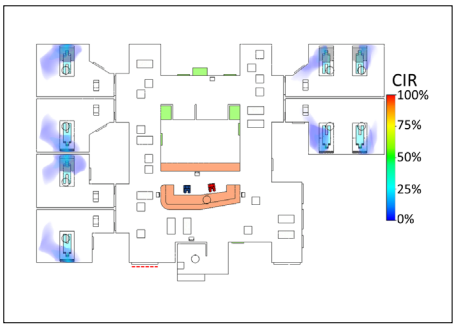


Figure 6-3 – Predicted cumulative infection risk (CIR) distribution at an elevation of 1.6 m over the hospital ward for a susceptible occupant donning a surgical mask after eight hours' exposure to infectious in-patients in ward rooms who are donning N95 masks. The overall ACH value is 8.6. The red dashed line in all distributions in this chapter denotes an external door through which some aerosol escapes.

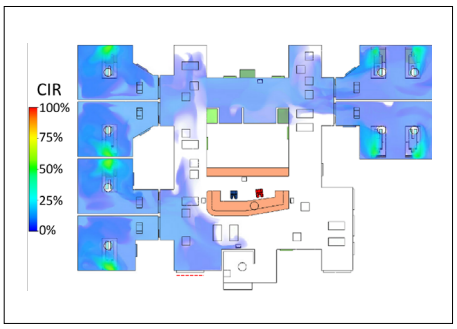


Figure 6-4 – Predicted CIR distribution at an elevation of 1.6 m due to eight hours' exposure to in-patients infected with the Omicron variant. This assumes all in-patients & staff don surgical masks and the overall ACH is 8.6.

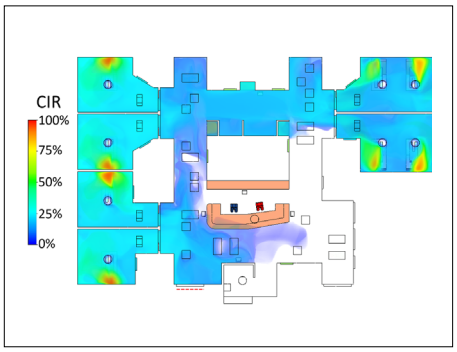


Figure 6-5 – Predicted CIR distribution at an elevation of 1.6 m due to eight hours' exposure to in-patients infected with the Omicron variant. This assumes in-patients are unmasked, staff don surgical masks and the overall ACH is 8.6.

These results indicate that the air supply from the in-patient rooms promotes transport of pathogenic aerosols into the corridors and common ward area, including the nurses station. This is significant as the nurses' station, which (as is shown in section 6.2) has the highest density of occupancy by susceptible staff (Figure 6-2).

6.4 Non-Pandemic Ward Scenario – Impact of an Infected Visitor

CFD modelling was used to predict airflow, aerosol transport, and infection risk on the hospital ward using the layout and HVAC system information presented in section 6.1 and with the ward operating in non-pandemic mode, i.e. with all beds occupied with in-patients not infected with (and thus susceptible to) COVID-19. In these cases, the risk is posed by visitors – who are infected with the COVID-19 Omicron variant – to uninfected staff & in-patients. The scenarios modelled involved a single infected visitor present at (i) the nurse's station for 5 minutes, and (ii) the in-patient's bedside in Room 2 for 90 minutes. For both scenarios, all occupants throughout the ward section were modelled as wearing surgical masks. Figure 6-6 presents the predicted aerosol concentration distribution predicted 15 minutes after the infected visitor arrives at the nurses' station, i.e. when aerosol transmission causes its concentration to reach its steady state at one of the nurses' locations. At this time, the aerosol plume extended throughout the nurses' station and down two of the corridors towards the ceiling HVAC outlet vents. Figure 6-7 presents the aerosol concentration (non-dimensionalised by dividing by the concentration expelled by the infected visitor) & cumulative infection risk over a 65-minute period after the arrival of Visitor 1 at the nurses' station. Both the concentration & CIR results in Figure 6-7 include three profiles each, which correspond to (i-ii)

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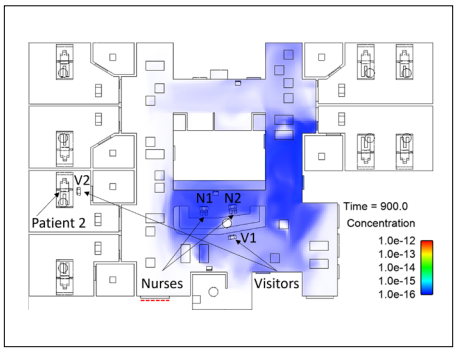


Figure 6-6 – Predicted aerosol concentration distribution at an elevation of 1.6 m caused by infectious visitor 'V1' at the nurses' station after 15 minutes' exposure. V1 dons a surgical mask and the overall ACH is 8.6.

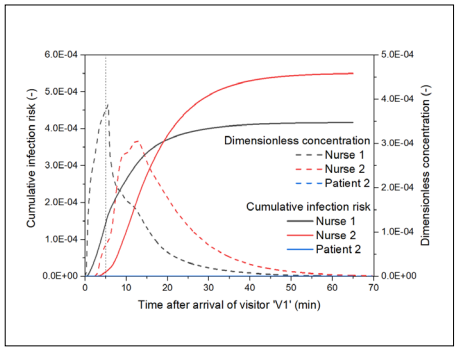


Figure 6-7 – Predicted aerosol concentration (divided by concentration at infected visitor V1's mouth) & CIR profiles at an elevation of 1.6 m over 65 minutes after V1's arrival. All occupants don surgical masks and the overall ACH is 8.6. Profiles are plotted for locations 'N1', 'N2', and 'Patient 2' depicted in Figure 6-6.

the locations of two stationary nurses at the nurses' station, and (iii) the in-patient in Room 2 (see annotations to Figure 6-6).

Figure 6-7 shows that after 5 minutes & 10 minutes, the pathogenic aerosol concentration inhaled by Nurse 1 (closest to the infected visitor) & Nurse 2, respectively, peaks far below than that exhaled by Visitor 1, after which the concentrations decay back to zero. Due to this short exposure time & low concentration, the maximum cumulative infection risk experienced by both nurses over the time window studied is low (< 0.1%).

Figures 6-8 and 6-9, i.e. for Visitor 2 visiting the in-patient in Room 2 for 90 minutes, show the same general pattern of results as Figures 6-6 & 6-7 for Visitor 1 at the nurses' station. In Visitor 2's case, their aerosol plume after 60 minutes extends from Room 2 into the local corridor area where it is extracted by the ceiling HVAC outlet vents, and only low concentrations extend to the nurses' station. The aerosol concentration inhaled by the in-patient in this room and the nurses at the nurses' station all peak at ~95 minutes and at concentrations much lower than that exhausted by the visitor. As expected, the cumulative infection risk for the in-patient (who similarly to the nurses dons a surgical mask with 75% filtration efficiency) is significantly higher than that for the nurses, but for all three uninfected occupants, their absolute cumulative infection risk is low (≤ ~0.1%). In the corresponding cases of Room 2's in-patient in other masking situations, i.e. N95 mask, procedure mask (filtration efficiency 38.5%), and unmasked, their final CIR over the period studied (profiles not shown for brevity) increase essentially linearly with mask filtration efficiency. When unmasked, the CIR maximum over the time window studied thus increases by ~4x to ~0.4% (i.e. still relatively low).

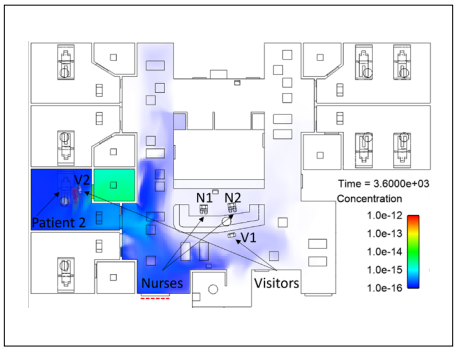


Figure 6-8 – Predicted aerosol concentration distribution at an elevation of 1.6 m caused by infectious visitor 'V2' visiting in-patient Room 2 for one hour (3600 s). V2 dons a surgical mask and the overall ACH is 8.6.

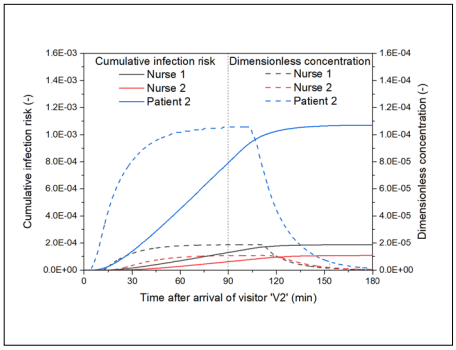


Figure 6-9 – Predicted aerosol concentration (divided by concentration at infectious visitor V2's mouth) & CIR profiles at an elevation of 1.6 m over three hours after V2's arrival. All occupants don surgical masks and the overall ACH is 8.6. Profiles are plotted for locations 'N1', 'N2', and 'Patient 2' in Figure 6-8.

6.5 Particulate Measurements

As explained in detail in section 3.3, the correlation between signature peaks/spikes in the $PM_{2.5}$ profiles is used in this report to characterise aerosol transport around each workplace. As the hospital ward section sources its HVAC feed air from the outside (externally), it is possible that external $PM_{2.5}$ particles survive HVAC filtration and enter the ward. This secondary transport process may therefore complicate the interpretation method described in section 3.3 for using $PM_{2.5}$ transport between sensors as a proxy for aerosol transport from infectious ward occupants. Figure 6-10 presents the positions of eight particulate sensors placed throughout the ward; the relative magnitude of signature peaks are presented in Figure 6-10(c), the time lags between peaks in Figure 6-10(b), and the correlations between pairwise $PM_{2.5}$ profile shapes as they decay over time are in Figure 6-10(a). All peaks & subsequent decay profiles were recorded on 28$_{th}$ March 2022 between 6 am & 2 pm, which corresponds to the start & end of a standard eight-hour working shift.

Figure 6-10 shows that the $PM_{2.5}$ profile shapes measured by the sensors are highly correlated, and that the time lags between peaks

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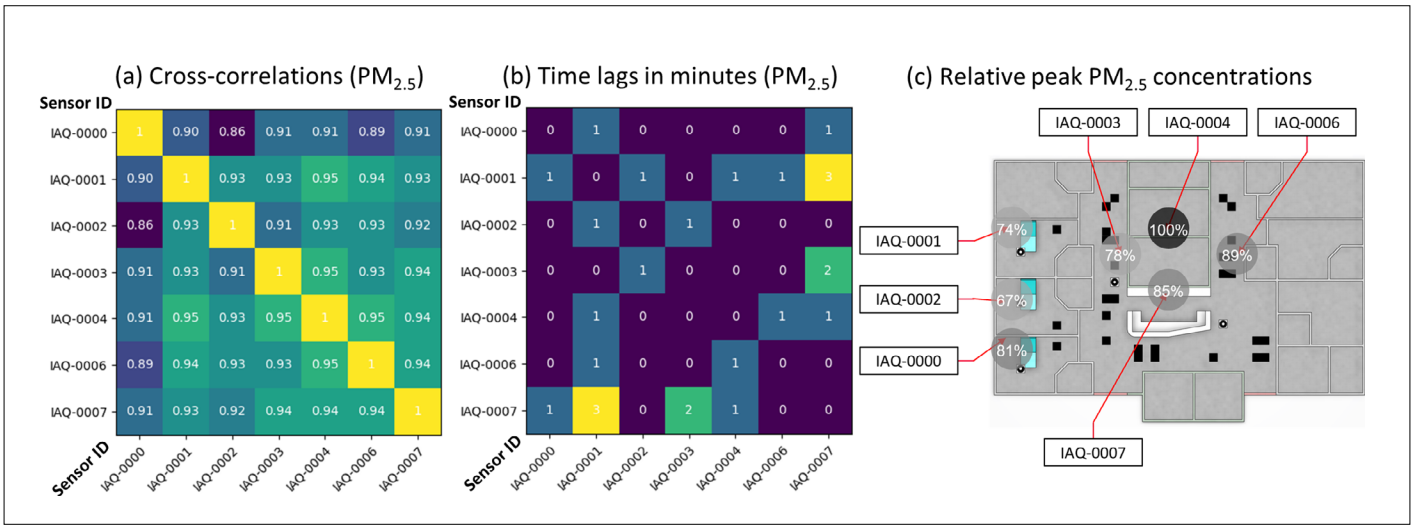


Figure 6-10 – (a) Cross-correlations, (b) time lags available to the nearest minute, and (c) relative magnitudes of the $PM_{2.5}$ concentration peaks measured in the hospital ward section studied during this project. The circled values in (c) are concentrations divided by the largest peak value recorded and are thus dimensionless.

appears short relative to the ward section's size. In the absence of an external particulate source, this indicates that either (i) if no particulate matter is introduced from outside then internally generated particulate matter is being dispersed rapidly & extensively throughout, or (ii) particulate matter is being introduced from outside at a rate larger than it is generated from internal ward sources. To investigate this further, the mean $PM_{2.5}$ value during the morning shift was examined in two single-patient rooms, both when the rooms' main doors are closed (limiting transport between the room and common ward area) and open. However, the mean $PM_{2.5}$ values for the two rooms did not show a systematic change. This indicates that particulate inflow from outside cannot be discounted as a source, and transport of $PM_{2.5}$ is therefore a potentially unreliable proxy for infectious aerosol transport throughout the ward section. These data are therefore not discussed further in this chapter.

6.6 Immediately Deployable Risk Mitigation Strategies

Two specific cumulative infection risk mitigation strategies were investigated for this Case Study that were possible to implement without any alterations to the HVAC system or this workplace's operational practices. For these studies, it was assumed that there was a single infected in-patient in each in-patient room, all occupants of the ward section were wearing surgical masks (assuming in-patient mask wearing is practical in this case), and exposure to the resulting aerosol concentration distribution lasted for the whole eight-hour work shift.

i. Introduction of locally placed air purifiers
ii. Activation of the air extraction system in every in-patient room's ensuite

Later in this chapter (section 6.7), other potential mitigation strategies are presented that would require significant alternations to the ward section's design and/or operational practices. These are presented for consideration during long-term planning of ward construction or refit as they require significant work to implement into existing wards.

i. Pandemic Ward Scenario – Introducing Locally Placed Air Purifiers

Two cases incorporating locally placed air purifiers were investigated via CFD simulation. The first mitigation simulation assumes the ward is functioning in pandemic mode as described in section 6.1, i.e. where the infection risk is to uninfected staff from infected in-patients in all rooms. In the first case, minimal air purification is provided at the nurses' station (the most frequent region occupied by staff as shown in Figure 6-2) via two lower-capacity (301 m^3/hr) air purifiers placed at either end of the station. The cumulative infection risk distribution predicted after eight hours' exposure is presented in Figure 6-11 and should be compared with that presented in

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Figure 6-3 (no purifiers). The second mitigation simulation models 11 higher-capacity (701 m³/hr) virtual air purifiers positioned throughout the ward section. The cumulative infection risk distribution after eight hours' exposure is presented in Figure 6-12,

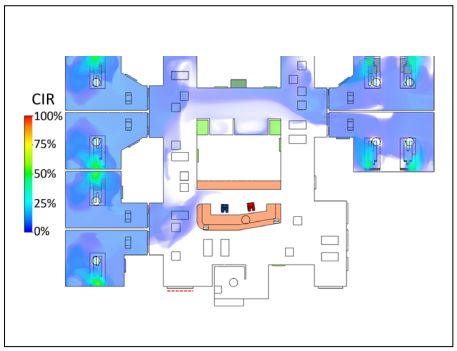


Figure 6-11 – Predicted effects of two lower capacity air purifiers on CIR distribution at an elevation of 1.6 m after eight hours' exposure to infectious in-patients in every bed. All occupants don surgical masks and the overall ACH is 8.6.



Figure 6-12 – Predicted effects of 11 higher capacity air purifiers on CIR distribution at an elevation of 1.6 m after eight hours' exposure to infectious in-patients in every bed. All occupants dons surgical masks and the overall ACH is 19.0.

and again should be compared with Figure 6-11 (two purifiers) and Figure 6-3 (no purifiers). Note that the overall ACH value for the hospital ward section increased only slightly with two purifiers (relative to the no-purifier value of 8.6) but was significantly higher with 11 purifiers (19.0).

Comparing Figure 6-11 (two purifiers) with Figure 6-3 (no purifiers) demonstrates that dual, lower capacity purifier installation at the nurses' station slightly reduces the local cumulative infection risk to staff. Comparing Figure 6-12 (11-purifier approach) with Figure 6-3 demonstrates a dramatic reduction in cumulative infection risk to near-zero throughout the ward section except in close proximity to infected in-patients. Note that this 11-purifier approach also increases the effective air exchange rates throughout the ward section, e.g. Room 2's effective ACH value increases from 10.7 to 19.9 (high), and the common ward area's effective ACH value increases from 10.8 to 17.2 (high). We do note, however, issues with introducing large air purifiers into in-patient rooms, which due to their size and/or noise may be moved and/or turned off. Assessing the relative benefit of small- or medium-sized air purifiers to in-patient rooms is thus an area for future research.

ii. Pandemic Ward Scenario – Activating Air Extraction System Within the In-Patient Room Ensuites

The second cumulative infection risk mitigation strategy investigated for the hospital ward section Case Study also assumes the ward is functioning in pandemic mode as described in section 6.1, and infection risk is thus to uninfected staff (and visitors). Both uninfected staff & infected in-patients are modelled as wearing surgical masks with 75% filtration efficiency. In this case, the mitigation strategy involves modelling the doors to all in-patient ensuites as fully open and each ensuite's air extraction system as continuously switched on, i.e. to remove aerosol by acting as additional (passive) HVAC outlets. Modelling the ensuites in this way means does not change the overall ACH across the ward section from its (pandemic-era) value of 8.6 as these extra outlets are modelled as operating under the condition of gauge pressure rather

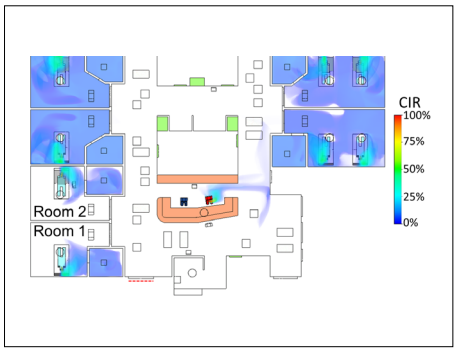


Figure 6-13 – Predicted CIR distribution at an elevation of 1.6 m after eight hours' exposure to infectious in-patients in every bed (Omicron variant). Note that both (i) the doors to in-patient rooms are kept closed, and (ii) the doors to in-patient ensuites are fully open with their air extraction systems continuously switched on. All occupants don surgical masks.

than a fixed air throughflow rate. Preliminary CFD simulations of this approach (not presented here for brevity) revealed that this strategy was most effective if the main doors to the in-patient rooms were simultaneously kept closed (though a 10 mm door gap under each door remains). The resulting cumulative infection risk to staff after eight hours' exposure is presented in Figure 6-13.

Figure 6-13 demonstrates that cumulative infection risk to staff is reduced to near-zero throughout the common ward area by activation of all the ensuite air extraction systems and closing of all the in-patient room doors. Furthermore, risk to staff in Rooms 1 & 2 is also near-zero across most of these rooms, i.e. except for the path between the infected in-patients and their ensuite door, where the risk is comparable to when not using this strategy (Figure 6-3). Risk to staff remains significant throughout all other in-patient rooms. These different results for Rooms 1 & 2 may be because the ensuite doors in Rooms 3 - 6 are both (i) located further away from the infected in-patients' mouths, and (ii) do not directly face the infected in-patients' mouths. These two differences would slow transmission & removal of pathogenic aerosols by

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the ensuite air extraction systems of Rooms 3 - 6. While the results for this mitigation strategy (open ensuite doors & closed in-patient room doors) are encouraging for staff occupying the common ward area for long periods, we do note the practical difficulties experienced in ensuring the room & ensuite doors are kept in the correct state of fully closed & fully open, respectively.

6.7 Future Risk Mitigation Strategies

The results presented in section 6.6 are specific to this workplace's in-situ layout, HVAC operational mode, and COVID-19-specific workplace policies active in early-to-mid 2022. During & after this project, however, relevant aspects of the COVID-19 pandemic have continued to involve, including the development of new variant families, vaccine take-up and their vaccine-dependent and variant-dependent efficacy and protective duration, public health guidelines, and the public's level of adherence to these guidelines. It was quickly realised that the results presented here would be change somewhat in response to changes in these factors. Thus, the final quarter of this project focused on widening the applicability of the Case Study results presented for the hospital ward section studied here by adapting its CFD model to reflect more major alterations than would be immediately possible. These alternations were hypothetical only, i.e. realised & investigated solely via CFD simulations and not with parallel sensor measurements. Results from these simulations are thus more relevant to those workplaces that are returning to pre-COVID-19 operational modes and/or are planning for long-term building maintenance, refits, etc.

i. General Information on these Extension Simulations

During the two-week period in March - April 2022 that the hospital ward section studied during this project was monitored (see section 6 for details), the emergency smoke extraction system installed in the ward's ceiling (comprising separate fans and ducts) was continuously switched on as a COVID-19-era safety enhancement measure. This non-standard operational mode increased the overall air exchange rate in the ward section to a measured value of 8.6, with these additional ceiling fans modelled as operating in the same way as the regular HVAC outlet vents, i.e. they operate 'passively' to maintains the pressure of nearby air at atmospheric pressure). To better approximate standard conditions in this ward section, CFD extension simulations were run with the smoke extraction system switched off resulting in a lower overall ACH value of 6.0, which reflects the pre-pandemic setting. Furthermore, it was noted in the original Case Study (section 6) that the general airflow pattern from the in-patient rooms into the ward corridors promoted an increase in cumulative infection risk in the common ward areas, i.e. to hospital staff and their visitors. To reduce this general airflow, one further CFD extension simulation was run with each in-patient room containing an additional HVAC outlet vent placed in the ceiling.

ii. Extension 1 – Non-Pandemic Ward Scenario – 'Standard' ACH Value

As explained above, this CFD extension simulation was run with an overall ACH value lowered from pandemic-era value of 8.6 (smoke extraction system activated) to its pre-pandemic setting of 6.0. Otherwise,

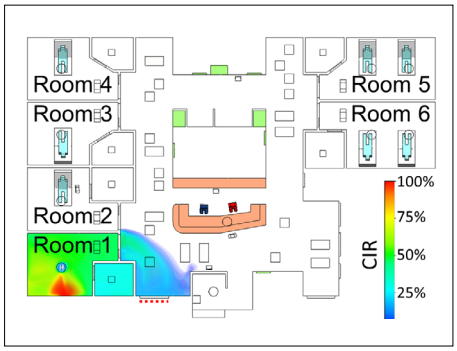


Figure 6-14 – Predicted CIR distribution at an elevation of 1.6 m after eight hours' exposure to an unmasked infectious in-patient in Room 1. The 'standard' (pre-pandemic) ACH value of 6.0 was assumed and all staff don procedure masks.

this CFD extension featured the same workplace layout as that presented in the original Case Study; see Figure 6-14. In-patients were modelled as not wearing masks and hospital staff were modelled as wearing either (i) 'procedure' masks (38.5% filtration efficiency), (ii) surgical masks (75% filtration efficiency), or (iii) N95 masks (95% filtration efficiency). Cumulative infection risk was calculated assuming an eight-hour working shift. The aerosol source was assumed to be a single infected in-patient (but not known to ward staff as being infected) placed as follows to create nine CFD extension simulations:

a. An infected in-patient in the single-patient Room 1, with hospital staff wearing either procedure, surgical, or N95 masks (Figures 6-14 to 6-16)
b. An infected in-patient in the single-patient Room 4, with hospital staff wearing either procedure or surgical masks (Figures 6-17 to 6-18)
c. An infected in-patient in either single-patient Rooms 2 or 3, or dual-patient Rooms 5 or 6, with hospital staff wearing surgical masks (Figures 6-19 to 6-22)

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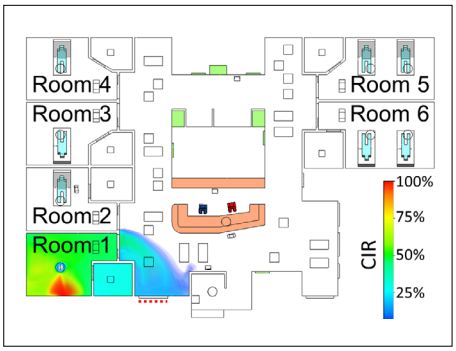


Figure 6-15 – Predicted CIR distribution at an elevation of 1.6 m after eight hours' exposure to an infectious unmasked in-patient in Room 1 with ACH = 6.0 and staff donning surgical masks



Figure 6-16 – Predicted CIR distribution at an elevation of 1.6 m after eight hours' exposure to an infectious unmasked in-patient in Room 1 with ACH = 6.0 and staff donning N95 masks

Figures 6-14 to 6-16 demonstrate that aerosol ejected by the infected in-patient in single-patient Room 1 is predicted to spread into the corridor towards the nearest HVAC outlet vent – note that there is no aerosol movement from in-patient room to in-patient room as all the ward section's HVAC outlets are located in the common ward area (Figure 6-1); thus, the general flow of air from the in-patient rooms is from their HVAC inlets towards the common area's HVAC outlets. The spread of aerosol from Room 1 to the common ward area increases its cumulative infection risk to staff by an extent that (as expected) decreases with increasing mask filtration efficiency. The use of procedural masks leads to cumulative infection risk well into the common ward area. This risk magnitude, though not its spatial extent, is predicted to be reduced when staff wear surgical masks and is further reduced if staff wear N95 masks. Staff use of either procedure masks or surgical masks, however, still leads to considerable cumulative infection risk within single-patient Room 1 itself.

Figures 6-17 and 6-15 demonstrate that aerosol ejected by the infected in-patient in single-patient Room 4 is predicted to spread cumulative infection risk to staff much further into the common ward area (encapsulating some of the nurse's station) than an infected in-patient in Room 1. Unlike Room 1, both the magnitude and spatial extent of this risk region for Room 4 are reduced when staff wear surgical rather than procedure masks (though it is still significant for both). As for Room 1, significant risk for Room 4 when staff wear N95 masks is localised to the immediate vicinity of the infected in-patient; this result is not shown for brevity. The above contrast between the cases of an infected in-patient in Rooms 1 & 4 at this lower ACH value of 6.0 is due to the presence of an external door to the ward section at the end of the corridor adjacent to Room 1. This promotes aerosol transmission into the external corridor, thus reducing transmission into the common ward area relative to that predicted for Room 4.

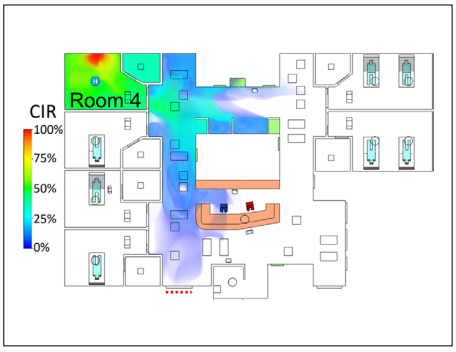


Figure 6-17 – Predicted CIR distribution at an elevation of 1.6 m after eight hours' exposure to an infectious unmasked in-patient in Room 4 with ACH = 6.0 and staff donning surgical masks

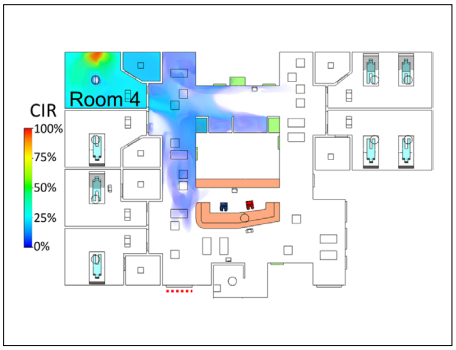


Figure 6-18 – Predicted CIR distribution at an elevation of 1.6 m after eight hours' exposure to an infectious unmasked in-patient in Room 4 with ACH = 6.0 and staff donning N95 masks

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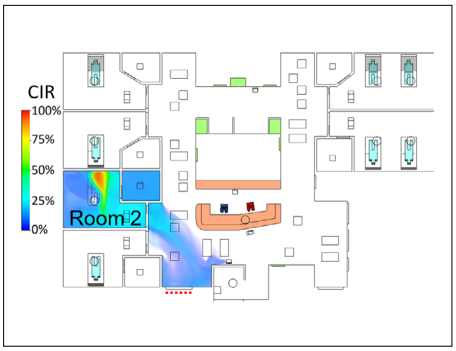


Figure 6-19 – Predicted CIR distribution at an elevation of 1.6 m after eight hours' exposure to an infectious unmasked in-patient in Room 2 at ACH = 6.0 with staff donning surgical masks

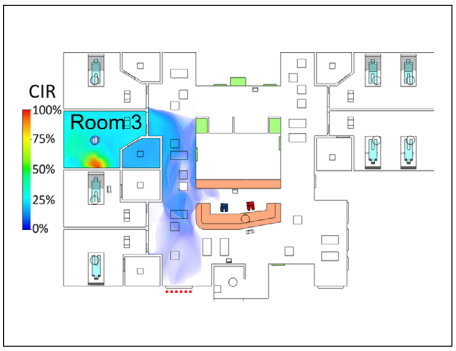


Figure 6-20 – Predicted CIR distribution at an elevation of 1.6 m after eight hours' exposure to an infectious unmasked in-patient in Room 3 with ACH = 6.0 and staff donning surgical masks

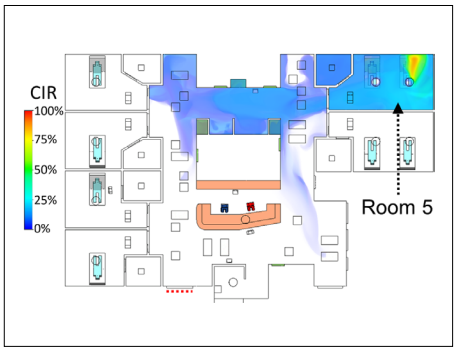


Figure 6-21 – Predicted CIR distribution at an elevation of 1.6 m after eight hours' exposure to an infectious unmasked in-patient in Room 5 with ACH = 6.0 and staff donning surgical masks

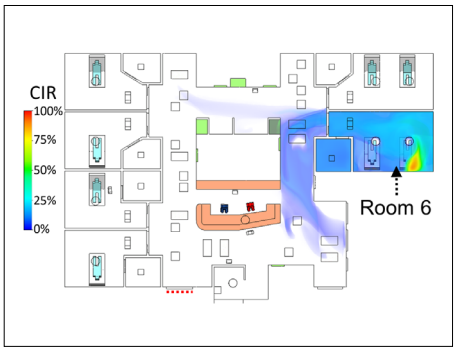


Figure 6-22 – Predicted CIR distribution at an elevation of 1.6 m after eight hours' exposure to an infectious unmasked in-patient in Room 6 with ACH = 6.0 and staff donning surgical masks

Figures 6-19 to 6-22 below demonstrate that the cumulative infection risk from an infected in-patient in Rooms 2, 3, 5, and 6 to staff wearing surgical masks resembles those for Room 1 (Figure 6-15) and Room 4 (Figure 6-17).

For all additional four in-patient rooms, Figures 6-19 to 6-22 demonstrate the infection risk to staff caused by a single infected in-patient in each room extends into the common ward area. However, Room 2's risk distribution (Figure 6-19) resembles Room 1's (Figure 6-15) in its much less extensive spread into the common ward area than for Rooms 3 - 6 (Figures 6-17 and 6-20 to 6-22). This is because for both Rooms 1 & 2, the door at the end of this section of the ward allows aerosols to flow into the next section of the ward, reducing the spread of risk into the common ward area.

iii. Extension 2 – Pandemic Ward Scenario – HVAC Outlet Vent in each In-Patient Room

In response to the above observations that considerable aerosol is predicted to escape from in-patient rooms hosting infected in-patients to the common ward area, a CFD extension simulation was constructed in which where an HVAC outlet vent was added to each in-patient room; see red arrows in Figure 6-23. The resulting cumulative infection risk distribution in Figure 6-24 assumes (i) the pandemic-era HVAC configuration (ACH = 8.6) as these outlet vents were modelled as operating in the same way as the pre-existing HVAC outlet vents in the simulation, (ii) in-patients do not wear masks, and (iii) hospital staff wear surgical masks. Although risk remains significant throughout all the in-patient rooms, and thus the risk to uninfected in-patients in shared rooms would be large, (i) the magnitude of risk relative to without HVAC outlets in in-patient rooms (Figure 6-17), is much smaller, and (ii) there is now minimal risk to the common ward area.

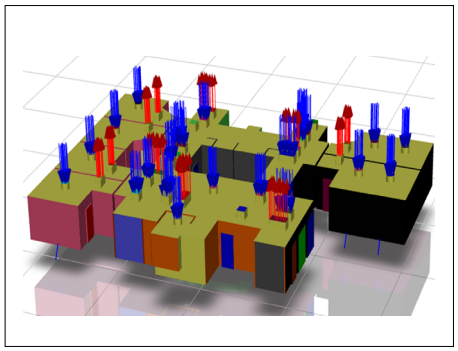


Figure 6-23 – Modified HVAC system proposed here, i.e. the original HVAC system supplemented with an outlet vent in each of the six in-patient rooms

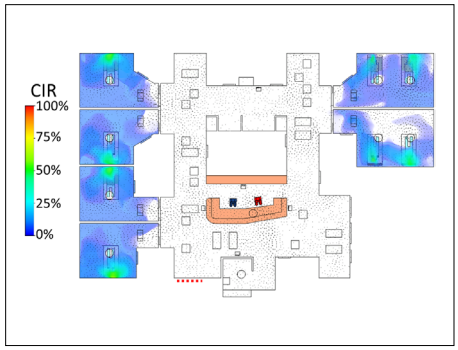


Figure 6-24 – Predicted CIR distribution at an elevation of 1.6 m after eight hours' exposure to an infectious unmasked in-patient in every bed, an extra HVAC outlet vent in each of Rooms 1 - 6 near-above the in-patients' heads, staff donning surgical masks, and a pandemic-era ACH value of 8.6

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6.8 Summary

The highest cumulative infection risk to uninfected ward occupants occurs (as expected) in in-patient rooms in which the in-patient is infected. This risk can be significantly mitigated if the patient is wearing a mask (though we note this is not always practical), and particularly an N95 mask, which reduces risk in both the in-patient rooms & common ward area. Infected visitors temporarily increase the cumulative infection risk to an extent increasing with the duration of their visit, e.g. less so for a short visit to the nurse's station but more so for a prolonged visit to an in-patient room. CFD modelling indicates that in cases where infected ward occupants are either unmasked or wearing a surgical rather than N95 mask, the cumulative infection risk extends outside in-patient rooms into the common ward area, i.e. including the nurses' station. The design of this particular ward section's HVAC system, i.e. with air inlets in in-patient rooms and outlets in the corridors, is partially responsible for this result. Attempts were made to study particulate transport throughout the ward section via monitoring of particulate concentrations. However, potential was found for fine particulates to enter from outside by surviving the HVAC inlets' filtration process. Onsite testing would clarify this issue and allow for a more in-depth experimental investigation of particulate transport.

The human movement analysis of the nurses' activities indicates that the most frequent location of the nurses is (as expected) in the vicinity of the nurses' station. Thus, it is critical for infection risk mitigation to include consideration of aerosol concentration around the nurses' station as well as in in-patient rooms.

With regards to more HVAC interventions, as the ACH value used in this ward section was already high, increases to the ACH were not studied in this Case Study for the purposes of immediately deployable risk mitigation strategies. Instead, two scenarios involving locally placed air purifiers were studied via CFD simulation. The more-limited scenario (two lower-capacity purifiers at the nurse's station) slightly reduced the local cumulative infection risk. The maximal-purification scenario (11 higher-capacity purifiers placed throughout the ward) instead decreased risk to near-zero throughout nearly all the ward section. However, this latter approach is obviously intrusive, and its implementation aspects therefore require further work to improve this approach's tolerability by staff & in-patients. Finally, a second mitigation strategy was simulated involving using continuous use of the air extraction systems in all the in-patient room ensuites alongside leaving the ensuite doors open. If the ensuite door was both close to and orientated towards the head end of each in-patient's bed, cumulative infection risk was decreased significantly throughout the ward. However, this approach is also intrusive, and its implementation aspects thus also require development to improve this approach's tolerability.

MAJOR FINDING: Ventilation systems should be designed so to prevent airflows from high-risk to low-risk areas, particularly if the low-risk areas have a high occupancy rate

MAJOR FINDING: Placement of additional HVAC outlet vents in areas of high cumulative infection risk can minimise the probability of aerosol spread from high-risk areas to low-risk areas

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7. Case Study 4: Scientific Research Laboratory

7.1 General Information and HVAC System Details

This scientific research laboratory studied during this project (henceforth referred to as the 'lab') was monitored for two weeks between December 2021 and January 2022. It contains Room 13 (right-hand side room in Figure 7-1) with a floor area of 51.35 m^2, and Room 14 (left-hand side room in Figure 7-1) with a floor area of 74 m^2, which are separated by an internal door normally kept open for the convenience of occupants carrying chemicals & samples between rooms. Both doors leading into this lab (two blue dashed lines in Figure 7-1) are normally closed. The lab rooms contain a series of benchtops for seated researchers with shelving above them. Separate to the benchtops are five floor-standing fume cupboards equipped with local air exhaust systems that are used for working with volatile chemicals. These are used only intermittently, are switched off when not in use, and have flue exits (red circles) in Figures 7-1 & 7-2.

The HVAC system in this lab employed a 'mixing ventilation' scheme. The air change rate (ACH) value for the lab (with the fume cupboards switched off) was measured as 20.0, which is relatively large due to the aforementioned presence of volatile chemicals. During the pandemic period, the HVAC system's inlet air was 100% fresh air. On-site tests demonstrate that slightly more air was supplied than was exiting through the HVAC outlet vents, meaning that the lab has a positive pressure relative to the surrounding corridors and labs. This would cause some inlet air to be continuously ejected via the gaps around its external doors; however the proportion of this air was found to be small relative to the background airflows imposed by the HVAC system within this lab, and thus this effect was neglected such that all air entering via the HVAC inlets was modelled as exiting through the HVAC outlets. All HVAC vents were ceiling-based (Figure 7-2) and are numbered as shown in Figure 7-3. These include four inlet vents in each room, two outlets in Room 13, and one outlet in Room 14. The HVAC inlet vent flowrates were measured to be 0.670, 0.650, 0.370, 0.670, 0.165, 0.175, 0.270, and 0.350 m^3/s for Vents IN1 - IN8, respectively. For simplicity, the outlet vents were modelled here as operating 'passively', i.e. simply maintaining atmospheric pressure, rather than active outlet vents via a fan-driven exhaust system. The airspeed distribution at an elevation of 1.6 m (average mouth height of a standing human) predicted via CFD simulation under this assumption is presented in Figure 7-3(a). Presented alongside is

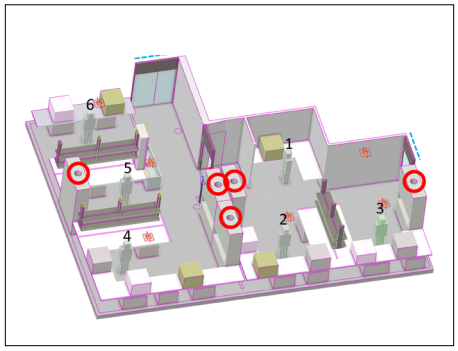


Figure 7-1 – 3D CAD schematic of the lab. Numbers indicate frequent occupant positions determined by monitoring of human movement. Red circles are explained in the text. Blue dashed lines denote external doors.

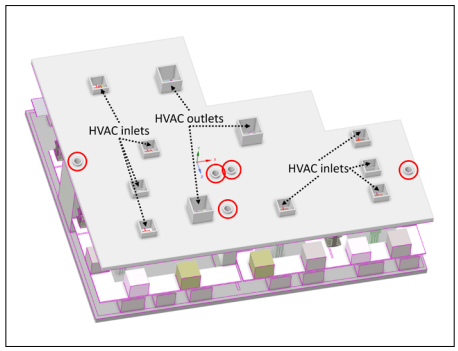


Figure 7-2 – 3D CAD schematic of the lab's ceiling showing positions of the HVAC system's inlet & outlet ducts and fume cupboard flues (red circles in Figure 7-1)

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the path taken by air from each HVAC inlet vent to its nearest outlet vent. These flowlines are separately for two different groups of inlet vents for clarity. One group of inlets provides air that flows relatively non-circuitously to its nearest outlet vent (Figure 7-3(b)) while the second group provides air that flows more circuitously towards 1 - 2 nearby outlet vents (Figure 7-3(c)).

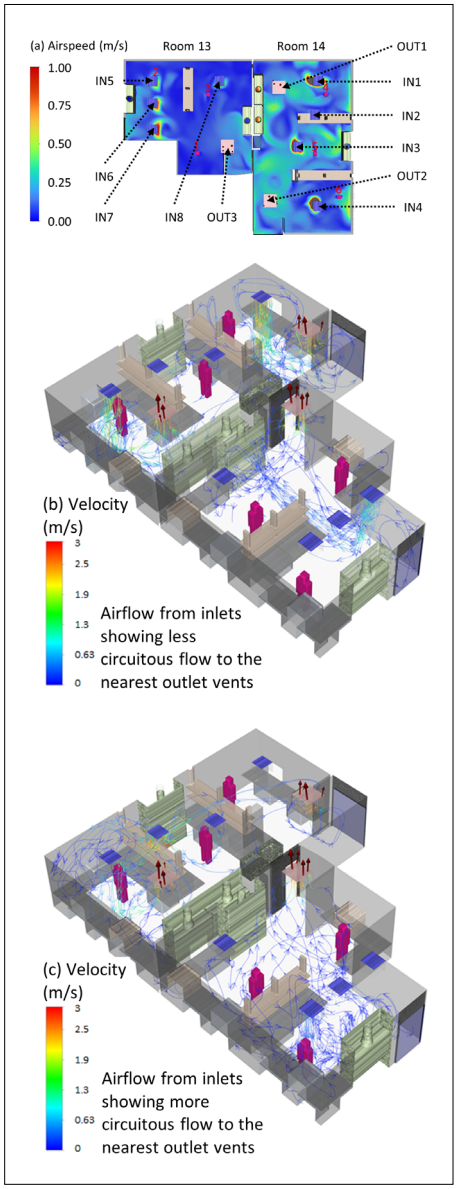


Figure 7-3 – (a) Predicted airspeed distribution at an elevation of 1.6 m where 'IN' & 'OUT' indicate HVAC system ceiling vents, (b) predicted airflow from HVAC inlet vents to outlet vents for inlet vents whose air follows a relatively non-circuitous path to their nearest outlet vent, and (c) airflow from inlet vents whose air follows a more circuitous path to the nearest outlet vent. In this simulation, the fume cupboards are switched off and the red numbers & pink figurines match the occupant positions in Figure 7-1.

Figure 7-3 demonstrates that airflow is from each HVAC inlet vent predominantly towards its nearest outlet vent, i.e. Room 13's airflow is from IN5 - IN8 to outlet vent OUT3, while Room 14's airflow is from IN1, IN2, and IN4 to whichever of OUT1 & OUT2 is closer. This airflow pattern is expected for rooms with a relatively dense arrangement of HVAC inlets & outlets. However, this does not mean that airflow occurs directly from inlet to outlet. Vents IN1 & IN4 at the 'top' & 'bottom' ends of Room 14 (as depicted in Figure 7-3) demonstrate fairly direct flow to their nearest outlet (Figure 7-3(b)). However, air from the centrally located inlets IN2 (which is directed at a shelf) & IN3 (located centrally between two outlets) flow to both OUT1 & OUT2, thus predicting a more 'spread out' airflow pattern in the central part of Room 14 (Figure 7-3(c)). In Room 13, vents IN7 - IN8 exhibit airflow fairly directly into OUT3, while IN5 - IN6's airflows are highly circuitous, with IN5's spreading over approximately half the lab's floor area before entering OUT3.

7.2 Aerosol Movement and COVID-19 Cumulative Infection Risk

With respect to the prediction of cumulative infection risk, the initial two scenarios investigated here via CFD simulation include a single occupant infected with the Omicron variant in the presence of five susceptible occupants. All occupants are either standing or seated (their modelled mouth height matches the average

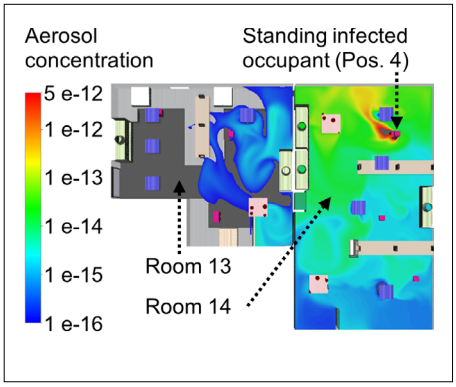


Figure 7-4 – Predicted aerosol concentration distribution at an elevation of 1.6 m from an infectious occupant in Room 14. Occupants are unmasked and the overall ACH is 20.0.

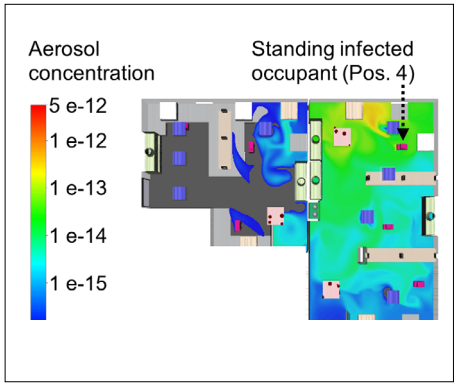


Figure 7-5 – Predicted aerosol concentration distribution at an elevation of 1.2 m from an infectious occupant in Room 14. Occupants are unmasked and the overall ACH is 20.0.

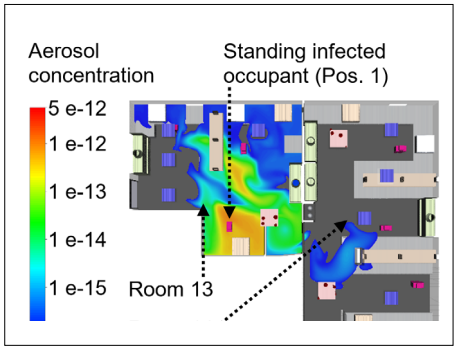


Figure 7-6 – Predicted aerosol concentration distribution at an elevation of 1.6 m from an infectious occupant in Room 13. Occupants are unmasked and the overall ACH is 20.0.

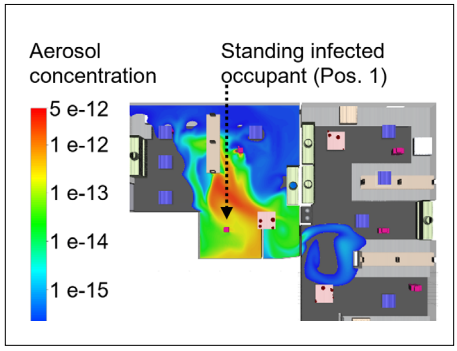


Figure 7-7 – Predicted aerosol concentration distribution at an elevation of 1.2 m from an infectious occupant in Room 13. Occupants are unmasked and the overall ACH is 20.0.

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human values of 1.6 m & 1.2 m, respectively), are stationary, remain unmasked, and all fume cupboards are switched off. Figures 7-4 to 7-7 present the resulting aerosol volumetric concentration (dimensionless), which use a relatively wide scale (10^{-16} - 10^{-12}). However, values below 10^{-14} are predicted to be unlikely to result in significant cumulative infection risk over an eight-hour working shift and were therefore set as transparent in all figures presented in this section for clarity.

Figures 7-4 to 7-7 demonstrate that aerosol concentration distribution depends strongly on the infected occupant's location within the lab, but only slightly with height at a given location. The open door led to aerosol from an infected occupant in Room 13 flowing into Room 14 but not vice versa. A more major result, however, comes from the position of the infected occupant relative to their nearest HVAC vents. Figures 7-4 & 7-5 demonstrate that the stationary infected occupant in Room 14 is predicted to be surrounded by a 'cloud' of significant aerosol concentration, principally because there are two nearby outlet vents, and so some aerosol ejected in the 'upper' half of Room 14 as depicted spreads towards the 'lower' half of Room 14. However, Figures 7-6 & 7-7 demonstrate for a stationary infected occupant in Room 13, the single nearby outlet vent is predicted to strongly draw in ejected aerosol, thus restricting high aerosol concentrations to the immediate vicinity of the infected occupant.

Given that the location of the stationary infected occupant is clearly critical, further CFD simulations were conducted with the stationary infected occupant placed in four further locations as depicted in Figure 7-1. The resulting cumulative infection risk distributions after eight hours' exposure (corresponding to a likely working shift) are presented in Figures 7-8 to 7-13 at a human standing mouth height of 1.6 m.

Figures 7-8 to 7-10 demonstrate that if the stationary infected occupant is in Room 13, there is near-zero cumulative infection risk in Room 14. Figure 7-8 with the infected occupant in Position 1 is close to Room 13's outlet vent and thus aerosol is rapidly drawn in preventing its spread, i.e. risk is minimised to between the occupant and outlet vent. Figure 7-9

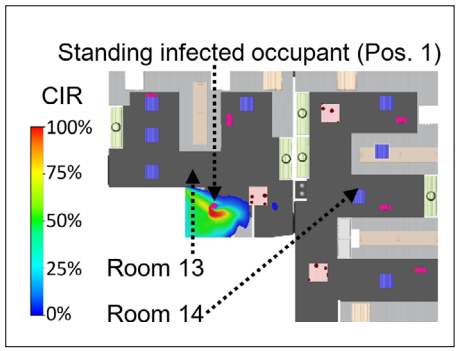


Figure 7-8 – Predicted CIR distribution at an elevation of 1.6 m after eight hours' exposure to an infectious unmasked occupant in Position 1. Occupants are unmasked and the overall ACH is 20.0.

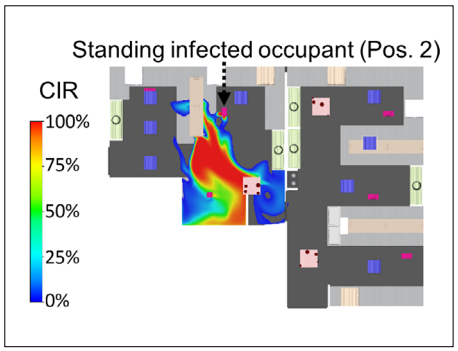


Figure 7-9 – Predicted CIR distribution at an elevation of 1.6 m after eight hours' exposure to an infectious unmasked occupant in Position 2. Occupants are unmasked and the overall ACH is 20.0.

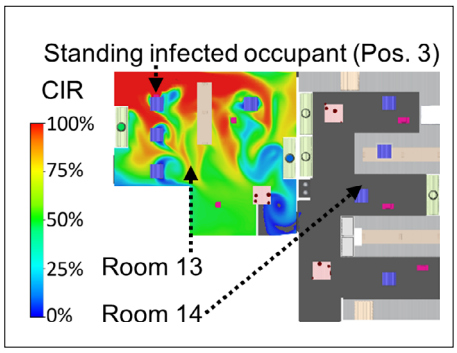


Figure 7-10 – Predicted CIR distribution at an elevation of 1.6 m after eight hours' exposure to an infectious unmasked occupant in Position 3. Occupants are unmasked and the overall ACH is 20.0.

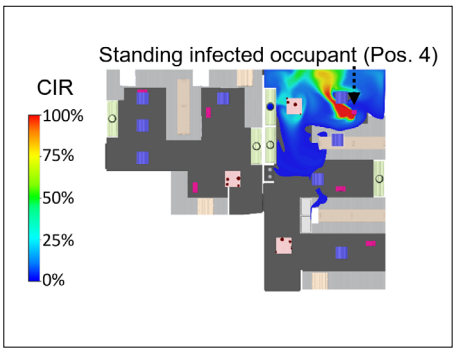


Figure 7-11 – Predicted CIR distribution at an elevation of 1.6 m after eight hours' exposure to an infectious unmasked occupant in Position 4. Occupants are unmasked and the overall ACH is 20.0.

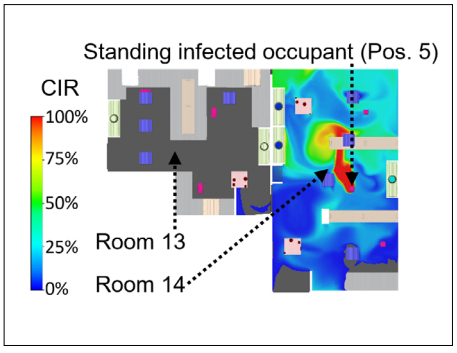


Figure 7-12 – Predicted CIR distribution at an elevation of 1.6 m after eight hours' exposure to an infectious unmasked occupant in Position 5. Occupants are unmasked and the overall ACH is 20.0.

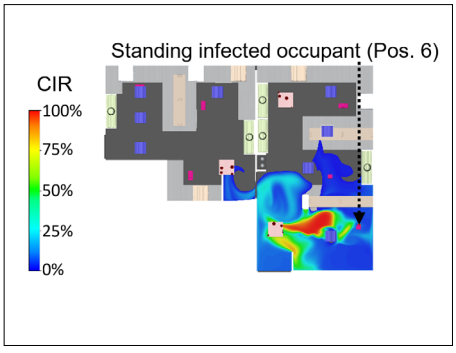


Figure 7-13 – Predicted CIR distribution at an elevation of 1.6 m after eight hours' exposure to an infectious unmasked occupant in Position 6. Occupants are unmasked and the overall ACH is 20.0.

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with the infected occupant in Position 2 is slightly further from the outlet vent, leading to aerosol spread and enlargement of the corresponding risk zone. Note also that the risk immediately around the infector is low because they are immediately below an HVAC inlet vent, resulting in ejected aerosol being immediately directed towards the floor. Figure 7-10 with the infected occupant in Position 3 is near the opposite corner of Room 13 to the outlet vent, so aerosol and cumulative infection risk are spread across Room 14. Figures 7-11 to 7-13 demonstrate a similar overall prediction, i.e. the position of infected occupant relative to their nearest outlet vent controls the spread of aerosol and cumulative infection risk, and this spread is almost all contained within Room 14. Figures 7-11 & 7-13 with the infected occupants in Positions 4 & 6, respectively, are both close to their nearest outlet vent, and the corresponding high-risk areas are predicted to be predominantly between the infected occupant and their closest vent. Note that for Figure 7-13, risk is reduced immediately around the infected occupant for the same reason as for Figure 7-9, i.e. a significant proportion of their ejected aerosol is directed towards the floor. Unlike Figures 7-11 & 7-13, Figure 7-12 features an infected occupant in Position 5, essentially halfway between their two nearest outlet vents. This leads to the resulting CIR distribution being much more widespread across Room 14.

7.3 Particulates Measurements and their Interpretation

In this Case Study, a different methodology was used for measurement of particulates relative to the other four Case Studies. The same

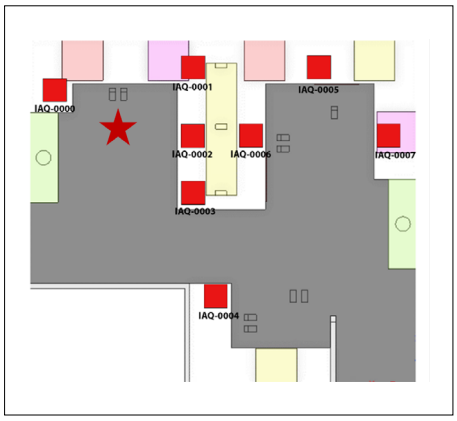


Figure 7-14 – Benchtop positions of particulate matter sensors within the lab's Room 14. The red star denotes the aerosol source (nebuliser) placed on a chair at similar height to the benchtops.

eight sensors were used but were distributed only in Room 13 and not Room 14 following the arrangement shown in Figure 7-14. The internal door between the lab rooms was kept closed during the experiments described in this section. An artificial particulate source was introduced into Room 13, which was a nebuliser with a mean evaporation rate of 14.7 ml/hr of liquid (emitted as aerosol particles) within an 8 l/min total emitted flowrate of aerosol-laden air. The aerosol generated had a size mostly ranging between 0.01 - 3.2 microns. Figure 7-15 presents the $PM_{2.5}$ density plots measured in Room 13, which were prepared by applying an inverse-distance-weighted *k*-nearest-neighbour interpolation scheme to the measurements at the eight sensors' locations (Kelleher et al., 2015). These readings were made dimensionless by division by the largest value recorded during the experiment, which lasted for 30 minutes. This experiment was conducted twice, once with the nearest fume hood switched on and again with the nearest hood switched off.

Figure 7-15(a) demonstrates that the measured pattern of aerosol dispersion while the nearest fume cupboard is switched off resembles the CFD-predicted cumulative infection risk distributions for an infected occupant at Position 2 (Figure 7-9), which is near-coincident to the position of the aerosol source shown in Figure 7-14. The highest measured $PM_{2.5}$ concentration measured occurs (as expected) closest to the humidifier aerosol source, with concentration decreasing monotonically towards the nearest HVAC outlet vent. The experiment was repeated with the nearest fume cupboard switched on, which as shown in Figure 7-15(b) dramatically reduces aerosol spread. Given this result, and as for the three prior Case Studies of an open-plan office (section 4), factory paint room (section 5), and hospital ward section (section 6), the correlations, time lags, and relative magnitudes of the measured $PM_{2.5}$ concentrations are presented in Figure 7-16.

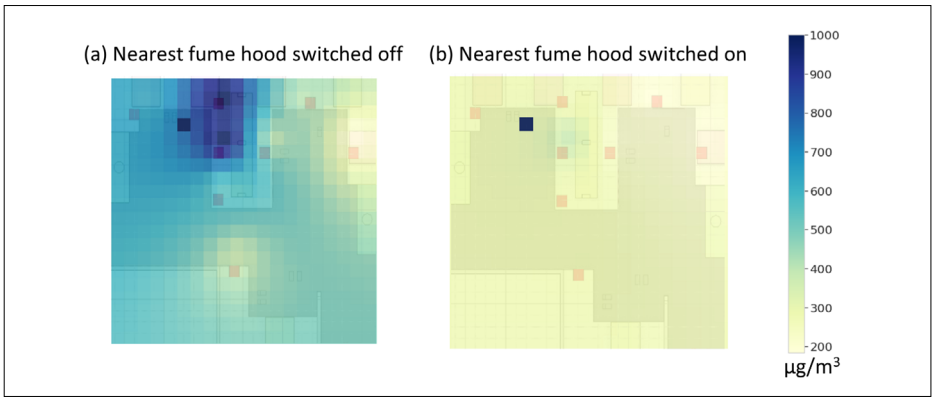


Figure 7-15 – $PM_{2.5}$ concentration distributions across Room 13 interpolated between eight benchtop particulates sensors in the two cases of the nearest fume cupboard being (a) switched off, and (b) switched on

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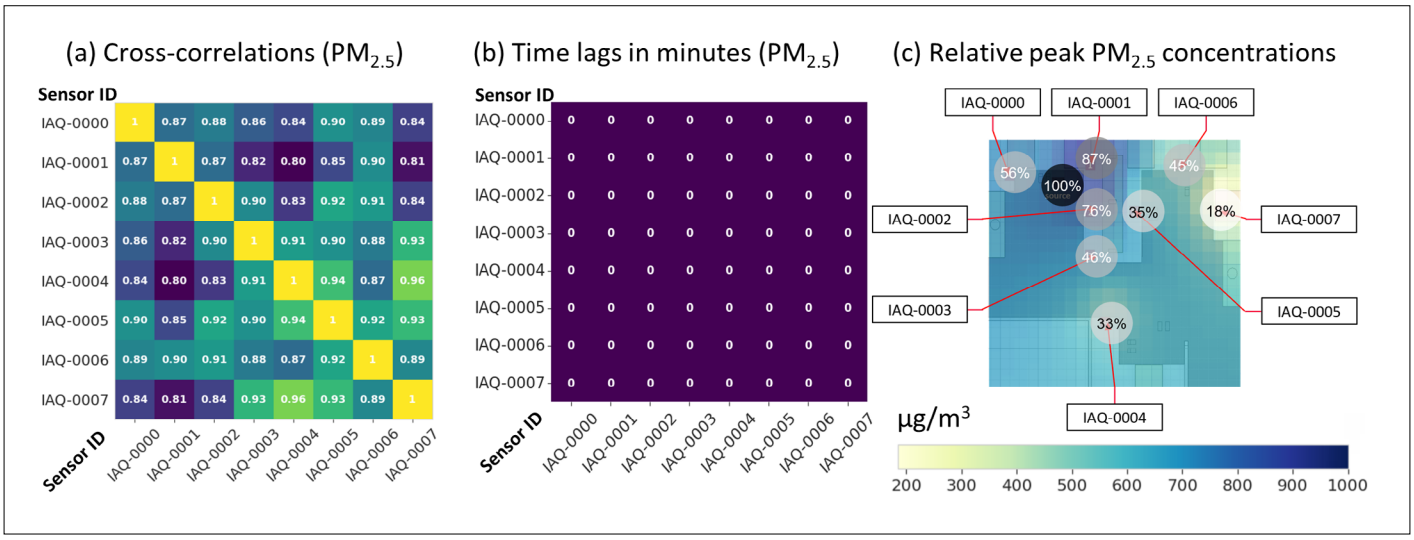


Figure 7-16 – (a) Cross-correlations, (b) time lags available to the nearest minute, and (c) relative magnitudes of the $PM_{2.5}$ concentration peaks measured in the lab's Room 14. The circled values in (c) are concentrations divided by the largest peak value recorded and are thus dimensionless.

Figure 7-16 demonstrates that the measured $PM_{2.5}$ concentrations were highly correlated and have very little time lag between them for this research lab. Their relative magnitudes follow the same pattern as in Figure 7-15, as is expected given that they are derived from the same data. Thus, the standard $PM_{2.5}$ concentration extrapolation analysis presented here has demonstrated validity under controlled conditions.

7.4 Immediately Deployable Risk Mitigation Strategies

Three risk mitigation strategies were investigated via CFD simulations for the scientific research lab studied during this project. Note that all other simulation aspects were left unchanged, i.e. a single infected occupant was present in the lab & masks were assumed not to be worn.

1. Placement of partitions along the lab benches
2. Closing the internal door between Rooms 13 & 14
3. Leaving the nearest fume hood to the lab's infected occupant continuously switched on

Strategy 1 involved placing virtual partitions along the long axis of the lab benches, thus filling up gaps in the shelving to remove the direct airflow pathway between pairs of occupants facing each other across the benchtops. Below the benchtops, the desks were already modelled in all simulations as solid down to the floor. This desk semi-partitioning strategy was not found to be effective for this lab and the resulting cumulative infection risk distributions are therefore not presented here for brevity. Figure 7-17 presents the cumulative infection risk distribution in the room hosting the infected occupant (Room 14) predicted after eight hours' exposure to their ejected aerosol with the internal door to Room 13 kept closed in an airtight manner. In this simulation, the infected occupant was located at Position 4 and thus this distribution should be compared with Figure 7-11 (infected occupant in Position 4, door open). Note that closing the internal door changes the effective ACH in each room as the HVAC ceiling vents solely

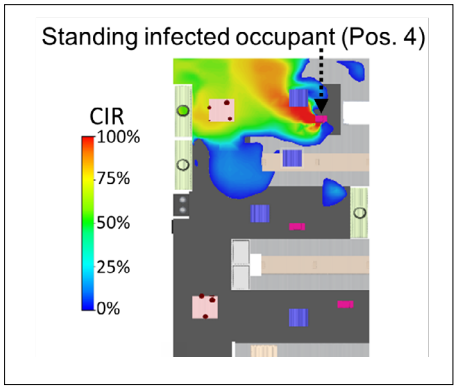


Figure 7-17 – Predicted CIR distribution at an elevation of 1.6 m after eight hours' exposure to an infectious occupant in the lab's Room 14 at Position 4. Occupants are unmasked. The internal door between rooms is closed & airtight, thus Room 13 is omitted. The equivalent distribution with the internal door open is in Figure 7-11. Note that closing the internal door drives an increase in Room 14's ACH from 20.0 (Figure 7-11) to 24.9.

circulate air through their associated room. The effective ACH value in Room 13 thus increases from 20.0 (door open) to 24.9 (door closed).

Figure 7-17 demonstrates that keeping the internal door between Rooms 13 & 14 (which was assumed to be open for all simulations presented in section 7.2) closed is predicted to minimise the cumulative infection risk in the room not hosting the infected occupant (Room 13). Furthermore, this change did not significantly increase the cumulative infection risk throughout Room 14.

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The third risk mitigation strategy attempted virtually for this lab was to model the nearest lab fume cupboard to the infected occupant as being continuously switched on, which thus introduced an extra air outlet at benchtop level. Note that the lab's overall ACH is unchanged from 20.0 in this case as the fume cupboard provided only an air outlet, not an inlet, and the flue was assumed to operate similarly to the HVAC system's outlet vents (section 7.1), i.e. passively to maintain atmospheric pressure in the fume cupboard. The cumulative infection risk distribution resulting from the nearby fume cupboard being switched on is presented in Figure 7-18 and should be compared with the equivalent 'hoods-off' case in Figure 7-11.

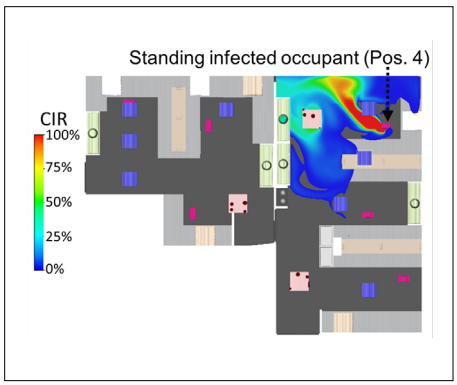


Figure 7-18 – Predicted CIR distribution at an elevation of 1.6 m after eight hours' exposure to an infectious occupant in Position 4. Occupants are unmasked and the overall ACH is 20.0. The infector's nearest fume hood is continuously switched on with the equivalent 'hood-off' distribution in Figure 7-11.

Figure 7-18 vs. Figure 7-11 demonstrates that switching on the nearest fume hood to the infected occupant in Position 4 is not predicted to decrease the cumulative infection risk distribution in Room 14 significantly. This was due to the 'upper' HVAC ceiling vent in Room 14 as depicted in Figure 7-18, which was closer to and thus superior at extracting aerosol from the infected occupant at Position 4 relative to the benchtop fume hood located further away from the infected occupant.

7.5 Future Risk Mitigation Strategies

i. General Information on this Extension Simulation

The lab layout used in the below two extension simulations was unchanged from other simulations for this Case Study (Figure 7-1) and consists of two rooms separated by an internal door that was modelled as always open. The HVAC ceiling vents & five fume cupboard flues exiting the lab through the ceiling were initially unchanged from this Case Study (Figure 7-2) and feature an original ACH value of 20.0 (as measured for this lab). Finally, all lab occupants were modelled as unmasked & stationary within the lab for the duration of an eight-hour working shift and were in the presence of a single infected unmasked occupant; both these conditions match the original lab Case Study.

ii. Extension Simulation – Extra HVAC Outlet Vent

As seen in the lab's HVAC layout (Figure 7-2). the smaller of the lab's two rooms (Room 13) included four HVAC inlet vents but only one outlet vent; this compares to four inlets & two outlets for the larger Room 14. An extra outlet vent in Room 13 is a potential risk mitigation strategy as it would reduce the mean distance that aerosol must travel from an infected occupant in worker Positions 2 & 3 (Figure 7-1) to their nearest HVAC outlet, thus reducing the cumulative infection risk in Room 13 to other susceptible occupants in the room. Note that this approach follows the major research finding from the hospital ward section extension simulations in section 6.7.3. The lab's single infected occupant was placed standing in Position 3 in Room 13, which was chosen as this region of the lab was the most prone to aerosol accumulation. Two different positions were simulated for the extra HVAC ceiling outlet vent in this room (Figure 7-19), though neither position drives any change in the ACH as the extra outlet was modelled as a constant-pressure outlet vent; thus the ACH value in both cases was determined solely by the (flowrate-controlled) HVAC inlet vents in each room.

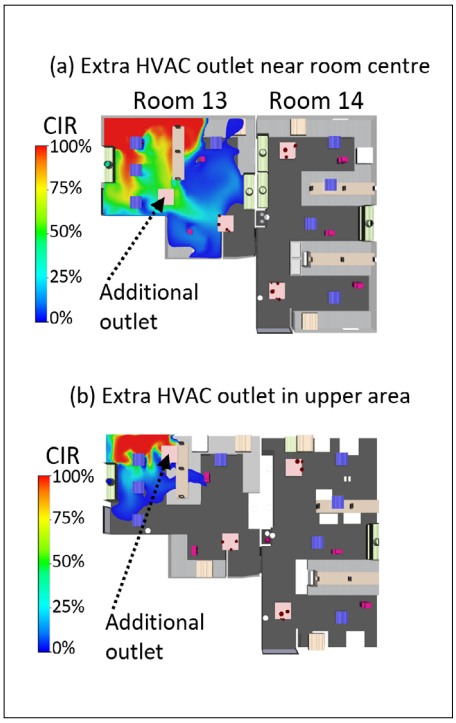


Figure 7-19 – Predicted airflow distribution & CIR distributions at an elevation of 1.6 m after eight hours' exposure to an infectious unmasked occupant in Position 3 (Room 13). Occupants are unmasked and the overall ACH is 20.0. There is an additional HVAC ceiling outlet in Room 13 in either of two positions, with the equivalent distribution (no extra vent) in Figure 7-10.

Figure 7-19 demonstrates that for the infected occupant in Position 3 and the extra HVAC outlet vent near the centre of Room 13, the CIR across the right-hand side of Room 13 is much reduced (vs. Figure 7-10). However, CIR is relatively unchanged in the left-

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hand side of Room 13. Therefore, a second CFD extension simulation was run with the extra outlet vent moved closer to Position 3. The resulting CIR was predicted to be significantly reduced everywhere in Room 13 except in the immediate vicinity of the (unmasked) infected occupant. These results therefore support the major finding for the hospital ward section extension simulations described in section 6.7.3.

7.6 Summary

In this Case Study of a real, two-room scientific research laboratory, the region of significant cumulative infection risk due to a single stationary infected occupant present for an eight-hour working shift was predicted using CFD simulations. These regions were generally constrained to the vicinity of the infected occupant, which was due to the dense spacing of HVAC ceiling inlet & outlet vents. These promoted local airflow between each inlet vent and its nearest outlet vent at the expense of cross-room airflows. This effect was predicted to be less strong in one of the two rooms (Room 13) due to its single outlet vent, leading to wider regions of significant cumulative infection risk than the neighbouring room with two outlet vents (Room 14). A longer-term, higher cost mitigation strategy would thus be to introduce a second HVAC outlet into Room 13 to reduce risk across a greater proportion of its floor area, for which simulation results are presented in the Future Risk Mitigation Strategies (section 7.5.2).

With regards to risk mitigation strategies for this scientific research lab, closing the internal door between the rooms (normally left open to allow occupants to carry chemicals between labs) essentially removes the risk to occupants in the room not containing the infected occupant, but not to susceptible occupants in the other room. Leaving the nearest fume hood to the infected occupant in this lab continuously switched on is predicted to have a limited effect in Room 14 when the infected occupant is already located near an HVAC outlet vent but does lower the risk in Room 13 particularly if the infected occupant is at Position 3, i.e. near the opposite corner to this room's sole HVAC outlet vent. It should be noted, however, that while continuously activating fume hoods does not require any major change to building or lab equipment, this is an energy-intensive way to reduce cumulative infection risk. This is because the exit air from fume hoods is not recyclable (as already-thermally-conditioned air) for use by the room's HVAC system due the possibility of it containing volatile chemical fumes.

MAJOR FINDING: Ventilation systems should be designed so to prevent airflows from high-risk to low-risk areas, particularly if the low-risk areas have a high occupancy rate

MAJOR FINDING: Placement of additional HVAC outlet vents in areas of high cumulative infection risk can minimise the probability of aerosol spread from high-risk areas to low-risk areas

8. Case Study 5: Lecture Theatre

8.1 General Information and HVAC System Details

This project included the monitoring, analysis, and simulation of a real-world lecture theatre; see Figure 8-1. This room was monitored for two weeks during August 2022 and contained 132 seats arranged in gently curving rows in front of the presenter's desk and projection wall. The room has a floor area of 131 m^2, which is flat near the presenter's desk and projection walls and slopes gently upwards towards the rear of the room. The ceiling is horizontal overall, resulting in a floor-to-ceiling height decreasing from 3.2 m at the front of the room to 2.1 m at the rear of the room. The HVAC system operated in a 'mixing ventilation' mode with eight air inlets in the walls and two in the ceiling, which were all placed to the left and right of the audience. The air outlet vents were located to just one of these sides, resulting in a prevailing crossflow of air from one side to the other. The air supply rate and exhaust rate by the HVAC system were 1.88 m^3/s and 0.85 m^3/s, respectively, leading to (i) an overall ACH value of 19.8, and (ii) significant leakage of air from the room into the surrounding corridors via the gaps under each of the two doors (Figure 8-1). Inlet air from the HVAC system was 50% external air and 50% recirculated air. The room was operated as a CO_2-controlled space. The above information was used to develop a CFD simulation of the lecture theatre to predict the airflow patterns within it. These are presented in Figures 8-2 and 8-3 in near-isometric view & plan view, respectively.

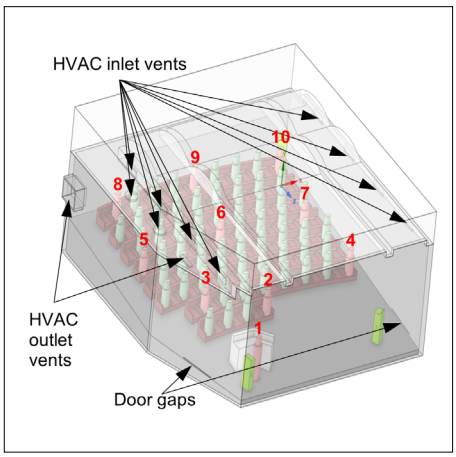


Figure 8-1 – 3D CAD schematic of the lecture theatre. Pink figurines indicate the position numbers for a potential infectious occupant might be located.

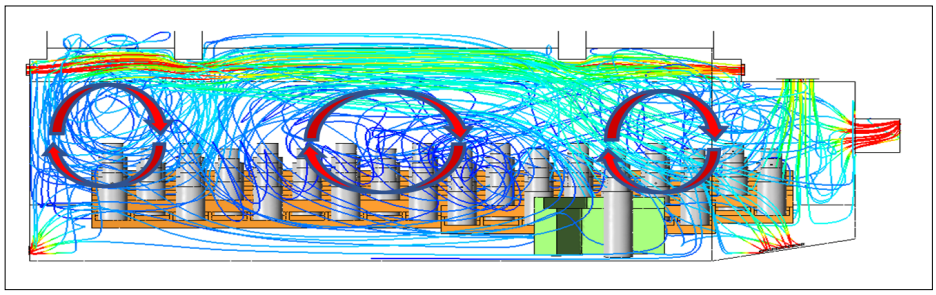


Figure 8-2 – Near-isometric view of the predicted air circulation pattern in the lecture theatre. Thick red arrows indicate significant air recirculation patterns. Thin coloured lines represent the air flowlines, with their colour indicating the local airspeed using the same scale as Figure 8-3. This near-isometric view accompanies the equivalent plan view in Figure 8-3.

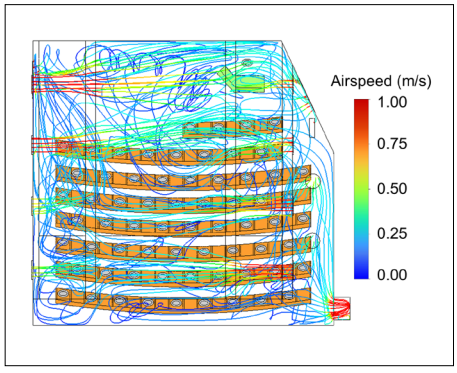


Figure 8-3 – Plan view of the air flowlines in the lecture theatre, with their colour indicating the local airspeed. This near-isometric view accompanies the equivalent plan view in Figure 8-2.

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Several points are evident from the airflow patterns in Figures 8-2 and 8-3. A large proportion of the HVAC system's inlet air moves across the theatre at a near-ceiling level from the inlet vents to the outlet vents. Below this, three recirculating zones are evident. An additional recirculation zone is also present at the front of the room and encapsulates the presenter's desk.

8.2 Human Movement

Human movement measurements were not undertaken independently by the project team for this Case Study. Instead, occupancy was measured by this industry partner's in-situ monitoring system, which was based on anonymised, infrared-based people-counter sensors. Figure 8-4 presents plots of human occupancy, CO_2 concentration, and $PM_{2.5}$ concentration during an eight-day section of the two-week monitoring period. As expected, there is a strong correlation between CO_2 & occupancy, and a reasonable correlation between $PM_{2.5}$ and occupancy, indicating human activity promotes the release and/or disturbance of particulate matter. The lower correlation of occupancy with $PM_{2.5}$ may be due to additional sources of particulates, e.g. external air brought in through the HVAC system's air inlet vents.

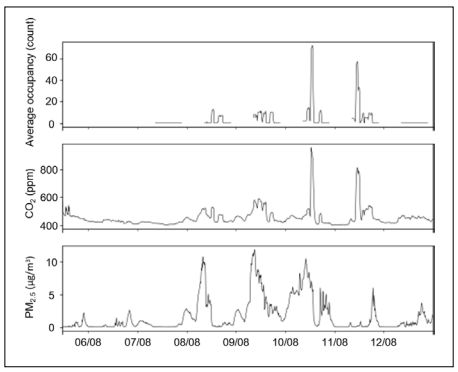


Figure 8-4 – Measured human occupancy, CO_2 concentration, and $PM_{2.5}$ concentration in the lecture theatre from 5/8/2022 to 13/8/2022

8.3 Aerosol Movement and COVID-19 Cumulative Infection Risk

CFD simulations of the lecture theatre were conducted during which one occupant was assumed to be infected with the Omicron variant and was placed at the various test positions indicated in Figure 8-1. Masks were assumed not to be worn by any room occupant and the resulting cumulative infection risk distributions were predicted assuming an exposure time of two hours, i.e. the duration of a 'typical' lecture in this room. Figures 8-5 and 8-6 present the predicted aerosol concentration and cumulative infection risk distributions, respectively, when the infected occupant was placed in Position 2, i.e. the row closest to the presenter at the mid-room end of the row. The height of these distributions corresponds to the average for a seated human at 1.2 m above the sloping floor.

Figures 8-5 and 8-6 demonstrate that aerosol is predicted to spread across the front of the lecture theatre, causing a corresponding increase in cumulative infection risk. Given the seating arrangement and location of the infected occupant, this risk primarily affects the presenter and their neighbouring audience member, both of whom are at risk to a relatively low (but still noticeable) extent (< 10%). The potential spread of aerosol from the infected occupant was further investigated by running further CFD simulations with them in each of eight additional test positions; see Figure 8-7.

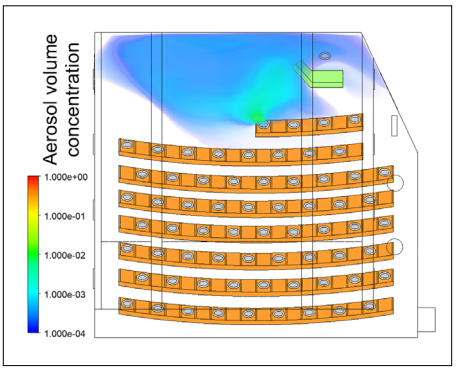


Figure 8-5 – Predicted aerosol concentration distribution at an elevation of 1.2 m caused by an infectious unmasked occupant in Position 2. The overall ACH is 19.8.

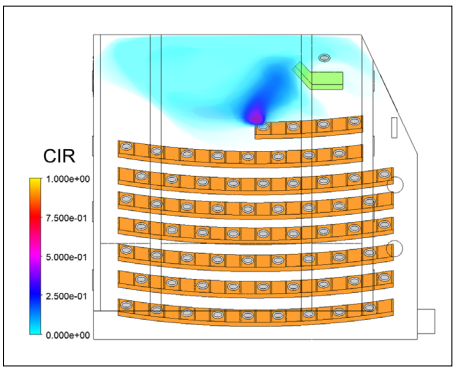


Figure 8-6 – Predicted CIR distribution after two hours' exposure to the aerosol concentration distribution in Figure 8-5

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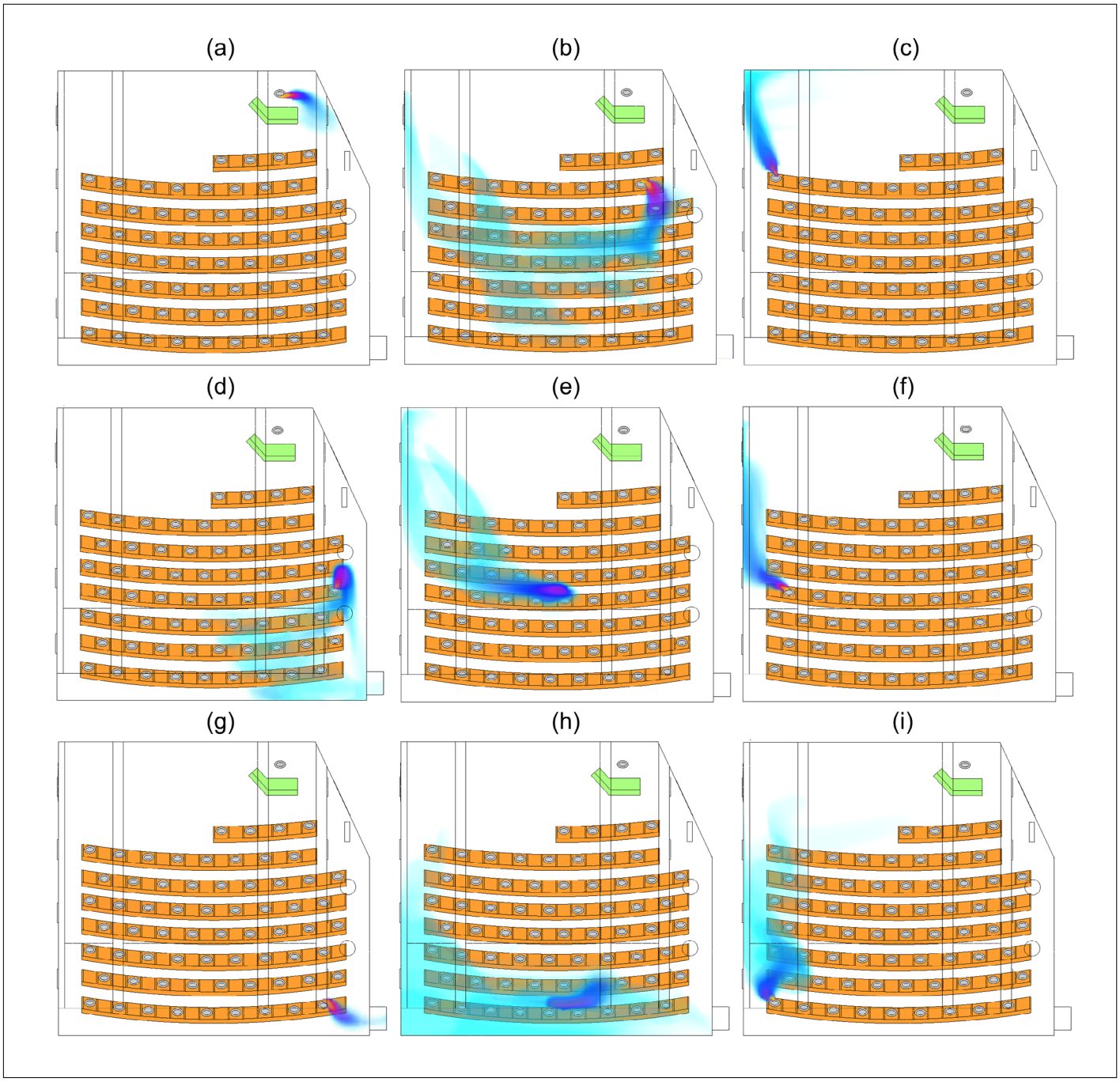


Figure 8-7 – Predicted CIR distribution at an elevation of 1.2 m after two hours' exposure to an infectious occupant in Positions (a) 1, (b) 3, (c) 4, (d) 5, (e) 6, (f) 7, (g) 8, (h) 9, (i) 10. All room occupants are unmasked with an overall ACH of 19.8. Distribution colour follows the legend in Figure 8-6.

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8.4 Particulates Measurements and their Interpretation

To analyse the likely extent of aerosol mixing and spread in the lecture theatre, the peaks in PM2.5 concentration measured during a given test day – 11th Aug 2022 after 4 pm, which describes the start of a lecture – were correlated between eight particulates sensors placed around the lecture theatre as shown in Figure 8-8. The peak value during this period was recorded for the particulates sensor IAQ-0002. The lag between peaks recorded by this sensor and peaks recorded for the other seven particulates sensors, as well as the magnitude of these seven sensors' peaks relative to the IAQ-0002, are presented in Figure 8-8(b-c), respectively.

It is apparent from Figure 8-8 that the extent of correlation between peaks recorded by their eight particulates sensors is high, the time lags between their peaks relative to those recorded at IAQ-0002 is limited (maximum 3 minutes), and the magnitudes of these $PM_{2.5}$ peaks relative to those recorded at IAQ-0002 are all >70%. This short lag and consistency in peak $PM_{2.5}$ values indicates rapid and extensive mixing of air, and thus aerosols, within the lecture theatre. These results are consistent with the extensive air mixing predicted by the CFD simulations (section 8.3).

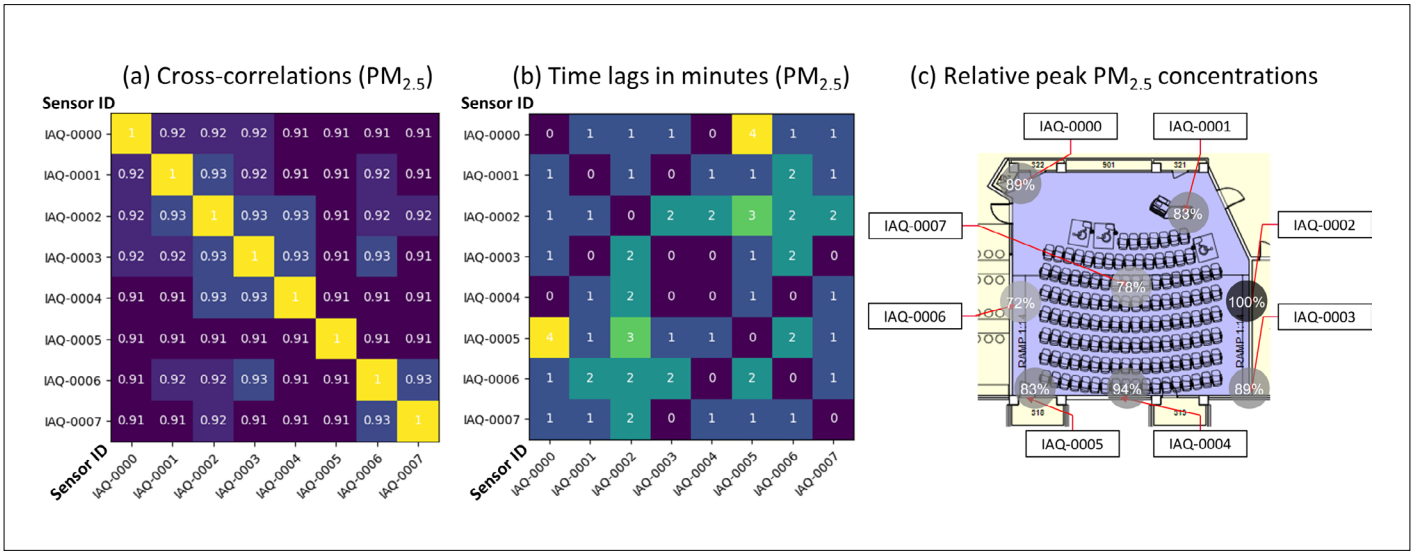


Figure 8-8 – (a) Cross-correlations, (b) time lags available to the nearest minute, and (c) relative magnitudes of the $PM_{2.5}$ concentration peaks measured in the lecture theatre. The circled values in (c) are concentrations divided by the largest peak value recorded and are thus dimensionless.

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8.5 Risk Mitigation Strategies

The CFD modelling predictions (section 8.3) & particulate concentration measurements (section 8.4) indicate that despite the high air exchange rates within this lecture theatre, depending on the location of an infected occupant, there can be a significant cumulative infection risk to both other audience members and the presenter. As mentioned in section 8.3, CFD simulations were run assuming neither the audience nor presenter were wearing masks in line with the 'norm' as of November 2022. Three possible mitigation strategies were investigated here via further CFD simulations:

i. Re-introducing masks
ii. Blocking out some of the seats
iii. Introducing locally placed air purifiers

i. Reintroduction of Masks

The impact of re-introducing masks depends upon the filtration efficiency of the mask being worn. These data are presented in Table 8-1 for three types of masking scenarios. The table data describe the maximum cumulative infection risk for seats adjacent to the infected occupant (25% risk without masks) and in the seats beyond the immediately neighbouring seats (10% risk without masks).

ii. Blocking Out Some Seats

The CFD simulation results presented in Figure 8-7 predict that the spread of cumulative infection risk varies strongly with the infected occupant's location but is potentially most problematic for seats in certain locations, e.g. when the infected occupant is in the first row of seats or in roughly the centre of the lecture theatre. Thus, if the lecture could operationally accommodate a small reduction in seating capacity, a significant overall reduction to cumulative infection risk to occupants in other locations is predicted to be achievable by preventing usage of the seats in these locations. However, determining these 'more strongly infecting' locations would require a significant body of CFD simulations to be conducted.

iii. Introducing Locally Placed Air Purifiers

Further CFD simulations of the lecture theatre were run with three virtual air purifiers positioned and oriented as indicated in Figure 8-9. These featured a capacity of 701 m^3/hr each and a filtration efficiency of 99.7%; note that the total rate of filtration led to a slight increase (<5%) in the overall ACH value for the room. The resulting predictions of cumulative infection risk are specific to this number, type (filtration rate and efficiency), and orientation (direction of inlet and outlet vents) of air purifiers.

The CIR distributions reveal that while the purifiers may change the prevailing airflow patterns, they do not significantly reduce the general magnitude of CIR across this lecture theatre. One exception to this pattern was the case of an infected occupant in the front row (Figure 8-10), for which the risk to the presented was significantly reduced relative to the case without air purifiers (Figure 8-6), as the prevailing airflow was partially redirected to the air purifier at the front of the lecture theatre at the opposite corner to the presenter's desk. Figure 8-11 shows the effect of air purifiers on the risk due to an infected occupant at a more central location (Position 6). However, in this case there was little change to the general magnitude and size of the risk distribution predicted without any air purifiers (Figure 8-7(e)), although the location of the aerosol cloud did change.

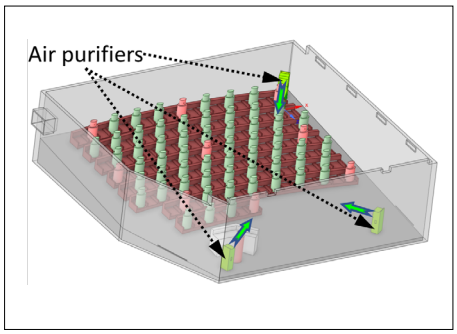


Figure 8-9 – Positions & orientations of air purifiers in the CFD simulations of the lecture theatre

Baseline results (no masks worn)	Surgical masks worn (75% filtration efficiency)	N95 masks worn (95% filtration efficiency)
25%	5%	0.2%
10%	2%	0.1%

Table 8-1 – Cumulative infection risk predicted by CFD simulations assuming two hours' exposure to a single infectious occupant. This prediction is presented assuming three different approaches to occupant masking

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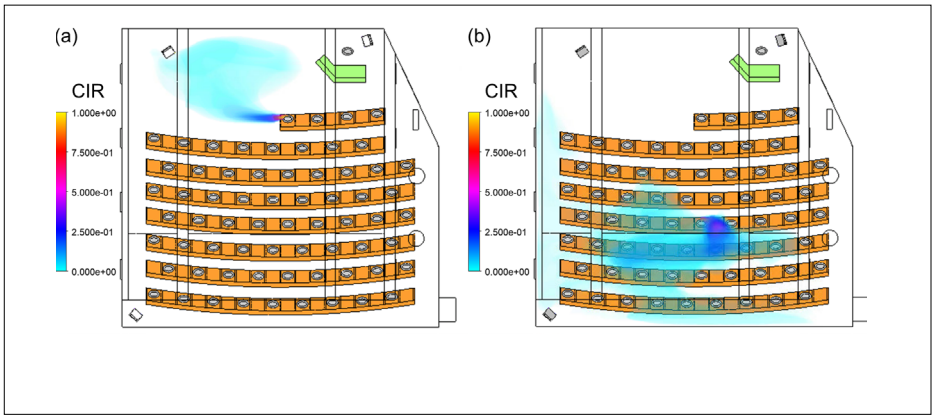


Figure 8-10 – Predicted effects of locally placed air purifiers on CIR distribution at an elevation of 1.2 m after two hours' exposure to an infectious occupant in (a) front row Position 2, or (b) centre of theatre at Position 6. All room occupants are unmasked with an overall ACH within 5% of the value measured without local purifiers present (19.8).

The cumulative risk distributions predicted via CFD and presented above are highly detailed and can be used to guide future lecture theatre design. For instance, the 'mixing ventilation' HVAC scheme and prevailing crossflow of air for this lecture theatre is shown to be non-ideal for limiting airborne pathogen transmission. In this case, it is speculated here that a system of vertically directed inlet vents in the floor with similarly placed outlet vents in the ceiling (thus limiting significant lateral dispersion and infection) may be more effective at preventing pathogenic aerosols emitted by infected occupants from risking infection to numerous nearby susceptible occupants. However, this case was not simulated here.

8.6 Summary

The lecture theatre selected for this Case Study features an HVAC system following a 'mixing ventilation' scheme with a high air exchange rate, which appears to promote extensive mixing of airborne particulate matter. The HVAC system is predicted to establish several air recirculation zones that in turn influence the predicted spread and magnitude of cumulative infection risk when a single infected occupant is present. These risk distributions are highly dependent on the location of this occupant. Risk to the occupants collectively is most robustly reduced by the wearing of masks and to a lesser extent by restricting seating in specific seats (or small seating areas). In general, standalone air purifiers were predicted not to be effective at significant risk reduction to the audience at large, which is a result of the predicted air recirculation zones promoted by the prevailing air crossflow in this lecture theatre.

MAJOR FINDING: Even at high air exchange rates, local cumulative infection risk may still be high when crossflow ventilation transmits aerosols from an infected person to multiple, closely spaced adjacent occupants, or when local recirculatory airflows occur

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9. Workplace Operator/Project Stakeholder Feedback

Of the five workplaces listed in section 2.2 and described in sections 4 - 8, two belonged to the same industry partner. Of the four independent industry partners therefore surveyed for feedback on the project's planning, execution, and results, substantive responses were received from the operators of the open-plan office, hospital ward section, and factory paint room. These operators were involved in every stage of the project and are therefore termed 'stakeholders' in this section. The impact that the quantification of cumulative infective risk distributions had on each organisation was found to vary, as did the actions taken based upon the risk mitigation recommendations given by the project team in each case. Key themes within the feedback received related to (i) the sensor monitoring process, (ii) the resulting evidence-based decisions, and (iii) the support of staff safety and wellbeing occurring as a result of engagement with this project.

9.1 The Modelling Process

Stakeholders noted that their involvement in the project's monitoring and modelling processes had been a positive experience and that the five-stage project workflow (Figure 2-1) was simple and not overly intrusive to their workplace environments and operations. However, for the hospital it was noted that a faster turnaround of cumulative infection risk distributions would have better informed decision-making. Note that this workflow spanned several weeks from sensor installation, monitoring, and data analysis, simulation development, running, and risk distribution quantification, and finally presentation of results to stakeholders. As hospital settings change rapidly in terms of in-patient and staff numbers and thus usage patterns within the ward, the ability to quickly adjust both operational aspects and HVAC settings in response to risk distributions delivered in near realtime was considered a valuable outcome to pursue. Subsequent to this first 'pass' of risk distribution quantification was the development of risk mitigation strategies in conjunction with the client (Figure 2-1). For the hospital ward section, some initial mitigation suggestions by the project team were considered impractical by the workplace operator (e.g. large scrubbers in in-patient rooms or plastic tented sheets draped over in-patient beds to limit aerosol dispersion), but the project team were described as always keen to listen and responsive to feedback. In other words, the presentation and feedback aspects system established worked effectively for the case of the hospital ward section.

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9.2 Evidence-Based Decision-Making

The aerosol concentration and cumulative infection risk distributions provided to each workplace operator informed subsequent decision-making:

i. Senior staff within the open-plan office participated in the stakeholder briefing delivered by the project team regarding the cumulative infection risk results. Because this office space was rented, detailed modifications to the building's HVAC system were not possible. But based on the distributions presented (section 4.2) and mitigation strategies suggested (section 4.5), senior staff acted immediately to purchase multiple air purifiers and furthermore sought evidence-based recommendations from the project team regarding optimal purifier orientation and placement.
ii. The factory paint room results (section 5.3) showed that this room already had appropriate HVAC ventilation in place and thus no modifications were required.
iii. The hospital ward section risk maps (section 6.3) were communicated to senior management and feedback indicated they might inform decisions about in-patient placement, staff movements, and local air purifier usage. The hospital operator also noted the potential for aerosol concentration & cumulative infection risk results to influence policy development, strategic decision-making, and future funding applications.

9.3 Supporting Staff Safety and Wellbeing

A key theme mentioned by the stakeholders operating the open-plan office, hospital ward section, and factory paint room was how cumulative infection risk quantification supported staff safety and wellbeing. As mentioned in section 9.2, no action was taken by the factory operator as the project team had confirmed that occupants were relatively safe. The hospital feedback indicated that the risk quantifications had reassured staff that the working environment was in general properly ventilated and largely safe. The office feedback was more comprehensive in this regard, noting that participating in this project and acting upon the risk mitigation discussion by buying, positioning, orienting, and operating air purifiers had demonstrated to staff that the organisation was concerned with their safety and wellbeing.



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10. Future Work Opportunities Highlighted by this Project

10.1 Short Term – Expansion to Further Industry Partners

Industry partner feedback was provided by the office, factory, and hospital ward workplace operators (termed 'stakeholders' as explained in section 9). Support for evidence-based decision-making and staff safety and wellbeing were identified as two key areas of impact arising from participating in this pathogen transmission research project. However, as each industry partner represented a different context and different results were obtained (and actions recommended) for each workplace, there exists an opportunity in the short-to-medium term to expand the methods and processes described in this report to additional public settings. High-priority examples include (due to higher risk of widespread transmission or serious illness) kindergartens, schools, and assisted-living facilities.

10.2 Short Term – Expansion to Further HVAC System Types

Aside from broadening this study as described above to include further workplace types, this study considered two major types of HVAC system configuration, i.e. the 'mixing' and 'displacement' types. There are a small number of other configuration types, each of which feature different airflow characteristics intermediate to the displacement-ventilation and mixing-ventilation limiting behaviours. These alternative HVAC configurations lead to unique patterns of recirculatory airflows, pathogen mixing, and local residence time distribution, and thus local regions of higher cumulative infection risk. Extending this project to these other HVAC configurations would be beneficial to translation of our findings to more workplaces.

10.3 Medium Term – Development of a Practical HVAC Air Mixing Test

Related to the above, an HVAC system's overall 'intensity of flow' within a room is generally rated at this time using the single metric of air changes per hour (ACH value). This term has widespread acceptance within the building and HVAC industries, but (as the results shown here and in a small but growing number of other studies demonstrate) this single metric does not reflect the airborne transmission risk from COVID-19 aerosol droplets ejected by infected occupants due to inhomogeneous air mixing within workplaces. A more sophisticated measure of risk is needed that better reflects how (i) airflow heterogeneities, e.g. local recirculatory airflows, and (ii) interactions between HVAC vent locations and a workplace's layout affects the local risk of pathogen transmission. The resulting metric,

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however, must (i) not require sophisticated equipment and calculations, as these are not readily field-deployable by contractors, and (ii) generate statistically robust results. In the medium term, identifying such a metric could be pursued by extending the approach of distributed Internet-of-Things environmental sensors and cloud-based analytic solutions used during this project to identify, capture, and study the unique characteristics of isolated regions in workplaces that do not mix rapidly with the main body of air within the space. This would generate large quantities of data. Therefore, this analysis would likely be best processed using machine-learning algorithms designed to incorporate the underlying physics of airflow and aerosol transport and trained to identify regions of slow air mixing from numerous sensor data, and thus lead to better sensor deployment plans and more accurate models.

10.4 Long Term – Follow-up Research Project

We begin by noting the project limitations described in section 2.5, which include (i) the well-known effect of the practical 'RANS'-type CFD model used here leading to 'smearing out' of cumulative infection risk distributions (which requires greater computing power to reduce the smearing effect), (ii) the aerosol ejected by infected occupants having a distribution of particle sizes rather than the single size modelled here (a potentially implementable improvement in the short term), (iii) updating the CFD model with clinical virological data for the most recent variant families to have become widespread (Omicron BA.5, BQ.1, etc.), and (iv) capturing waning vaccine effectiveness over time amongst as well as reduced vaccine effectiveness amongst more recent variants. Note that (iii-iv) are potentially implementable in the short-term.

While resolving issue (ii) and improvement (iii) listed above have potentially short-term implementation pathways, resolving issue (i) mentioned above would rely on the continued rapid growth in computational hardware and CFD software capabilities. This would enable more computationally refined analyses of aerosol transport in a workplace, which currently require a national high-performance computing facility to properly run. Thus, in the long term, the simulations described in this report will become possible using high-specification desktop workstation PCs or cloud computing platforms. Running large numbers of refined CFD simulations for a real workplace would then be much more cost-effective to run than is currently the case, e.g. for different arrangements of workstations and/or HVAC vents. However, analysing the results of these numerous CFD design variations would still be time-consuming and labour-intensive. The recent explosive growth in machine learning algorithm capabilities may mitigate this problem, with the accuracy of these algorithms further improved by designing and training them to be physics-informed, i.e. to respect the underlying processes of airflow and aerosol transport as described earlier in this section. However, the development and testing of such a model are non-trivial and require a dedicated research project with significant computational and experimental elements. The output would then be a computer model that can predict, to industrial reliability, the presence of isolated transport regions in indoor workplaces, the cumulative pathogen exposure risk within them, and the potential reduction to these risks for a range of minor workplace redesigns.

As explained in sections 2.3 & 3.3, a single air quality sensor data type ($PM_{2.5}$ concentration) was measured and used as a proxy for pathogenic aerosol concentration in all five workplaces studied, and its spatiotemporal variation was used to characterise aerosol transport throughout the workplace. However, with the increasing availability and decreasing costs of high-accuracy and high-measurement-frequency sensors, future work could include identification of pathogenic aerosols as distinct from non-pathogenic aerosols. This is important as non-pathogenic aerosols are highly common in workplaces and can present as interference during characterisation of pathogenic aerosol transport. The decreasing cost and increasing capability of indoor air quality sensors also makes increasingly possible the fusion of different sensor data types ('big data') to establish more a reliable proxy measurement for characterising the aerosol transport of each specific pathogen of interest.



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Similarly to aerosol characterisation, there are limitations and corresponding future work regarding the quantification of human movement. Key limitation (i) is that each participant was treated independently in our analysis, i.e. social interactions between them were not considered. This might be important as these interactions will normally involve talking, which might influence the air flow, air quality, and aerosol transmission. Key limitation (ii) is the direction that each participant is facing, particularly when they are located around the inlet and/or outlet vents. This information was not collected but may have important influences on local aerosol transport and thus indoor air quality. To address limitation (i), it may be helpful to measure the ambient noise level via microphones followed by anonymisation & analysis to determine the noise volume & generic type (human discussion or equipment noise, etc.). To address limitation (ii), more sensor types could be added, e.g. magnetic field sensors & accelerometers, and data analysis & sensor implementation protocols could be collectively updated to infer the facing direction of the participating workplace occupants. Finally, the role of human movement during the time of these CFD pathogen transport simulations has not been addressed in this report, which would occur to some extent for four of the five workplace types studied here, i.e. except for the lecture theatre. Future, more accurate models may thus include a realistic 'working path' in which both infected & non-infected people vary position, and infection risk may be calculated considering a transient risk map based upon dynamic positions of workers.



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Nomenclature

Abbreviation	Meaning
ACH	Air changes per hour, describing the overall rate of air exchange at this site
CAD	Computer-aided design
CFD	Computational fluid dynamics
CIR	Cumulative infection risk
DNS	Direct Numerical Simulation turbulence modelling method
HVAC	Heating, ventilation, and air-conditioning
LES	Large-eddy simulation
PPE	Personalised protective equipment
RANS	Reynolds-averaged Navier-Stokes turbulence modelling method

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Appendix

i. Limitations of Infection Risk Mode

The infection risk model used in this study is based on an extension (Li et al., 2022) of the classical model proposed by Wells (1955) & Riley et al. (1978) for the transmission risk of airborne pathogens in indoor spaces. The Wells-Riley model quantifies the infection probability for a susceptible occupant of in terms of the exposure time, pulmonary ventilation volumetric flow rate, and the concentration of infectious 'quanta', the latter of which depends upon the concentration of pathogenic aerosols, the concentration of active virions within these aerosols, and the infection rate of these virions. One drawback of the conventional Wells-Riley model is that the aerosol concentration is assumed to be constant in the indoor space, whereas in practice aerosol plumes ejected from infectious occupants tend to be highly heterogeneous & localised. In response, Li et al. (2022) recently proposed a detailed generalisation of the Wells-Riley model that allows the aerosol concentration to vary in space & time, such that the cumulative infection risk profile for a susceptible occupant (whether moving or stationary) can be determined from the local aerosol concentration inhaled by the occupant and time elapsed. This model can be applied readily to different airborne pathogens (including COVID-19 variants), viral loads, and can include factors such as the efficacy of PPE worn by susceptible & infectious occupants.

As for the conventional Wells-Riley model cited above, there are several assumptions that underpin the risk model by Li et al. (2022) used here. The main one is that infection risk follows a homogeneous Poisson process, which means that probability of infection per unit time is a constant when all other factors are held constant. This is reasonable assumption as there is no evidence of airborne pathogen infections behaving to the contrary. The other assumptions are that the spatiotemporal aerosol concentration is known, the viral load & transmissibility of the virus shed by the infectious occupant is known, and the probability of infection of a susceptible occupant is known. The first assumption does not present a significant limitation as the aerosol concentration can be predicted (given the location of an infectious occupant) using numerical simulations (see section 13.2). For data regarding transmission between infectious & susceptible occupants, representative averages from clinical studies are used as described in further detail by Li et al. (2022). However, we recognise that there exist large variations within the population (such as 'super-spreader' infectors) and so the cumulative infection risk predictions from this study should be treated as relative predictions rather than absolute predictions of infection risk.

ii. CFD Model – HVAC Airflow & Aerosol Transport

Computational fluid dynamics (CFD) simulations were used extensively in this study to predict airflows & the resulting aerosol transport throughout five indoor workspaces; see Li et al. (2022). These simulations are used to determine the spatiotemporal concentration of pathogenic aerosols that form an input for the infection risk model described above. The CFD models for the five workplaces were generated from CAD models coupled with field measurements of air flowrates through their HVAC supply & exhaust ducts.

While sputum droplets are ejected via speaking, sneezing, and coughing from infectious occupants with a broad size distribution ranging from ~1 - 1000 microns, droplets larger than ~100 microns fall rapidly to the floor. The remaining droplets evaporate within seconds to form desiccated aerosols whose size distribution mostly spans 1 - 10 microns, which are modelled here as monodisperse droplets with volume-averaged size of 6 microns. In terms of integration into the CFD simulations presented in this report, these simulations are based on a two-fluid Eulerian formulation for air & aerosol droplets, with a simple drag law for interphase momentum transfer. A Reynolds-averaged Navier-Stokes (RANS) turbulence model was used for the building-scale simulations, which is less computationally expensive than the alternative large eddy simulation (LES) & direct numerical simulation (DNS) methods. However, a major limitation of multiphase aspect of the CFD model used here arises from the single size fraction of aerosol droplets that was modelled, which neglects the individual transport dynamics of each aerosol size fraction. As such, the predicted spatiotemporal aerosol concentration distribution is taken to be representative of the bulk aerosol plume. The two-fluid model used here also does not fully resolve the complex transport dynamics of the aerosols or the interactions between aerosols, but rather models the aerosol and air phases as interpenetrating continua.

With regards to the RANS turbulence model described above, this does not capture the detailed features of the turbulent flows (small-scale structures such as eddies & vortices), but rather represents an averaged flow field. As a result, aerosol transport is also resolved in an averaged sense and so should be interpreted as such. These simplifications allow aerosol transport to be computed in a feasible timeframe, but do not fully resolve the detailed aerosol plume structure. This tends to 'smear out' the aerosol plume, increasing dispersion but reducing the magnitude of 'hotspots' of high aerosol concentration. Although these shortcomings can be important at small scales, they are less important at the larger scales (~1 m) that are representative of the built environment. Furthermore, simulation validation studies by Li et al. (2022) show that this computational model can accurately predict the aerosol concentration distribution in HVAC airflows.

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iii. Environmental Sensing Details

a) Sensor Device Key Parameter Summary

Device	Parameters & Units	Data Update Interval
SenseCAP barometric pressure sensors	- Barometric pressure (Pa) - Battery level (%)	- 10 minutes - Battery level transmitted every 10 messages (i.e. 10 × sensing interval) - Currently set to 10-minute intervals
Netatmo Weather Station	Indoor module - Temperature (°C) - Humidity (%RH) - Barometric pressure (mbar) - CO_2 (ppm) - Ambient noise (dB) Outdoor module - Temperature (°C) - Humidity (%RH)	- Measurements taken every 5 minutes - Unit transmits to Netatmo platform every 10 minutes - Maximum data query limit is 1 per 10-minute window. - Data for all stations is returned simultaneously
Cloud Garden indoor air quality monitor	- Temperature (°C) - Humidity (%RH) - CO_2 (ppm) - VOCs (ppb) - Particulate matter, $PM_{1/2.5/10}$ (µg/m³)	- Measurements taken every minute - Data is pulled from CG platform every 15 minutes - Data for all units is returned/updated simultaneously
Monnit open/close sensors (ALTA industrial version)	- Door/window status change (binary state) 1 = closed, 0 = open	- Data sent to iMonnit platform on state change - Webhooks used to relay data to ingest system
LAF Technologies particle sizer	- Particle sizes: 10.00 nm 14.00 nm 19.00 nm 27.00 nm 37.00 nm 52.00 nm 72.00 nm 100.00 nm 139.00 nm 193.00 nm 274.58 nm 323.88 nm 381.74 nm 449.48 nm 530.18 nm 625.38 nm 737.02 nm 867.18 nm 1021.47 nm 1205.86 nm 1424.96 nm 1679.58 nm 1978.13 nm 2332.27 nm 2745.80 nm 3238.77 nm 3817.43 nm 4499.40 nm 5307.20 nm 6253.83 nm 7370.21 nm 8685.62 nm 10240.20 nm 12069.47 nm 14226.56 nm 16773.33 nm 19768.32 nm 23301.03 nm 27467.18 nm 32375.50 nm 38162.42 nm - Additional particle sizes: Inhalable (ug/m³) Thoracic (ug/m³) Alveolar (ug/m³) PM_{10} (ug/m³) $PM_{2.5}$ (ug/m³) PM_{1} (ug/m³) - Relative humidity (%) - Temperature (°C)	

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b) Network Devices Key Parameter Summary

Manufacturer	Name/Part no.	Network access protocol	Network access protocol
Teltonika	RUT240 (4G Wi-Fi Access point)	4G LTE	Mains powered – EU/AU adapter required
Dragino	LPS8 LoRa gateway	Wi-Fi backhaul	Mains powered – 5 V USB type-C
Monnit	ALTA 4G LTE gateway	4G LTE	Mains powered ~24 hr internal backup battery
TP-Link	4G LTE Mobile Wi-Fi access point	4G LTE	Mains powered – 5 V micro-USB adapter

c) Device-ID/Sensor Asset Name (SAN) mapping

- Device-ID
  - Describes the application/device-specific naming or UID given to each device by the vendor
  - Device-ID should make the device uniquely identifiable within the subset of a particular device type (e.g. for LoRaWAN devices – DevEUI '00-ff-34-4d-34-8a-86-ab')
- SAN
  - Refers to the system-wide naming convention and asset class for all active sensing physical sensor devices
  - Alphanumeric code is in two parts (i.e. XXX-YYYY)
    - XXX is the device class or asset type identifier
    - YYY is the unique device identifier
  - Asset type identifier uses a three-letter code to represent the type of asset
  - Device identifiers are numeric and assigned to each asset starting at 0 (i.e the first device of asset type XXX will have the SAN 'xxx-0000')
  - Device identifiers will thus be in the range 0-9999 and will always be zero-padded to ensure SANs are all of equal length

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