A CFD-based framework to assess COVID-19 airborne infection risk and the effect of openings

Giulio Vita*[1,2], Thomas Avery-Hickmott[1], Patricia Pino[1,3], Rob Rowsell[1], and Darren Woolf[1,3]

*Corr. author: giulio.vita@wirthresearch.com

[1] Wirth Research Ltd.
Charlotte Avenue
Bicester, OX27 8BL
United Kingdom

[2] University of Birmingham
School of Engineering
Edgbaston, Birmingham, B15 2TT
United Kingdom

[3] AIRBODS
https://airbods.org.uk/
United Kingdom

ABSTRACT

The COVID-19 pandemic has prompted huge efforts to further the scientific knowledge of indoor ventilation and its relationship to airborne infection risk. Exhaled infectious aerosols are spread and inhaled as a result of room airflow characteristics. Many calculation methods and assertions on relative airborne infection risk assume 'well-mixed' flow conditions. However, ventilation in buildings is complex and often not relatable to well-mixed conditions. Ventilation guidance is typically based on the provision of generic minimum ventilation flow rates for a given space volume, floor area or occupancy level, irrespective of the effectiveness in the delivery of the supply air. Furthermore, the air movement might be influenced by the specific room characteristics and conditions (for example the opening of windows), which would potentially generate draughts (an example of a secondary consideration) and non-uniform flows. As a result, fresh air dilution could be highly variable depending upon a susceptible person's position in a room and, as a result, associated airborne infection risk.
A computational fluid dynamics (CFD) framework is presented to assess relative infection risk in a real building. The coupled influence of wind on the internal airflow characteristics resulting from open windows is evaluated to test the framework's capabilities. Using the 'transfer efficiency' approach to evaluate relative infection risk , the results clearly demonstrate the importance of understanding detailed indoor airflow characteristics and associated dilution patterns in order to provide detailed ventilation design guidance, e.g. occupancy, vents and furniture layouts, to reduce relative airborne infection risk.

KEYWORDS

COVID-19; Indoor Ventilation; CFD;

1 INTRODUCTION

Research and innovation on ventilation design in buildings has been recently gaining significant momentum due to a major scientific effort to identify the way SARS-CoV-2 has spread in buildings, helping to drive the COVID-19 pandemic (Morawska & Milton, 2020). Research over the last year has provided additional clarity that the airborne transmission route, involving particles travelling through air dominated by advection over gravitational effects, is the main vector for the virus to be transported and therefore transmitted in the near as well as the far field (Buonanno et al., 2020). Click or tap here to enter text.
Airborne transmission is mainly driven by the ventilation patterns in buildings. Dynamic thermal modelling (DTM) is considered the state-of-the-art method for energy and thermal comfort assessments supporting the design of mechanical and natural ventilation systems (Chartered Institution of Building Services Engineers., 2020). While DTM is generally reliable and robust, one key 'simplification' it operates is a mixed-zone approach to

calculating the heat and air transport pattern / exchange between neighbouring zones as its calculations are based upon a nodal network. A more complex method, computational fluid dynamics (CFD), calculates the ventilation performance of a building at a much finer spatial scale, e.g. millimetres or centimetres instead of metres. Strengths and weaknesses of different physics models also exist.

Some recent CFD studies have specifically focussed on SAR-CoV-2 transport in air, and risk of outbreaks (Mohamadi & Fazeli, 2022). While there is a significant body of evidence being generated as part of the pandemic response which will potentially influence future policy and/or guidance for ventilation design, e.g. along the lines of the new Approved Documents F and O (HM GOVERNMENT., 2022b, 2022a), there is already sufficient evidence that room ventilation and layout play an important role in transmission. This, in turn, means that the localised flow patterns are able to affect the airborne infection risk in a building (Bhagat et al., 2020). A good review of CFD-related studies can be found here (Mohamadi & Fazeli, 2022).

In this study, a methodology framework is proposed to assess airborne infection risk. The CFD model scenario and associated surface temperatures are informed by DTM results. The relative airborne infection risk is calculated following well-established intake fraction methods that are modified to post-process a steady CFD output . The methodology is implemented to perform a sensitivity study, investigating the effect of the season, viral parameters, and outdoor openings on the relative airborne infection risk.

2 METHODOLOGY

2.1 Background to method

The methodology framework implemented in this study follows well-acclaimed analytical methods of airborne infection risk, as explained in several major international studies (Buonanno et al., 2020). Besides the fact that the methods are well-established, the COVID-19 pandemic has highlighted the need for better ways of incorporating viral parameters into more resilient, safer ventilation designs.

Amongst available methods, the intake fraction method is based on the calculation of the intake fraction of the emitted infectious dose that is conveyed to a susceptible receptor (Nazaroff, 2021). This method is more developed and better suited to deal with variable concentrations of respiratory fluid as those predicted in CFD. Nevertheless, the hypothesis of well-mixed condition is still central to this method (Nazaroff, 2021).

The importance of the well-mixed condition assumption within the formulation of different analytical calculation methods is not normally investigated in detail but it is accepted that its adoption helps to reduce the complexity of the calculations. This study argues the importance of considering how the flow behaves, which is only possible by simulating or measuring it. Our proposed way of simulating the flow is to combine DTM and CFD calculation techniques, also in recognition of their inherent limitations .

2.2 Methodology framework

Figure 1 shows the methodology framework implemented in this study which includes the following steps with some addition details provided in the sections below:

1) DTM calculation to capture thermal environment throughout the year on an hourly basis.
2) Incorporation of a simple CO_2 calculation in 1) above by defining number of people in each zone (CO_2 sources) and an outside air condition with background CO_2 levels. The latter is effectively a CO_2 sink (reducing concentrations) as the diluting fresh air comes in through the open windows and also, to a lesser extent, via uncontrolled infiltration (not represented in the CFD model in this instance).
3) A CFD design scenario is then chosen. This is a given day and hour with a peak CO_2 level in a zone of interest. Note the DTM captures the impact of a variation in

occupancy and ventilation profiles amongst other varying elements such as climate and internal heat gains which may all directly or indirectly influence ventilation flow rates. The peak CO_2 level is chosen as this represents a time when the combined factors indicate higher occupancy / lower ventilation ratios. This therefore acts as an indicator to when there might be increased airborne infection risk although there is not a direct correlation.

4) The CFD model is set up using the DTM surface temperatures. Ideally, the CFD and DTM models should have some correlation on surface naming and even zonal definitions if other transposition of DTM-parameters is required, such as a mean radiant temperature, but this was not undertaken in this study.
5) Inclusion of any convective component of the DTM internal heat gains in the CFD model at the given time as the DTM would have resolved all the solar-thermal radiant exchanges. It is important to ensure that there is no double-counting or omission of heat gains. Note there are a number of ways to approach this which might be a heat flux instead of a fixed surface temperature and it could be applied at a surface or in a zone or at a point, but this does not form the focus of this study.
6) The CFD includes a representation for individual occupants at fixed points noting that only a small subset will be applied as infectious persons..
7) CFD results are then post-processed manually to calculate the intake fraction at each susceptible person's location (i.e., throughout the computational domain), based on the spatially varying concentration of exhaled breath. This uses an Eulerian 'volume-of-fluid' (VOF) approach without resorting to Lagrangian particle tracking models.
8) Viral parameters are chosen, and a probability-based methodology is applied to calculate the relative airborne infection risk.
9) The sensitivity of several viral or ambient parameters is then investigated by modifying relevant values and help drive the decision-making process on how to improve the ventilation design within given constraints through reducing airborne infection risk.

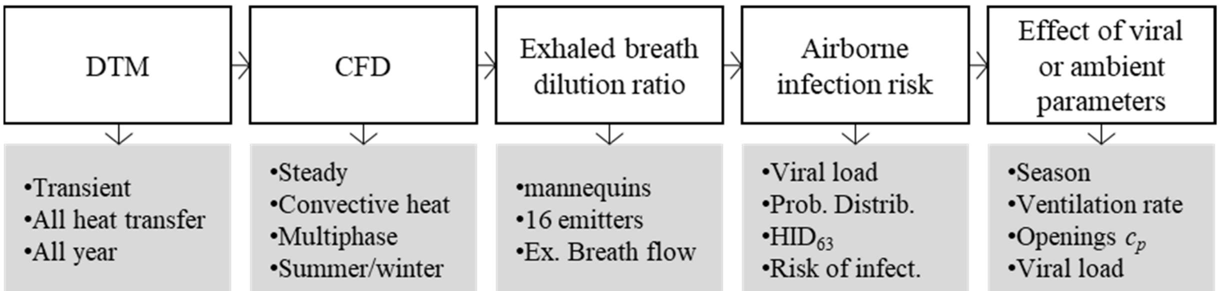

Figure 1. Methodology framework

2.3 Sensitivity study

The above modelling process is used to evaluate the effect of ambient and viral parameters on the relative airborne infection risk. In particular, the following effects are tested using the combined DTM & CFD approach:

- Effect of different period of year (cool and warm natural ventilation modes)
- Effect of viral load (i.e. respiratory activity and viral load)
- Effect of opening / window design (one wind direction).

2.4 DTM model overview

Figure 2 shows a view of the assessed floor level with the perimeter offices mainly on the left-hand side of the image (predominantly square in plan except for the corner offices) and then the zoning elsewhere for open floor plan office connected by corridors. The DTM was

also split into 3 zones vertically (floor plenum, occupied zone and above). It also shows the full building model noting that surrounding buildings were included as shading elements but are not shown below.
A detailed description of the DTM is not provided here as a standard approach was used other than the inclusion of CO_2 calculations (initially discussed above). Occupancy profiles were applied with resulting estimates for CO_2 levels in the occupied zones of the three key zones shown in Figure 2. Peak values were then used to assign a CFD design scenario of interest. In constant supply air flow rate systems, the peak CO_2 levels would often correlate quite well with peak occupancy periods.

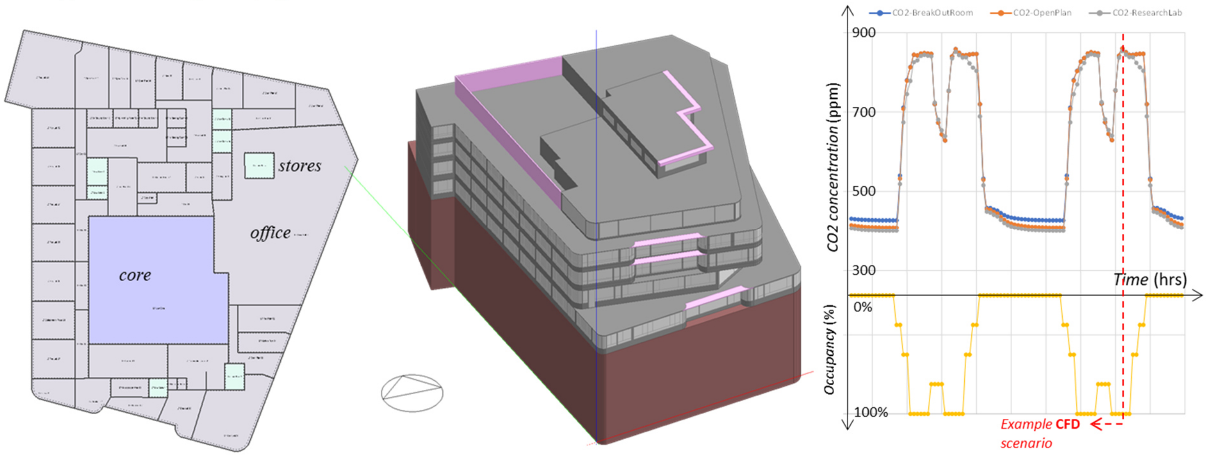

Figure 2. (*LHS and centre*) Views of the DTM model - internal zoning on assessed floor level and external full building model.(*RHS*) Occupancy profiles and CO_2 estimates in three key occupied zones over a 2-day period.

The DTM model was setup to assess the variation in indoor air conditions on an hourly basis over a full year accounting for variations in outdoor wind and thermal conditions including sun position and humidity levels. In addition, CO_2 levels have been simulated which can complement the assessment of ventilation performance in the CFD and act as a proxy for exhaled air. A comparison between DTM and CFD CO_2 concentrations was made giving increased confidence in the results. The details of this verification activity has been omitted from this paper as the focus of this paper is on the framework.

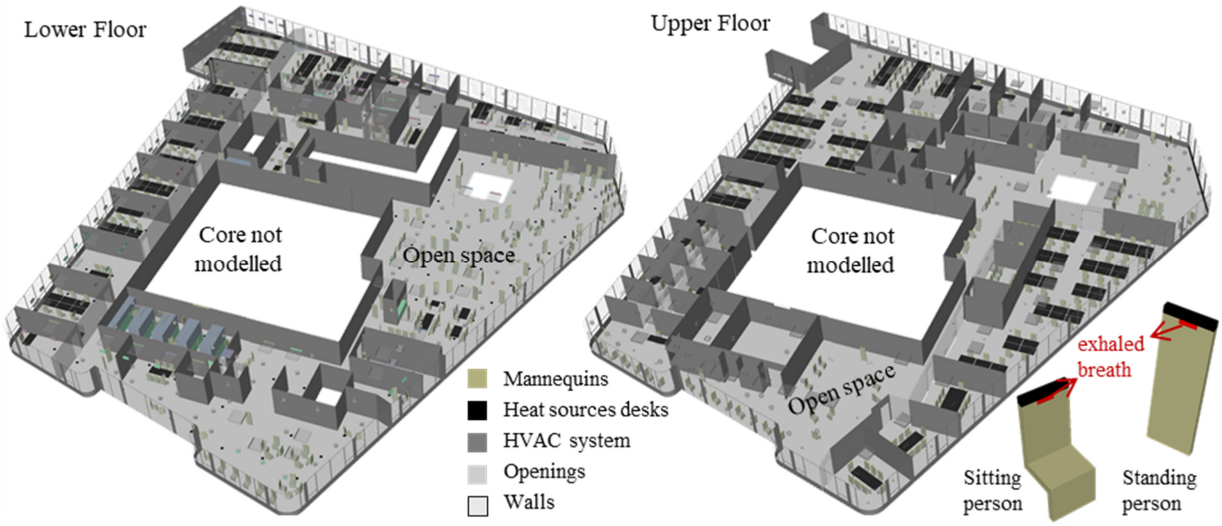

Figure 3. Detailed geometry with mannequin models to introduce infectious flow in form of exhaled breath.

2.5 CFD model overview

The investigated building consists of an open plan office partially surrounded by perimeter offices. The total floor plan area is ~12,000m^2 and 340 occupants are included in the model.

Figure 3 shows the CFD model with each workstation and person modelled individually. The person 'mannequins' represent both susceptible and infectious persons at a specified occupancy density representative of a typical working day. The heat gain from equipment or lighting in this model is applied on the top surface of every table. The heat gain from occupants is applied as a differential heat flux applied to the different parts of the mannequin. The CFD model has been constructed in a way that findings of the DTM analysis could be easily incorporated in the CFD setup. Boundary walls, windows, ceilings and flooring are therefore named individually with DTM-generated surface temperatures applied to the CFD model.
Supply and extract air flow rates along with operational profiles including occupants in the DTM analysis. The internal heat gains modelled in the DTM were represented in the CFD for the specified design scenario.
The simplified mannequin model included mouths with a mass flow rate of exhaled breath of 0.5 m^3/hr. This value takes into account the alternation between exhalation and inhalation. The average air speed at the mouth is consistent with the statistical averages of respiratory activity observed in transient experiments and simulations(Buonanno et al., 2020).

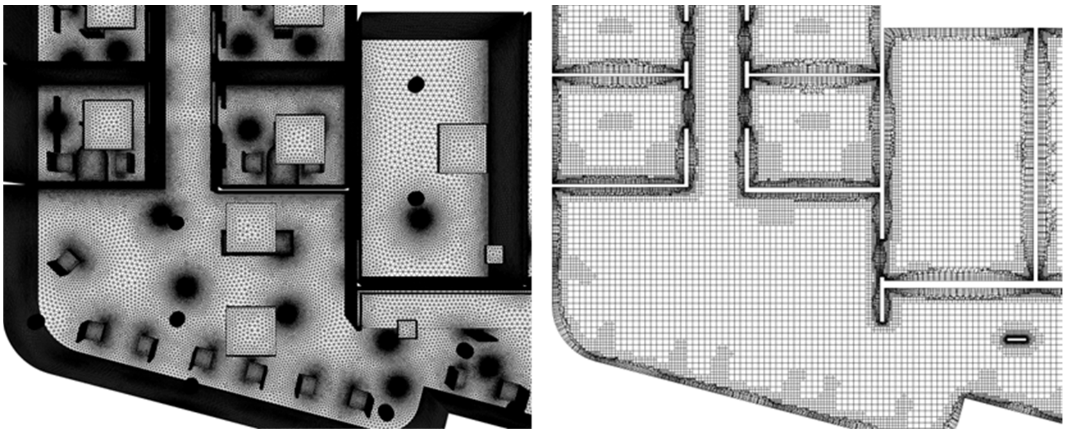

Figure 4 CFD computational grid.

CFD simulations use the Reynolds Averaged Navier-Stokes (RANS) technique implementing the k-ε realisable turbulence model, with the computational grid shown in Figure 4. The assessment of airborne infection risk is carried out through the use of species transport equations. This approach is chosen over the most commonly found Eulerian-Lagrangian particle tracking approach as RANS flow features do not have a resemblance of the instantaneous flow features an aerosol would disperse into. Two species have been set up in the model, having the same physical properties:

- Fresh air supplied through vents
- Exhaled air from occupants' mouths.

Air is also extracted via grilles located at high level and close to the building services core. Of the 340 occupants modelled in each floor, 17 emitters are identified, representing infected people. They are placed around the building, so they would test the risk within different types of rooms/areas within the office.
The CFD simulations yield the dilution ratios ξ_i for each i-th species modelled. The dilution ratio is used within the airborne infection risk calculation process, and it could also be monitored to assess CO_2 levels within the office. Although CO_2 concentration within a space has limited validity as a proxy for potential risk of infection (other than poor ventilation in combination with high occupancy at the extreme) (Zivelonghi & Lai, 2021), it was a useful parameter to gain confidence over the assumptions of the CFD model correlating with DTM results.

The background levels of CO_2 are assumed at 412ppm. The proportion of CO_2 within exhaled breath per occupant was assumed to be approximately 4.5% or 45000ppm. This calculation considers the CO2 emitted by all occupants and was verified with zonal results from DTM.

2.6 COVID-19 relative Airborne Infection Risk Assessment

An AIRR assessment is undertaken following the procedure identified in Buonanno et al. 2020 with breathing parameters calculated following (Nazaroff, 2021). Results are presented in terms of an Hourly Airborne Infection (HAI) rate, which is calculated dividing the diluted infectious phase by an infectious dose, defined as indicated in literature (Buonanno et al., 2020). Rather than representing a realistic scenario, HAI is here used to stress test the ventilation system and assess its response against the transport of airborne infection sources.

3 RESULTS AND DISCUSSION

3.1 Stress-testing the space: the hourly airborne infection rate

In support of the framework, a sensitivity study for winter and summer design scenarios is shown in Table 1.

Table 1. Sensitivity analysis parameters

Run	Season	Viral Load c_v	Activity	Opening pressure c_p
1 - Baseline	Winter	$3e^9$	Mouth breathing	-
2 - Season	**Summer**	$3e^9$	Mouth breathing	-
3 - Viral load	Winter	$\mathbf{1e^7,1e^{10}}$	Mouth breathing	-
4 - Activity	Winter	$3e^9$	**Coughing**	-
5 - Opening	Winter	$3e^9$	Mouth breathing	**0.0**

The most significant areas of relative risk were observed in small meeting rooms on the lower floor (see Figure 5). The office space in the south-west corner in winter and summer shows HAI~15% or more with slightly different spatial distributions. The open space areas of the office show a higher transport of the viral material due to the large number of vents and increased mixing of the exhaled breath and its transport over longer distances.

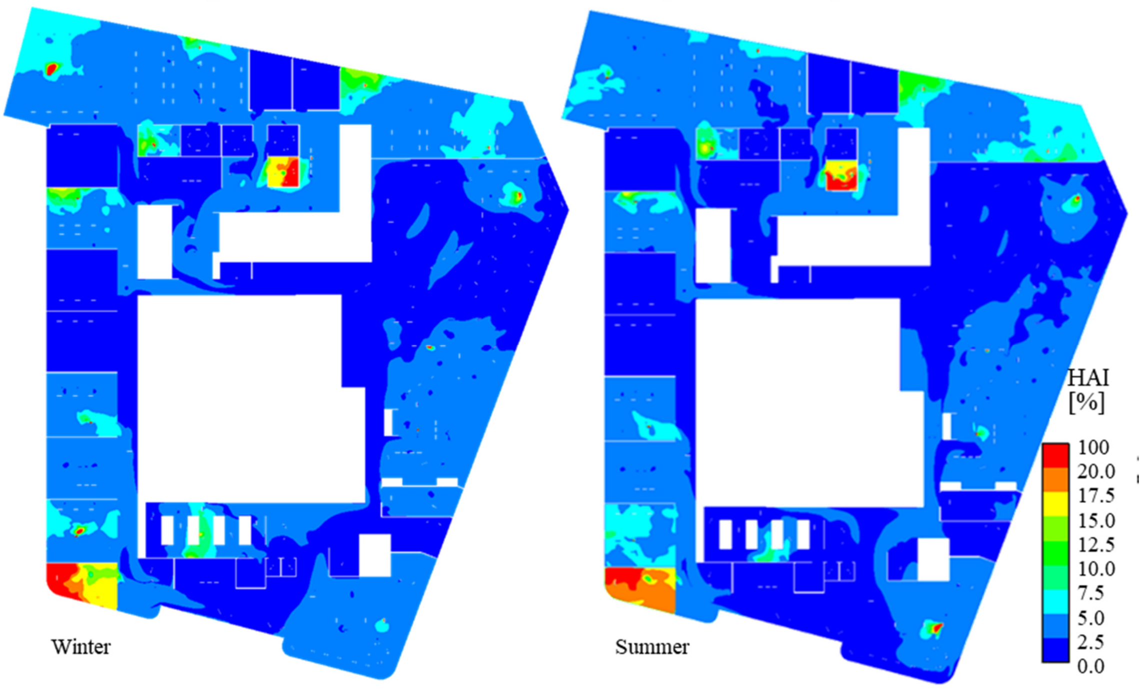

Figure 5. Estimated HAI in winter and summer (Lower Floor).

3.1.1 Effect of season

The small changes in the flow characteristics of the room, in this test case, between summer and winter conditions including a small variation in surface-to-air temperature differences and localised buoyancy effects leads to slight variations in the estimated HAI. In some spaces with greater seasonal variations, it could be important to adapt the safety of occupants depending on the seasonal performance of the ventilation system and room airflow characteristics.

3.1.2 Effect of respiratory activity and viral load

Figure 6 shows the lower floor of the building in the winter with variations in the viral load and respiratory activity. Traditionally an increased infection source would lead to perceptions of increased risk of infection but this link is less well defined in well-ventilated spaces.

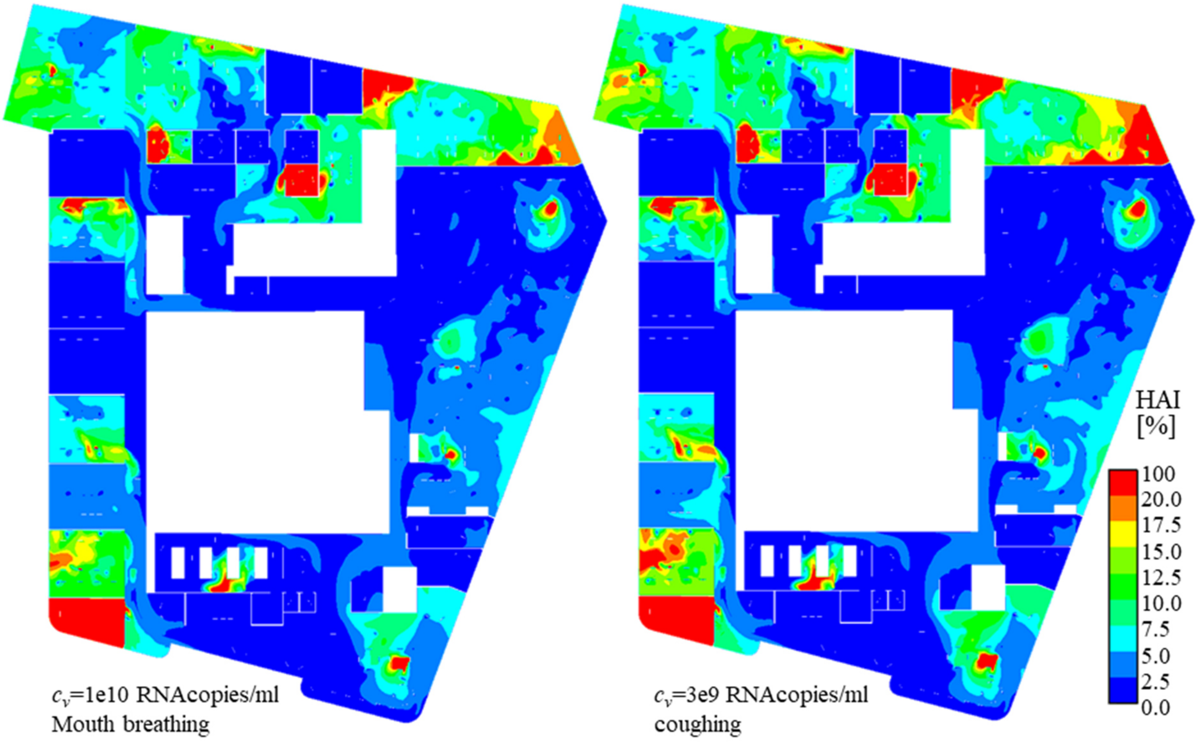

Figure 6. Estimated HAI for different viral loads: $3e^9$ (right) and $1e^{10}$ (left) RNA-copies/ml equivalent to mouth breathing and coughing respectively (Lower Floor).

The estimate HAI supports this hypothesis, i.e. the space is well-ventilated, however, there are two features of note:

- A higher viral load (i.e. concentration of RNA-copies per ml of respiratory fluid) can result from an increase in concentration at infector source and/or from a different respiratory activity. Further research is needed on how the direct modelling of particles using droplet transport (Lagrangian methods) may differ from the results shown here as two different aerosol sources may behave differently in an instantaneous flow. That said, the 'relative' influence of different viral loads presented here does provide insights into ventilation performance and potential for improved safety.
- Areas with high ventilation rates are less sensitive to changes in the viral parameters with similar concentrations shown at a relatively short distance from the emitter. Not shown here, but areas with insufficient ventilation would show a strong increase of HAI akin to the small office estimates.

While the variability of results is an issue in the context of absolute risk, tuning the viral parameters can be useful to stress-test the ventilation system and assess its resilience against potential 'super-spreader' events as well as basic improved safety.

3.1.3 Effect of window openings

The introduction of window openings modifies the air velocity and air temperature distribution significantly with increases of air speed up to ~40-60% in the winter case as shown in Figure 7 for the associated estimated HAI.

The general effect of increased ventilation resulting in reducing estimated HAI from the opening the windows is evident. However, the following should be noted:

- HAI reduces greatly in single and small offices that have openable windows.
- A change in relative airborne infection risk in a specific area around the emitter and how it transports viral material some distance away is evident due to the change in room airflow characteristics.
- Although open spaces tend to show a greater overall reduction in HAI due to the open windows, close to the emitter the estimated HAI may in fact increase as a function of local flow / dilution conditions, i.e. the infectious material is distributed differently
- Neighbouring spaces in open floor plans worsen as viral material is transported to larger distances through doorways in the given test case (circled area in RHS of Figure 6).

The wider variation in conditions due to opening windows demonstrates the impact of closing windows on the relative airborne infection risk when there are higher natural ventilation flows in a hybrid ventilation system due to larger indoor-outdoor air temperature differences. The impact of openings on energy, comfort and draught risk is also an important consideration.

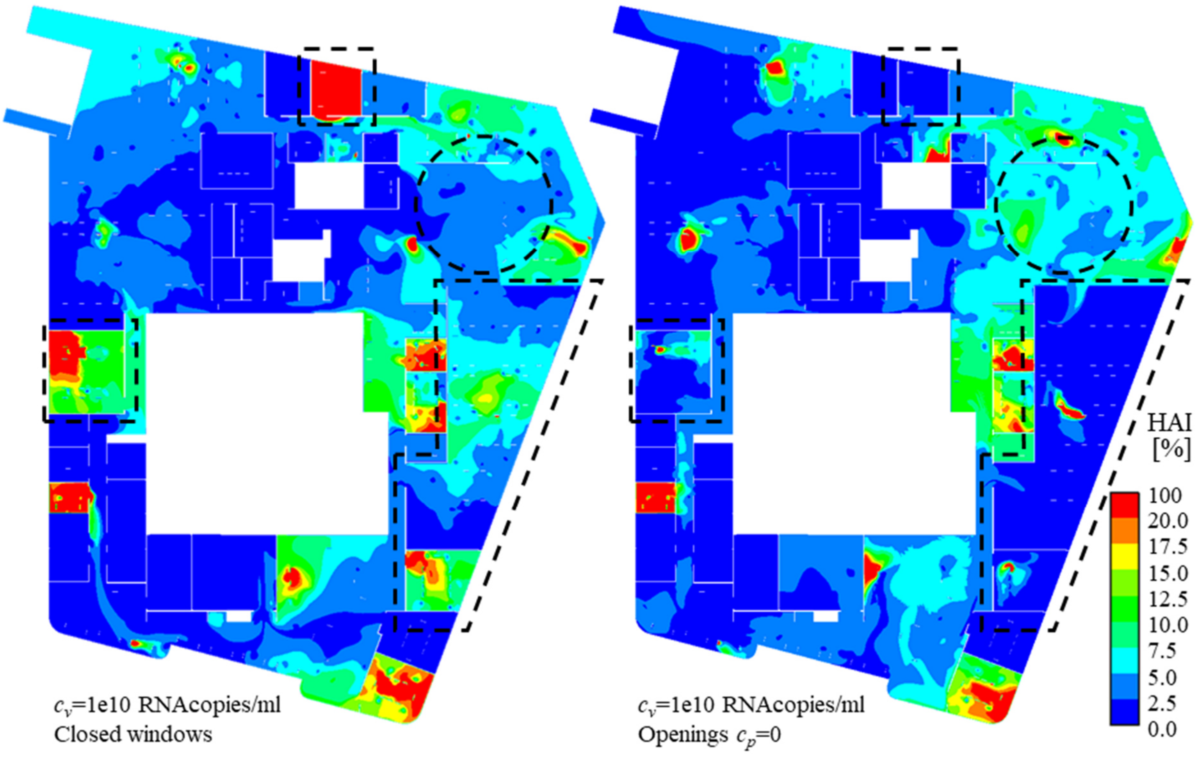

Figure 6. Estimated HAI for closed (left) and open (right) windows (Upper Floor) in winter.

4 CONCLUSIONS

In this study, a methodology framework is proposed, which is CFD based and aided by DTM techniques. that the framework could help designers to investigate the performance of a ventilation system in a real building against airborne infection risk. An easy to interpret parameter is proposed, the hourly airborne infection rate (HAI). This captures the airborne concentration of viral material and normalises it to a human infectious dose value of interest, such as the HID_{63} (Buonanno et al., 2020) and could be easily modified within this methodology for different diseases or on new available research results.

Assumptions to set up this methodology relied upon sparse and highly uncertain SARS-CoV-2 emission data. There is also broad scientific debate on airborne infection that might require building designers and ventilation specialists to adapt quickly and tune their methods to design ventilation systems capable of reducing airborne infection risk in a future airborne infection outbreak. Our results confirm that the framework is extremely versatile and could easily respond to any necessity future adaptations on the quantification of risk although the comparative qualitative uses to guiding designs may still be valid.

The main conclusions to the work can be summarised as follows:

- There is a marked difference in airborne infection risk in spaces with different ventilation systems. In particular, safety levels depend on the ability of the system to displace the infectious emission locally which can greatly differ in a single or small office with a few vents compared to a large open space with many vents.
- Increasing ventilation rate does not significantly influence the airborne infection risk in well-ventilated areas, i.e. the open space office in this building. It is therefore important to consider using other means to control the spreading of the virus in well-ventilated environments.
- Increasing the ventilation rate is of extreme importance to poorly-ventilated spaces. Conversely, design guidance based on occupancy alone might not be sufficient to guarantee that a space is well-ventilated. In general, single offices with small occupancy and small offices with medium occupancy are the least safe spaces with same ventilation rate per person rates.
- Viral parameters have a large impact on risk although the impact is less defined in the well-ventilated open space tested here.
- Adding natural ventilation openings to a mechanically-ventilated space may have a counter-intuitive effect on safety in some locations. They may reduce risk generally in small and large offices, however, there might be an increase in risk in the vicinity of the emitter depending upon local room airflow characteristics. Far-field transport of viral material may also lead to a different safety distribution in the same and/or adjacent rooms with open doorways.
- Wider impacts on thermal comfort, energy and draught risk can also be assessed with the CFD outputs using further analysis.

The spatial detail with CFD outputs and room-specific recommendations to improve safety (e.g. moving a desk or vent) can be captured by the CFD whereas this may not be possible using methods reliant upon the 'well-mixed' hypothesis. Background data outputs in CFD related to aerosol transport are extensive including, for example, air velocity, local turbulence / mixing levels and dilution ratios.

This preliminary work shows the need for more research towards the formulation of guidance to design ventilation systems capable of reducing airborne infection risk. However, the value to building designers is available using this framework which is quite flexible in nature. The limitations of this study could be extended in further studies to include:

- Modelling of opening with an effective area depending on type of opening
- Modelling of pressure conditions at openings using actual aerodynamic coefficient of building depending on weather conditions and wind direction

- Identification of metrics to normalise airborne infection rate effectively, e.g. based on occupancy
- Identification of probability distribution of viral parameters to calculate airborne infection risk and individual risk of infection
- Identification of occupancy patterns and metric to include those into risk assessment.

5 REFERENCES

Bhagat, R. K., Wykes, M. S. D., Dalziel, S. B., & Linden, P. F. (2020). Effects of ventilation on the indoor spread of COVID-19. *Journal of Fluid Mechanics*, *903*. https://doi.org/10.1017/jfm.2020.720

Buonanno, G., Stabile, L., & Morawska, L. (2020). Estimation of airborne viral emission: Quanta emission rate of SARS-CoV-2 for infection risk assessment. *Environment International*, *141*. https://doi.org/10.1016/j.envint.2020.105794

Chartered Institution of Building Services Engineers. (2020). *Operational performance of buildings : CIBSE TM61: 2020.* 139.

HM GOVERNMENT. (2022a). *APPROVED DOCUMENT F : ventilation - volume 2.*

HM GOVERNMENT. (2022b). *APPROVED DOCUMENT O : overheating (2021 edition).* https://www.gov.uk/government/publications/overheating-approved-document-o

Mohamadi, F., & Fazeli, A. (2022). A Review on Applications of CFD Modeling in COVID-19 Pandemic. *Archives of Computational Methods in Engineering*, *1*, 1–20. https://doi.org/10.1007/S11831-021-09706-3/FIGURES/6

Morawska, L., & Milton, D. K. (2020). *It is Time to Address Airborne Transmission of COVID-19*. https://doi.org/10.1093/cid/ciaa939/5867798

Nazaroff, W. W. (2021). *Indoor Aerosol Science Aspects of SARS-CoV-2 Transmission*. https://escholarship.org/uc/item/14t2t7xs

Zivelonghi, A., & Lai, M. (2021). Mitigating aerosol infection risk in school buildings: The role of natural ventilation, volume, occupancy and CO2 monitoring. *Building and Environment*, *1446*(89), 108139. https://doi.org/10.1016/j.buildenv.2021.108139