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Opening windows as a supplementary ventilation strategy for large classrooms in a pandemic situation: field measurements and simulation

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Abstract:

The coronavirus disease 2019 (COVID-19) has led to significant global health emergencies in recent years, prompting widespread recommendations across various regions for opening windows in building codes. However, official guidelines have not adequately addressed the details of window opening arrangements related to the supporting evidence from existing literature. This study investigated the risk of disease outbreaks via respiratory transmission in large university studio classrooms. It examined the effectiveness of window-door opening strategies combined with mechanical ventilation in mitigating the infection risk of respiratory diseases in such spaces. A full-scale school ventilation performance test bed was used to measure indoor airflow and CO₂ distribution patterns. Comparisons were made with the numerical simulation of exhaled viral emissions. A modified Wells-Riley equation was employed to calculate inhalation exposure and disease infection risks at the room level. Measurements showed that fresh air ventilation from the mechanical system was relatively low compared to existing standards, especially in pandemic situations. The results show that opening windows can lead to a decrease to low probabilities (below 5%) of infection risk in 85.02% area of a classroom over an 8-hour period, which demonstrates that window-opening behavior is an effective supplementary strategy for large educational spaces with mechanically ventilated systems during emergencies when active measures are insufficient for diluting diseases. Furthermore, the study reveals that maximizing outdoor air rates by opening all windows may occasionally result in adverse indoor airflow redistribution, increasing virus load from 0.0382 to 0.8926 *quanta/m³* near the virus source locations.

Key Words: Classroom, Carbon Dioxide, Window Motion, Airflow, Airborne Transmission, Infection Risk

1. Introduction

1.1 Overview

COVID-19 is one of the most significant global public health events of the new century, resulting in over 700 million infections by August 2023, according to WHO [1]. While many countries have declared victory against the disease, the pandemic continues to influence social behaviors and daily urban life, reshaping policymakers' perspectives on the built environment. Enclosed and crowded spaces are more susceptible to airborne transmission, playing a crucial role in the spread of respiratory infectious diseases, including COVID-19 [2,3,4], SARS [5], and ordinary flu [6]. Indoor air conditions have gained attention in building codes and regulations worldwide with recommended measures to ensure air freshness and reduce virus infection risk in mechanically ventilated environments [7]. University classrooms, as typical crowded public indoor spaces, are frequently occupied even during pandemics and flu seasons. Investigating strategies to mitigate infection risk for various ventilation systems is essential for public buildings, particularly university classrooms.

Carbon dioxide (CO₂) is an initial parameter of indoor air quality [8,9,10]. It is non-toxic and can be easily gathered, thereby being widely used as a tracer to investigate indoor airflow and ventilation [11] and to evaluate air safety risks [12] as a surrogate method [13]. Specifically, Carbon dioxide (CO₂) has been widely investigated in many research projects on classroom indoor ventilation [14,15,16]. The existing literature [9] has concluded that additional natural ventilation systems were necessary to maintain CO₂ concentrations below 1000 *ppm* within classrooms. Studies have shown that the CO₂ concentration can effectively evaluate the indoor ventilation rates in both mechanically [17] and naturally ventilated classrooms [18]. Dai and Zhao's study [19] shows that the ventilation rate is a key factor in reducing the probability of indoor airborne respiratory disease infection during the pandemic; therefore, CO₂ concentrations can be monitored as a significant indicator of infection risk in educational spaces [20]. In 2022, Fantozzi et al. [21] developed a cost-effective CO₂ monitoring system. They presented a method to predict the probability of infection due to airborne transmission by monitoring the CO₂ concentration in naturally ventilated classrooms. To summarize, findings from the existing literature during the pandemic have proved the significant role of CO₂ concentration in epidemic prevention and control.

Several studies have investigated indoor air quality (IAQ) by monitoring CO₂ concentration in Hong

Kong classrooms. Lee [22] found a maximum CO₂ concentration of 5,900 *ppm* in one classroom, while Lee and Chang [23] and Lee et al. [24] revealed inadequate ventilation in mechanically ventilated classrooms with CO₂ levels exceeding 1,000 *ppm* recommended by the HKIAQO level II standard. Jia et al. [25] found that CO₂ concentrations above 1,095 *ppm* caused discomfort among students, and Che et al. [26] used CO₂ measurements as indicators of ventilation and occupancy in 32 schools. However, the existing literature on optimization strategies for maintaining good indoor air quality, especially the mitigation measures for airborne disease in large educational spaces is limited. Therefore, there is an urgent need to explore the mitigation strategy in Hong Kong, to reduce the infection risks of indoor respiratory infectious diseases in this post-epidemic era.

1.2 The previous studies on the influence of window/door opening behaviors on indoor air quality

Existing studies of the behaviors of window and door opening and their impacts on indoor airflow conditions were carried out using different methodologies, including real-time measurements [27,28], theoretical methods of mathematics [29], and computational fluid dynamics (CFD) simulation [30,31]. Villanueva et al. [32] continuously monitored the ventilated conditions in 19 classrooms in Spain, which proved that opening windows and doors minimized the risk of indoor infections of COVID-19 but caused CO₂ concentration to exceed the recommended limit value. Zhou et al. [33] investigated the impact of the opening and closing process of sliding doors on airflow patterns in an operating room, and they observed contaminants accumulating in the upper space of the room due to airflow and temperature. Tung et al. [34] found that an air velocity of about 0.2 *m/s* prevented airborne infection through an opening door with CFD models. Using CFD models, Hang et al. [35] revealed that the opening door increased the infection risk of inter-cubicle transmissions.

On the other hand, keeping windows and doors open has also been suggested for both naturally and mechanically ventilated indoor spaces. The opening window is suggested as a measure for a safe university [36] and for improving infection control in domestic rooms [37,38,39]. Ding et al. [40] investigated 36 classrooms in 11 secondary schools in the Netherlands, with only 2 equipped with centralized ventilation systems. They claimed that opening the windows and door protocol failed to maintain the indoor air quality and thermal comfort always in line with standards. Even though it should not be assumed that the HVAC system will always fail to ventilate a room with no opening

windows [12], it is debatable whether opening windows can be an effective supplementary method to dilute the virus accumulation and reduce the risk of infection in a classroom when the active ventilation system is not efficient enough over a limited period.

ASHRAE recommends opening windows in commercial buildings to enhance outdoor air [41] and disabling the interlock in the building automation system. Still, this strategy regarding detailed window management and opening schedules is unclear. Fresh air ventilation standards for occupied spaces are provided by ASHRAE and increased rates are recommended in pandemic situations. However, it is often the case that standards are not met in some spaces, even with mechanical ventilation, especially where occupant density may be high. Additional ventilation through window openings, therefore, is crucial in diluting virus-infected spaces.

1.3 Research gaps and conclusions of literature review

Existing literature primarily focuses on airflow distribution patterns in mechanically or naturally ventilated conditions [20,42], with insufficient evidence exploring the influence of opening windows and doors on indoor airflow in combined mechanical and natural ventilation settings. Specifically, no studies have investigated this behavior as an emergency strategy for large educational spaces with mechanical ventilation systems when active measures are insufficient for disease dilution. Building codes in many countries suggest increasing ventilation rates to mitigate infection risks in schools and universities, such as ASHRAE's recommendation to maximize outdoor air flow rates [43]. However, there is still no evidence on whether the maximum ventilation rates achieved by opening all windows will lead to the lowest infection risk. In certain situations, opening more windows may not consistently increase the ventilation rate in a room. It is essential to have a better understanding of indoor airflow and its impact on ventilation performance, and this understanding must be more extensively incorporated into current investigations of window opening behaviors. In public health emergencies such as COVID-19 and seasonal flu, it is crucial to explore the indoor airflow distribution pattern and its impact on CO₂ concentration in crowded and large-scale indoor spaces. However, this important aspect of ventilation assessment has been less investigated, especially in educational buildings.

This study aims to explore a double-ventilation strategy (a composite system with both mechanical and natural ventilation) during the pandemic, examining how windows and doors opening can

mitigate infection risks in large educational environments when mechanical ventilation systems fail to control disease in a limited time. Through coupling field experiments and simulations, spatial distribution patterns of air flowing within large classrooms were investigated to evaluate the impact of airflows on CO₂ and viral particle concentration levels. The approach bridges the gap between airflow distribution and window opening behaviors in crowded and large educational spaces by providing data and evidence of the role of indoor airflow in CO₂ and viral particle distribution. COVID-19 has been a particular focus recently, and this work also applies to other infectious diseases, which will be an important issue for a long time in the future.

2. Methodology

2.1 Research methods

This study uses a combination of field experiment measurements and computational fluid dynamics (CFD) simulation predictions. The research framework is illustrated in **Fig. 1** and can be divided into the following stages: Background Investigation, Construction of the CFD Simulation Model, Field Measurements and model verification, Simulations of 5 Scenarios, and Ventilation Strategy during the Pandemic.

Background information was collected during the investigation, and data on airflow and CO₂ levels were gathered to create a three-dimensional model of initial boundary conditions. Computational fluid dynamics (CFD) simulations were conducted to analyze the effectiveness of various ventilation strategies, and field experiments were carried out to validate the model results. The study simulated 64 individuals, including one virus carrier, staying in a classroom on the eastern side of the U-shaped Critic Room through five scenarios of different configurations of windows and doors. The ratio of the classroom area occupied by various infection rates over three durations (1, 4, and 8 hours) in different scenarios was computed. The study also conducted correlation analysis to demonstrate the relationship between CO₂ levels and virus concentration, validating CO₂ as a valid tracer for airborne respiratory disease aerosols. Furthermore, it investigated the most efficient ventilation approaches to minimize viral transmission in classrooms equipped with mechanical ventilation systems.

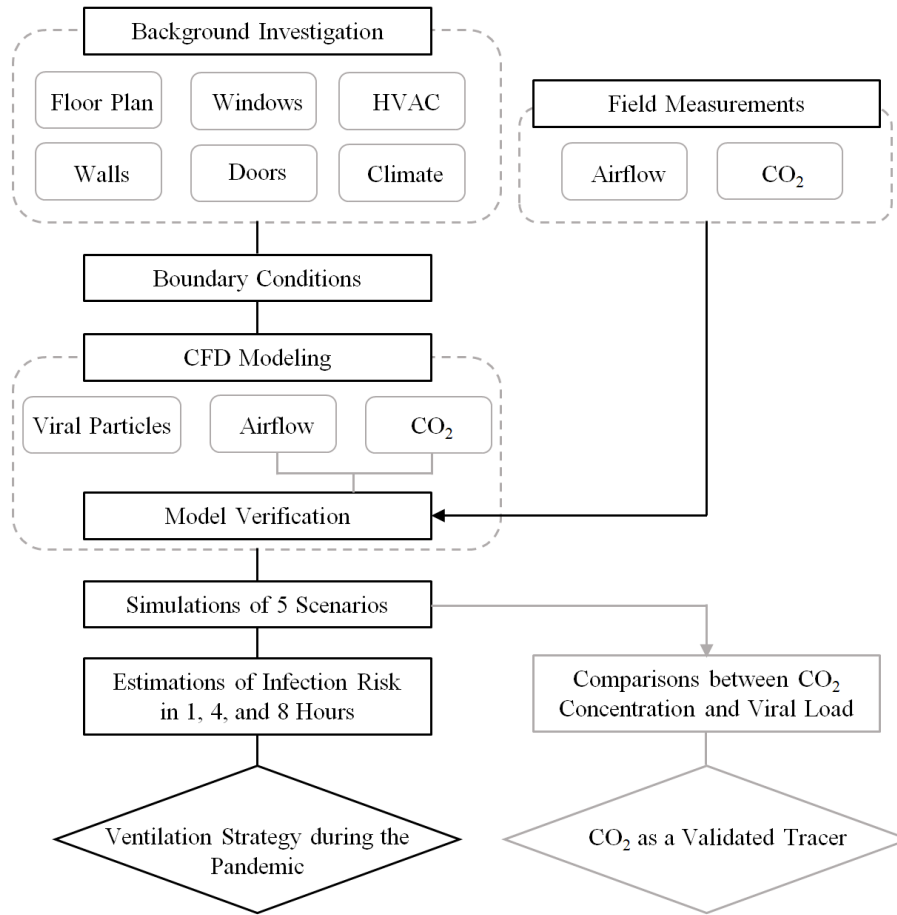


Fig. 1. Research Framework and workflow.

2.2 Background

The subtropical local climate of Hong Kong Island is characterized by summer temperatures ranging from 24°C to 30°C (June to September), with relative humidity consistently exceeding 80%, and monthly precipitation levels reaching 490mm. Located on the 3rd floor of the Knowles Building at the University of Hong Kong, the U-shaped Critic Room (**Fig. 2**) comprises three large classrooms, namely, Eastern Studio, Southern Studio, and Western Studio, accommodating approximately 200 architectural design students. A spacious hallway occupies the central area, which is adjacent to the classrooms and is connected to the surrounding office rooms by corridors that encompass five elevators. **Fig. 3** illustrates a plan of the classrooms, and **Table 1** lists various features such as architectural dimensions (floor area, room volume, window area, and door area) and student occupancy. The classrooms' floor areas range from 222.0 to 437.1 m^2 , and their volumes extend from 714.9 to 1424.1 m^3 . Student occupancy varies between 60 and 80 individuals, resulting in a density of 0.1533 to 0.2748 $person/m^2$. These classrooms experience continuous occupancy throughout the day due to the long-lasting design work, a common practice in university

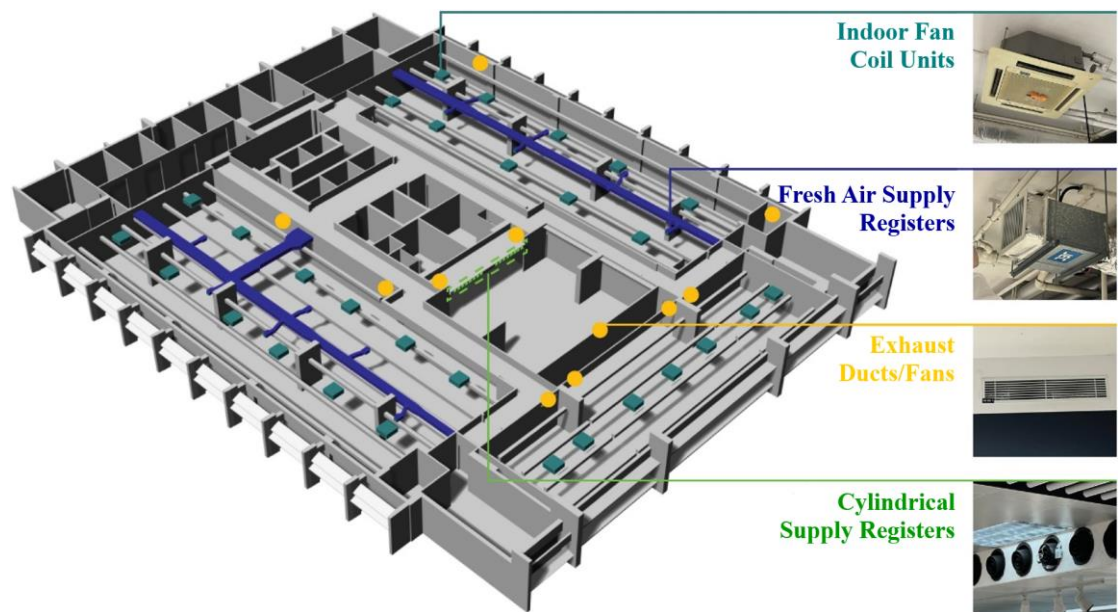


Fig. 2. Mechanical ventilation system of 3rd floor at Knowles Building, HKU. Detailed devices include indoor fan coil units (teal), distributed fresh air supply registers (blue), exhaust ducts/fans (orange), and cylindrical supply registers (green).

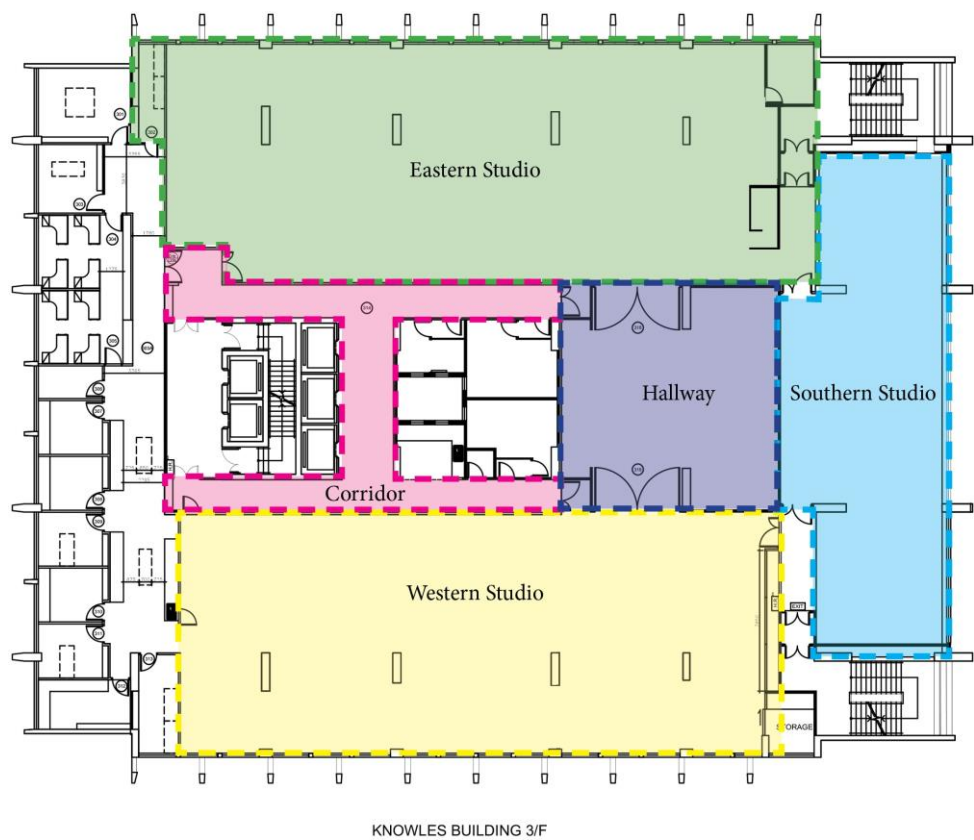


Fig. 3. Plan view of the investigated classrooms and corridor on the 3/F of Knowles Building.

Table 1. Characteristics of the investigated classrooms on 3/F of Knowles Building.

SPACES	Eastern Studio	Southern Studio	Western Studio	Corridor
Ventilation Type	Central Mechanical	Central Mechanical	Central Mechanical	Central Mechanical
Floor Area (m^2)	442.3	222.0	437.1	110.5
Room Volume (m^3)	1424.1	714.9	1407.5	273.6
Total Window Area (m^2)	54.2	56.3	55.3	-
Door Area (m^2)	9.9	5.5	12.7	-
Total Opening Area* (m^2)	75.0	61.7	78.8	-
No. of Students	64	61	67	-
Density (P/m^2)	0.1988	0.2748	0.1533	-

*10.9 m^2 of hallway door is accounted for in the total opening area of the Eastern Studio and the Southern Studio, respectively.

Fig. 2 depicts the entire floor, excluding two staircases, ventilated by the mechanical HVAC system. This system is a constant air volume (CAV) unit, which comprises distributed fresh air supply registers (in blue in **Fig. 2**, 270 mm dimension rectangular shape, at 2.53 m height) and cylindrical supply registers in the hallway room's false ceiling (in green in **Fig. 2**, 260 mm diameter, at 2.42 m height). The supply air speed and temperature are controlled as shown in **Table A.2** and **Table A.8**. The rectangular registers in Eastern Studio and Western Studio draw and supply 100% fresh air directly from outdoor spaces by passing a return air exchanger on the 4th Floor. Cylindrical supply registers in the hallway room provide fresh air mixed with indoor return air at proportions of 70% and 30%, respectively. In addition, there are ceiling-mounted fan coil units (in teal in **Fig. 2**, at 2.72 m height) in the classrooms (10 units in Eastern Studio, 12 units in Western Studio, and 7 units in Southern Studio) with leaving water temperature at 12°C. The fan volume speed is at 135 $m^3/hour$, and the indoor temperature was set at 17.5°C. As shown in **Table A.1**, the air temperature measured from the outlets of fan coils varies from 11.1°C to 24.3°C due to different working conditions, which remain constant throughout the experiment period. For the exhaust components, several exhaust ducts/fans in each classroom (in orange in **Fig. 2**) serve as stale air extracts, driven by the positive pressure generated by supply air. **Table A.1**, **Table A.2**, and **Table A.3** provide a comprehensive overview of the HVAC system's daily working conditions, as measured with a portable airspeed meter (*Kestrel 4500*) (**Fig. A.1**) and an air volume hood (*Testo 420 Series*) (**Fig. A.2**).

2.3 Full-scale measurements and experimental setups

2.3.1 Field Measurements of Airflow

Indoor movement and ventilation significantly influence air freshness and purification, impacting on the cross-infection of respiratory infectious diseases [30,44]. **Fig. 4(a)** presents experimental equipment for indoor airflow measurement in the Eastern Studio classroom, using anemometers, including 1 unit of *YOUNG Model 81000* and 2 units of *YOUNG Model 86000* (specifications of both types are shown in **Table A.4**). The Eastern Studio measures 32.40 *m* in length, 12.95 *m* in width, and 3.32 *m* in height. On the experiment day, the outside conditions were 30.9°C air temperature, 71% relative humidity, and no rainfall.

In the experiment, students were evacuated from classrooms with restricted access. The HVAC system was set to a medium fan-switch and indoor temperature of 17.5°C. Anemometer monitoring systems were positioned at a height of 1.5 meters in various locations (**Fig. 4(b)**), including the Eastern Studio (at points S1-S4, S11-S14), the Hallway Room (at points H1 and H2), the Corridor (at points C1-C3), and the connecting space (at points M). During the experiment, the entrance doors and windows of the Eastern Studio and Western Studio were closed, while the Hallway Room and Southern Studio doors remained open.

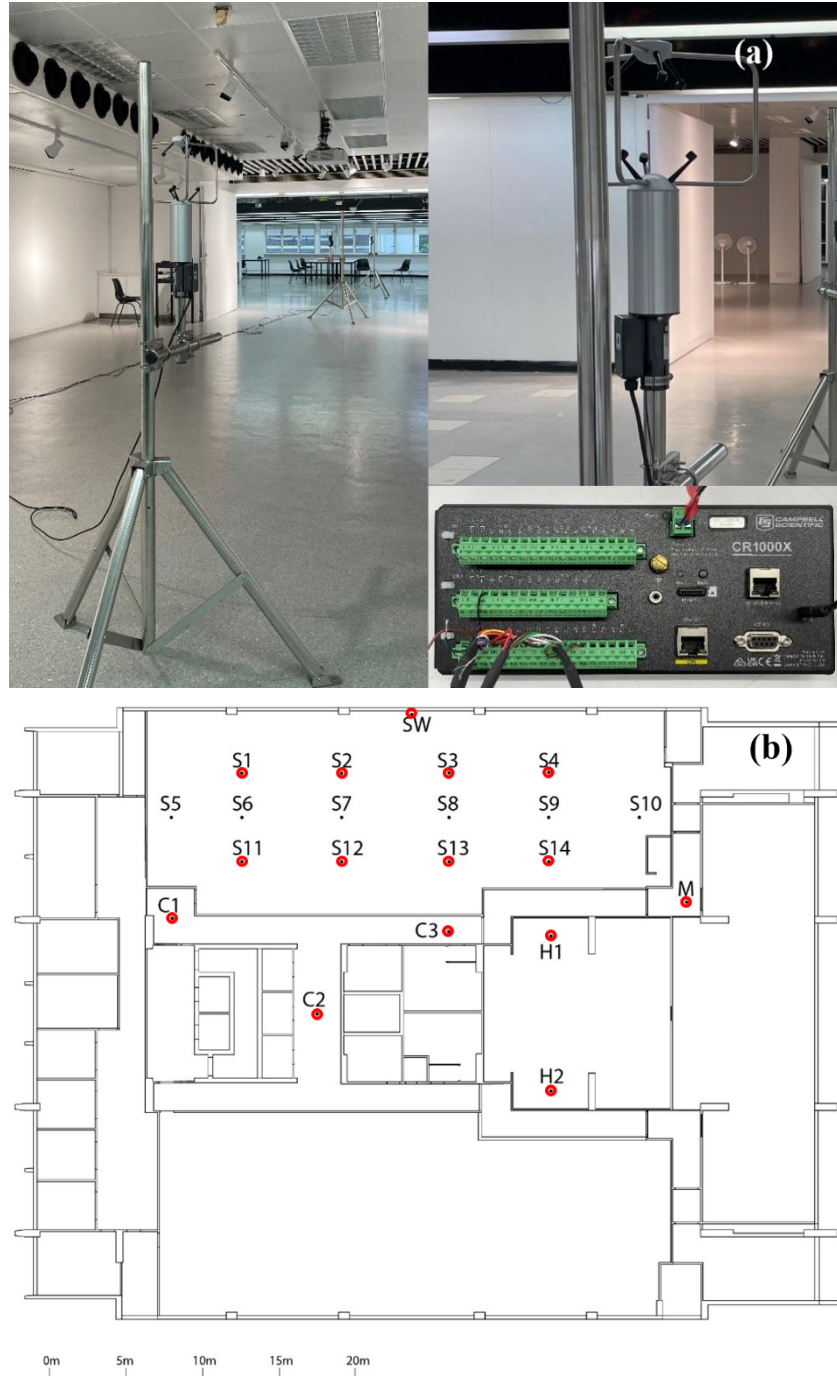


Fig. 4. (a) Monitoring system of anemometers. **(b)** Positions of critical spots on the floor plan of the test bed in areas around the Eastern Studio (positions of anemometers are marked with red circles).

2.3.2 Field measurements of CO_2

CO_2 levels were measured at displays 24 positions in the Eastern Studio (**Fig. 5(d)** light blue dots) by the Spatial Exposure Notification (SEN) devices (**Fig. 5(a)**) (integrated with CO_2 sensor module (**Fig. A.3**)) attached to the lampshade at a height of 2.15 meters. Furthermore, considering the impacts of air leakage in cracks of buildings on ventilation rates [45], CO_2 readings of the door

cracks at the Eastern Studio's main entrance were obtained using a mobile detector (Fig. 5(b)). Technical specifications of the CO₂ sensor and mobile CO₂ detector are presented in Table A.5 and Table A.6, respectively.

The experiment restricted student access to classrooms as per Section 2.3.1, while one individual remained in the Eastern Studio near Sensor No.13 (pink dot in Fig. 5(d)). A CO₂ generator, simulating an adult exhaling 250 ml/min of carbon dioxide [46,47], was installed (Fig. 5(c)). CO₂ levels of the HVAC systems (Table A.7) were measured using a mobile CO₂ detector (Fig. 5(b)) at various locations, including door cracks. Notably, the outdoor reading was 397 ppm, and readings below this value were considered sensor errors since fresh air supply registers draw air directly from the outdoors.

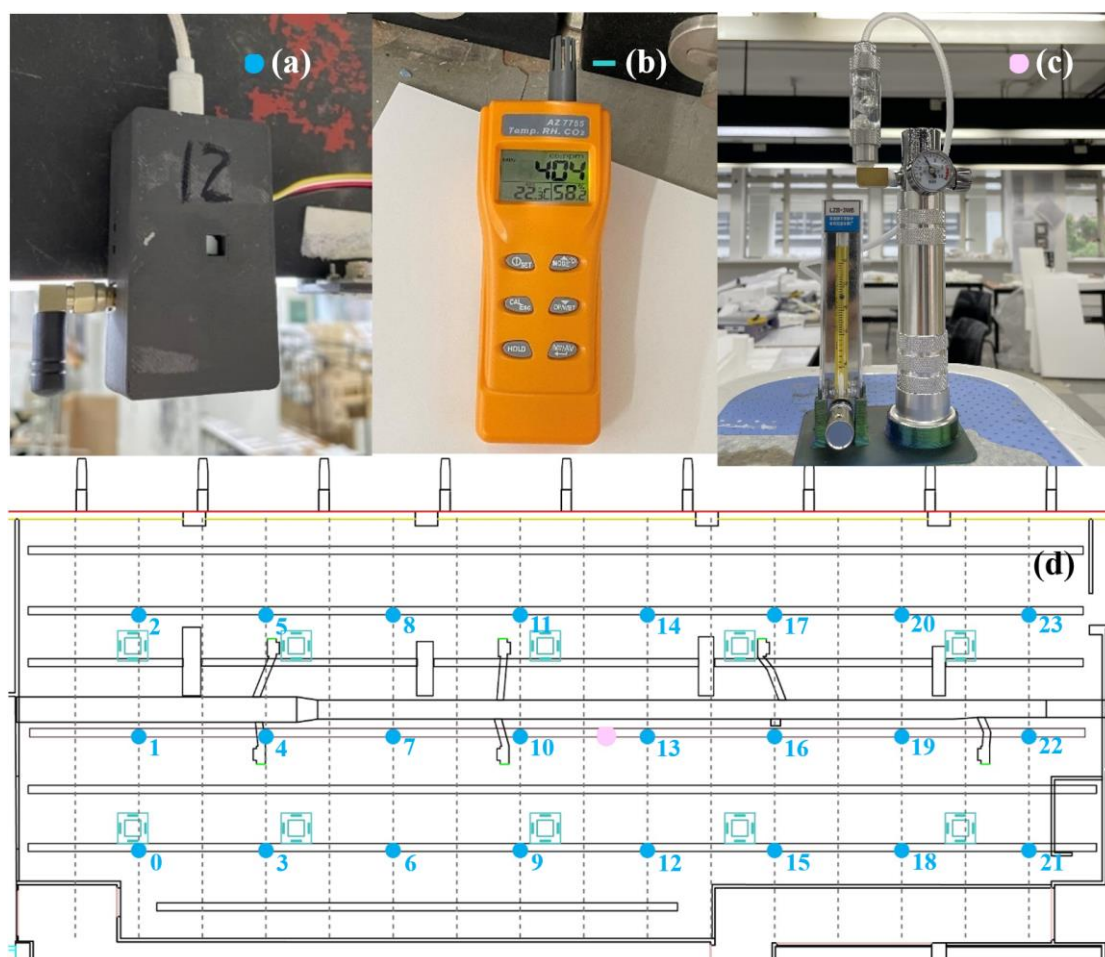


Fig. 5. (a) Monitoring system for CO₂ concentration. (b) Mobile CO₂ detector. (c) CO₂ generator. (d) Positions of the matrix of CO₂ sensors in the Eastern Studio at the height of 2.1 m (top view).

2.4 Numerical modeling and comparison with measurements

This study included Computational Fluid Dynamics (CFD) analysis using *AKL FlowDesigner 2020*

Update 2 [48] to investigate airflow patterns in the classrooms. The 3D simulation software evaluates indoor and outdoor urban microclimates with a high-precision, high-performance algorithm based on *SIMPLE-C*, automatic mesh generation, and visualization capabilities for airflow, CO₂ concentrations, and contamination distribution [49]. *AKL FlowDesigner* offers rapid and reliable calculations, performing well in comparison to other major CFD software such as *Ansys Fluent* and *PHOENICS*, as demonstrated in several studies [50,51]. A three-dimensional numerical analysis was conducted to assess indoor airflow and airborne disease transmission in large university classrooms.

2.4.1 Computational geometry and CFD setups

Fig. 6 presents the computational domain and boundary conditions, based on the material properties of classrooms and ventilation conditions provided by the HVAC systems on the 3rd floor of Knowles Building. The total air supply rate of 579 m³/hour from all fresh air supply inlets in the Eastern Studio was derived from measurements (**Table A.8**) at each HVAC device. The air is extracted through the exhaust ducts/fans (fans were switched off). Detailed boundary conditions can be found in the supplementary documents (**Table 1** and **Table A.1**), indicating an overall fresh air ventilation rate of 0.407 AC/hour. Air supply from each supply device is assumed to be constant and evenly distributed on the inlet interface. An outdoor air temperature of 27°C was applied to this model, corresponding to the monthly and daily average temperature in Hong Kong, and the initial condition of the model domain was assumed at the standard atmospheric pressure. The computational domain encompasses non-office areas such as three classrooms, a Hallway Room, a corridor, and all ventilation system inlets and outlets (**Fig. 6**). *AKL FlowDesigner*'s meshing program was used to generate the computational grid based on this domain, employing a tetrahedral grid (**Fig. A.4**). All walls maintain their real thickness, as derived from construction drawings. A 5,000,000-element grid was created and utilized for the numerical simulations.

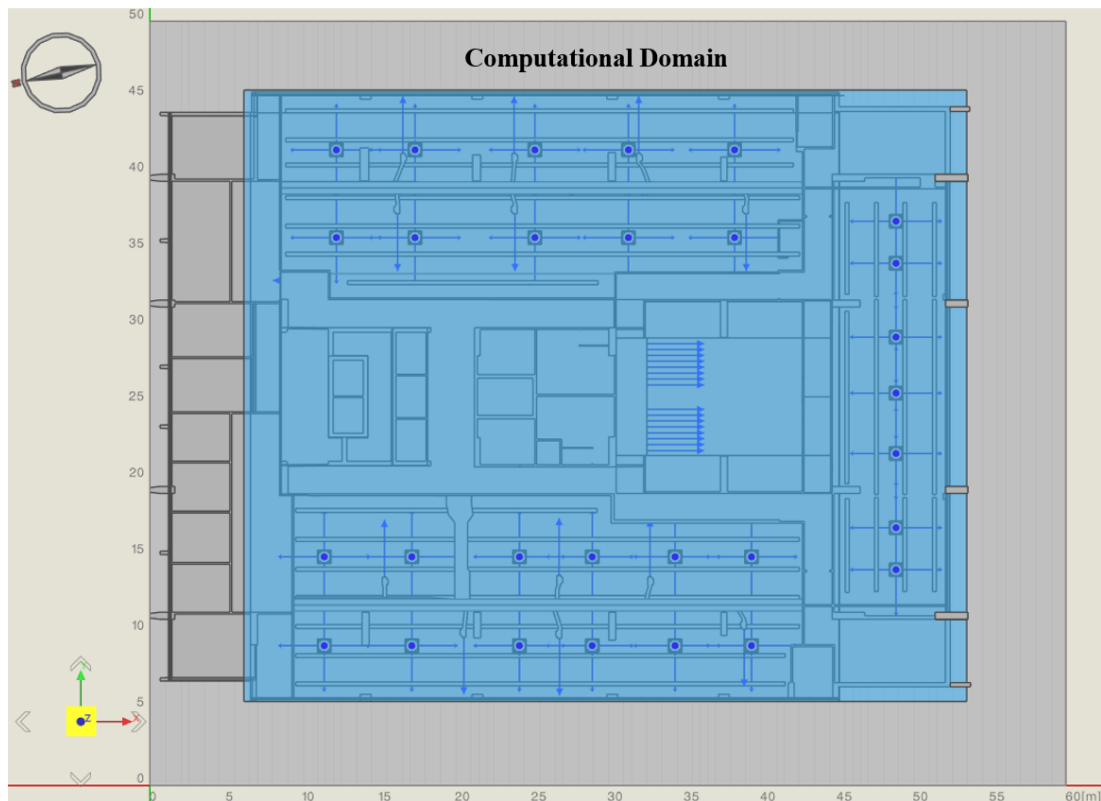


Fig. 6. Computational domain in CFD model.

2.4.2 Comparison with measurements and model validations

The CFD model's accuracy in predicting air speed is validated by comparing simulated and measured values at 15 observation points on a 1.5-meter-high plane in the Eastern Studio. In this test, the room was unoccupied, and the furniture was removed to avoid the airflow barriers. All simulated results were obtained for a steady-state situation. **Table A.9** compares measured and simulated airflow speeds at the 15 observation points, and **Fig. 7** illustrates the model's effectiveness, showing a reasonable agreement between simulated and measured data. The Root Mean Square Error (RMSE) of 0.019 is calculated, and Pearson's r value is 0.756, indicating the high reliability of the CFD model in predicting airflow speeds.

The simulated CO_2 concentration of a single individual condition is presented in **Fig. 8**. The individual stood at the pink dot (near Sensor No.13), which is close to both the center of the classroom and the Hallway room, as shown in **Fig. 5(d)** and **Fig. 8**. Indoor CO_2 concentrations were measured using the matrix of CO_2 sensors as described in *Section 2.3.2*, with average values of five minutes stable readings obtained during the experiment, as shown in **Table A.10**. **Fig. 9** shows a strong correlation between measured and simulated CO_2 concentrations, with a Pearson's r value of

0.748. The measured-predicted differences range from 1 *ppm* to 13 *ppm*, with an RMSE value of 6.403. In conclusion, the developed model has been verified to estimate CO₂ concentrations with relatively high accuracy, thereby validating the numerical CFD model for this application.

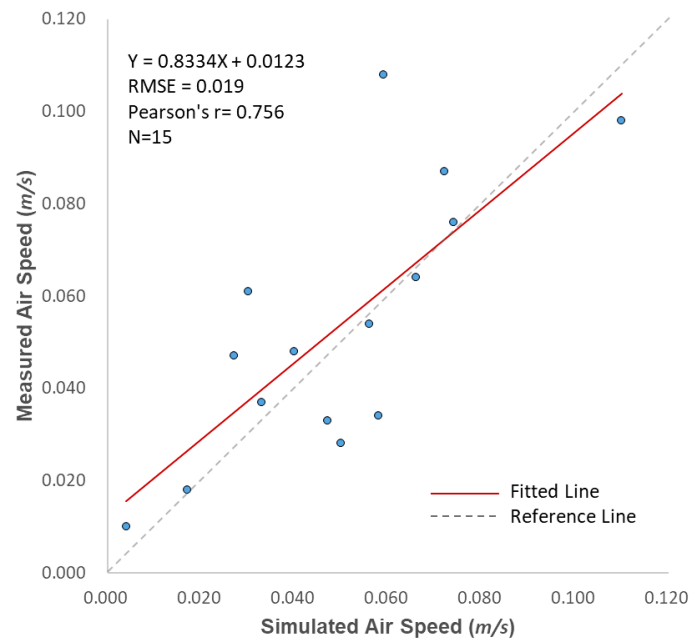


Fig. 7. Scatter plots of the measured and simulated airflow speed at 15 observation points (at a height of 1.5m).

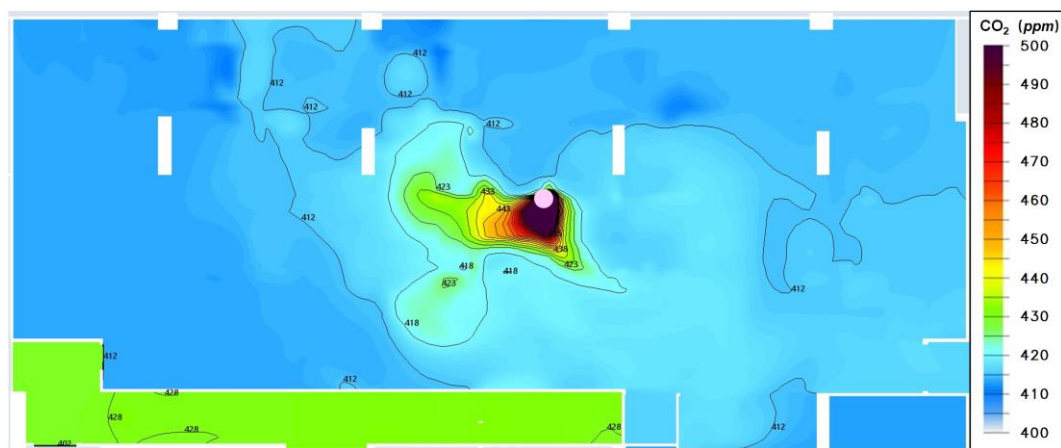


Fig. 8. The simulated CO₂ concentration in the Eastern Studio with one individual (pink dot) around Sensor No.13.

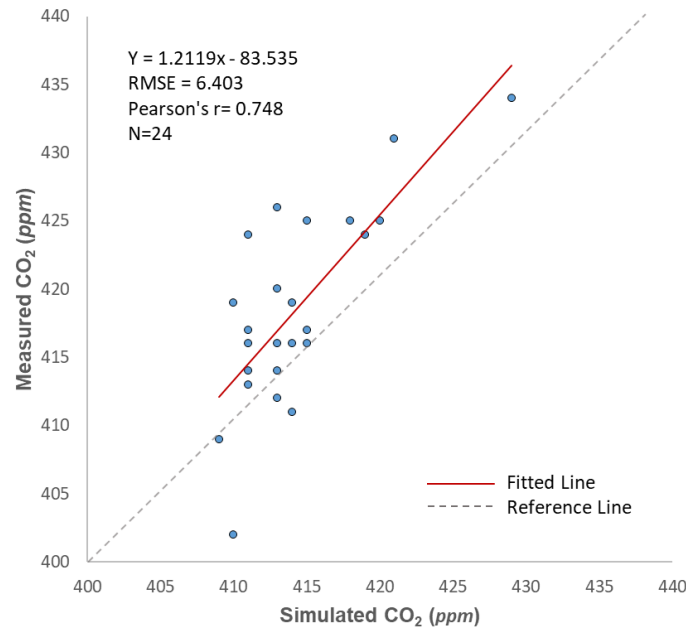


Fig. 9. Scatter plots of the measured and simulated CO₂ concentration values at 15 observation points (at a height of 2.1m).

2.5 Classroom configurations of five scenarios

To investigate the impact of airflow on viral particles and CO₂ concentration, a simulation condition featuring 64 individuals evenly distributed in the Eastern Studio was designed, including one virus-emitting patient (located at the pink dot in **Fig. 5(d)** and **Fig. 10(a)**). Each of the five scenarios was based on a typical working day with full attendance for architectural design students. The fresh air ventilation rates were set to be 2.51 l/s/person. This is low compared to the ASHRAE recommendations, the 'inadequate ventilation issue' is frequently found in other classrooms in Hong Kong [24], and it is believed that the low occupancy rate issue has been considered in scheduling the operating ventilation rates. *Scenario 1* is a control group with all windows and doors closed (except for the doors of the Southern Room and the Hallway). The other four scenarios were designed to investigate the impact of opening behavior on airborne disease control. **Table 2** details the window and door settings in three classrooms across the five scenarios, each scenario has been applied with 64 occupants and a fully working HVAC system. The CO₂ and viral particle concentration simulations are conducted based on the configurations of those five scenarios accordingly.

As measured or derived from existing literature, the quanta emission rates of an infected person range from 31 quanta/hour in speaking conditions [52] to 60 quanta/hour during heavy activities [53]. Some researchers have reported an emission rate of up to 142 quanta/hour for asymptomatic infectious SARS-CoV-2 [52], which is applied in this analysis to evaluate an 'extreme condition'.

Alongside an inhalation rate (IR) of $0.54 \text{ m}^3/\text{h}$ [52], the viral load of particles (quanta inhaled) in this study is calculated to be $263 \text{ quanta}/(\text{m}^3 \cdot \text{h})$, which is the load of airborne viral particles a 'patient' exhales from their mouth, and a $3.80 \text{ cm} \times 1.37 \text{ cm}$ oral surface [46] is modelled in the simulation models. At the same time, the CO_2 emission of $40,000 \text{ ppm}$ [47] has been applied to each individual in this study. We are assuming the same distribution behaviors between CO_2 and viral particles from the same individual, as the two elements are both driven by convection currents of air, and we do not take account of dispersion.

Table 2. Configuration of windows and doors in five scenarios.

<i>Ventilation Scenarios</i>	<i>Scenario 1</i>	<i>Scenario 2</i>	<i>Scenario 3</i>	<i>Scenario 4</i>	<i>Scenario 5</i>
Windows (the Eastern Room)	CLOSED	CLOSED	OPEN	OPEN	OPEN
Doors (the Eastern Room)	CLOSED	OPEN	CLOSED	OPEN	CLOSED
Windows (the Western Room)	CLOSED	CLOSED	CLOSED	CLOSED	OPEN
Doors (the Western Room)	CLOSED	CLOSED	CLOSED	CLOSED	CLOSED
Windows (the Southern Room)	CLOSED	CLOSED	CLOSED	CLOSED	OPEN
Doors (the Southern Room)	OPEN	OPEN	OPEN	OPEN	OPEN
Doors (the Hallway)	OPEN	OPEN	OPEN	OPEN	OPEN

3. Results

3.1 Steady-state indoor airflow in Scenario 1:

Fig. 10(a) shows the air velocity at a height of 1.5 m, and velocity magnitudes range from 0.1 to 0.6 m/s. The predicted velocity field is shown in **Fig. A.5**. The 16 cylindrical fresh air supply registers (circular cross-sections with diameters exceeding 0.25 meters and airspeeds above 1 m/s) are in the ceiling at the floor's center (Hallway), and they generate high-velocity air streamlines (approximately 0.3 to 0.6 m/s). Air passes from the hallway doors into the Eastern and the Western rooms at speeds above 0.2 m/s, and two streams of air with speeds around 0.3 m/s enter the South Studio from the Eastern Studio and the Western Studio, respectively. Consequently, the Hallway room serves as an indoor airflow source for the floor, generating and enhancing airflows in all three classrooms. These strong airflows primarily dictate the spatial airflow distribution throughout the U-shaped classroom spaces.

Airflow streamlines beneath coil units in three classrooms exhibit diverse interactions and merging patterns due to uneven distribution and disparate working conditions. The arrangement of fan coil

units adds complexity to indoor airflow distribution in horizontal and vertical sections. **Fig. 10(b)** and **Fig. 10(c)** show high-speed airflows (sometimes $>3 \text{ m/s}$) from fresh air registers and fan coil units, which typically descend, disperse, and decelerate to $<0.5 \text{ m/s}$. Streamline directions vary significantly, causing uneven distribution at lower heights. 'Small islands' with air speeds between $0.2\text{-}0.3 \text{ m/s}$ are observed beneath each fan coil unit (**Fig. 10(a)**), with speeds in these areas around or below 0.3 m/s , falling within the comfortable airspeed zone ($<0.5 \text{ m/s}$) [54,55]. **Fig. 10(d)** demonstrates that large lamp shades surrounding fan coil units obstruct airflow at certain angles, contributing to the uneven distribution pattern (more 'I'-shaped than 'cross'-shaped) in **Fig. 10(a)**.

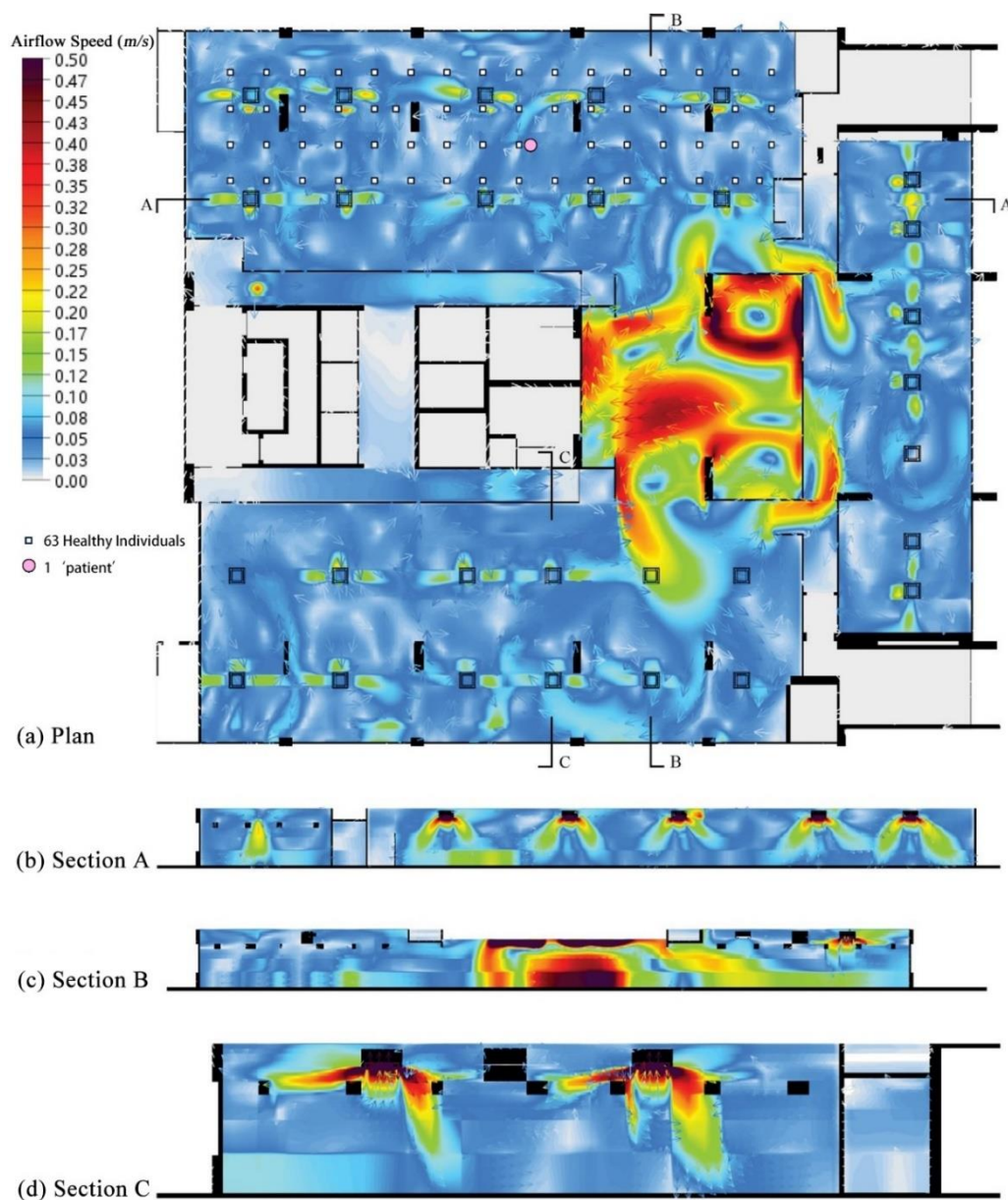


Fig. 10. (a) The air velocity at a height of 1.5m. **(b)** The airstreams on Section A (North-South). **(c)** The airstreams on Section A (East-West). **(d)** The airstreams around fan coil units and the lamp shed.

3.2 Results of CO₂ and viral particle level in Scenario 1

Fig. 11 and **Fig. 12** present the predicted CO₂ concentration and viral particle profiles, respectively, demonstrating significant impacts of airflow streamlines on their distribution patterns. Similar geometric features are observed in both maps, showing opposite trends compared to the airflow distribution maps (**Fig. 10(a)**). The 'yellow' and 'red' locations in **Fig. 10(a)** serve as 'safe islands' for effectively mitigating airborne disease accumulation. Previous studies suggest a close relationship between CO₂ concentrations and airborne particles [20,56]. In the 'one individual condition', the distribution of viral particles within the Eastern Studio (**Fig. A.6(a)**) exhibits patterns resembling the CO₂ concentration profile. Thus, CO₂ concentration levels can be assumed to indicate viral particle presence (**Fig. A.6(b)**). The reason for the concentration pattern difference between **Fig. 11** and **Fig. 12** is that there is only one virus source from the 'patient' whereas there are multiple CO₂ sources from each of the 64 individuals.

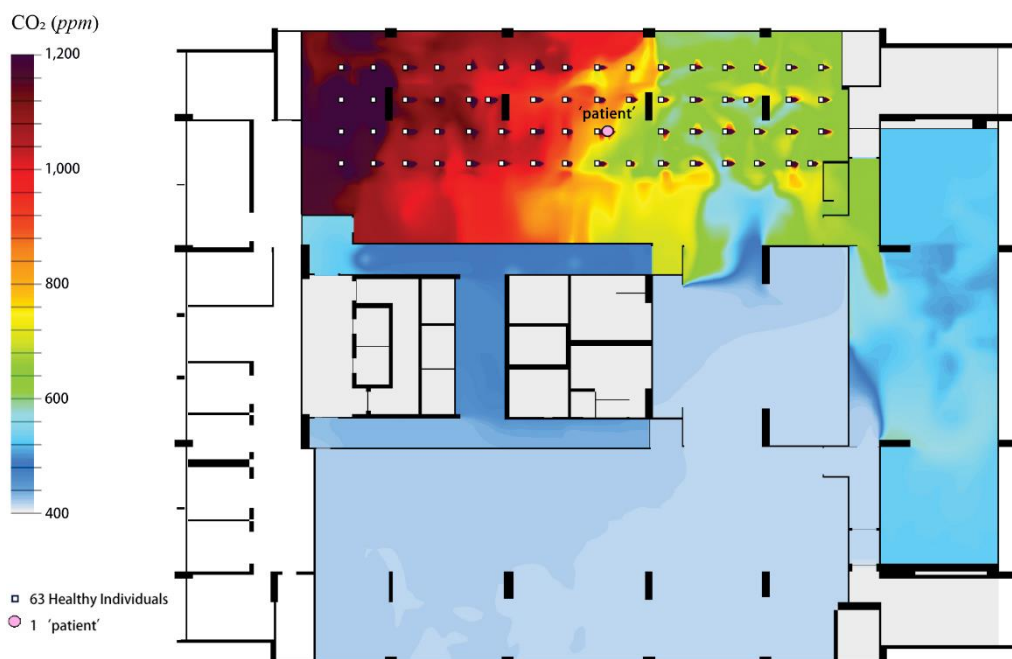


Fig. 11. The simulated CO₂ concentration across the target areas with 64 individuals in the Eastern Studio (Scenario 1).

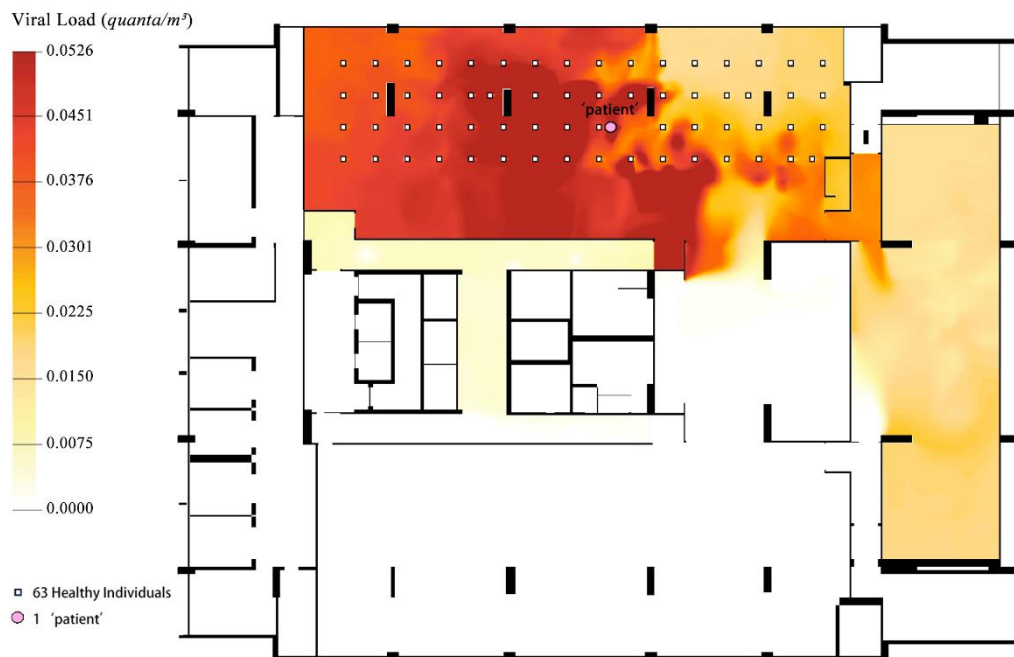


Fig. 12. The simulated viral particles spread across the target areas with 63 healthy individuals and 1 infected 'patient' in the Eastern Studio (*Scenario 1*).

3.3 Results of CO₂ concentration and viral load in five scenarios and comparisons

3.3.1 The estimated CO₂ concentration

Table 3 shows CO₂ concentration ranges from 412 to 1202 ppm in *Scenario 1* at various critical points. Compared to *Scenario 1*, *Scenarios 2* and *5* exhibit increased and decreased CO₂ concentrations at different locations. *Scenario 2* has reduced concentrations in the northern and middle sections of the Eastern Studio but increased in the southern part and corridor spaces. *Scenario 3*, with windows open. There are decreased CO₂ concentrations at all 21 points, with the most significant reduction at S5, S6, and SW. Opening both windows and doors (*Scenario 4*) results in greater reductions at points further from the windows than in *Scenario 3*, suggesting this is the most effective measure for mitigating CO₂ concentrations at the whole floor scale. *Scenario 4* also exhibits reductions at all 21 points compared to *Scenario 2*, emphasizing the importance of window opening ventilation. The most significant reduction in this scenario occurs at S5 (728 ppm). In *Scenario 5*, where windows are open (but doors remain closed) in all studios facilitating the cross-ventilation condition on the floor, the decreases in CO₂ concentrations are less significant at most points compared to *Scenario 4*, with insignificant increases in the southern part of the Eastern Studio. **Table 3** highlights reductions at H1, M, and SW in all scenarios, while minor variation is observed at H2. This result indicates that opening windows and doors effectively mitigates CO₂ concentration

366 at the boundary positions of the Eastern Studio.

367 **Table 3.** Estimated CO₂ concentration (*ppm*) at critical points by scenarios (differences to *Scenario 1*).

Critical Spots	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
S1	1089	-49	-582	-547	-528
S2	990	-49	-434	-425	-272
S3	826	19	-337	-300	-227
S4	681	80	-131	-109	-140
S5	1202	-108	-618	-728	-580
S6	1065	-51	-506	-600	-425
S7	1045	-244	-387	-509	-137
S8	690	7	-66	-209	129
S9	614	76	-101	-148	24
S10	631	169	-21	-37	87
S11	1014	-209	-446	-574	-411
S12	926	-155	-400	-467	-326
S13	765	-65	-270	-338	-162
S14	578	-8	-105	-154	86
C1	529	357	-97	-107	-96
C2	457	197	-27	-42	-27
C3	479	94	-49	-52	-49
H1	600	-126	-181	-188	-85
H2	412	-1	-1	-2	3
M	657	-32	-250	-250	-203
SW	998	-96	-584	-468	-406

368 **Table 4.** Estimated viral load (*quanta/m³*) at critical points by scenarios (differences to *Scenario 1*).

Critical Spots	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
S1	0.0398	-0.0233	-0.0397	-0.0311	-0.0179
S2	0.0582	-0.0385	-0.0576	-0.0382	-0.0199
S4	0.0360	-0.0162	-0.0258	0.0168	-0.0163
S4	0.0168	-0.0019	-0.0003	-0.0164	-0.0070
S5	0.0396	-0.0228	-0.0396	-0.0390	0.0015
S6	0.0438	-0.0245	-0.0435	-0.0427	0.0008
S7	0.0533	-0.0266	-0.0526	-0.0441	-0.0079
S8	0.0382	0.0096	0.2639	-0.0157	0.8926
S9	0.0272	-0.0074	-0.0047	-0.0272	-0.0172
S10	0.0283	-0.0052	-0.0275	-0.0282	-0.0207
S11	0.0456	-0.0171	-0.0453	-0.0451	-0.0085
S12	0.0542	-0.0227	-0.0524	-0.0529	-0.0185
S13	0.0447	0.0069	-0.0350	-0.0445	0.0084
S14	0.0279	-0.0053	-0.0168	-0.0279	-0.0058
C1	0.0070	0.0179	-0.0070	-0.0070	-0.0070
C2	0.0047	0.0174	-0.0047	-0.0047	-0.0047
C3	0.0068	0.0329	-0.0068	-0.0068	-0.0068
H1	0.0324	-0.0180	-0.0318	-0.0324	-0.0191
H2	0.0002	-0.0002	-0.0002	-0.0002	0.0001
M	0.0314	-0.0174	-0.0314	-0.0314	-0.0294
SW	0.0468	-0.0304	-0.0466	-0.0186	-0.0329

369 3.3.2 The estimated viral particles.

370 **Table 4** shows the estimated viral particle concentration in the Eastern Studio across five scenarios.

371 Compared to *Scenario 1*, opening doors (*Scenario 2*) reduces viral load at sixteen out of the twenty-

372 one observation points, but increases it at two points near the 'patient' (S8 and S13) and three at

373 points in corridors (C1, C2, and C3). In *Scenario 3*, opening windows while keeping doors closed

significantly reduces the viral load at most points, except for S8, which experiences an increase. Opening both windows and doors (*Scenario 4*) decreases viral load at twenty locations, with a slight increase at point S3. This scenario highlights the combined effects of window and door ventilation, with window ventilation having a more substantial impact on airflow redistribution. Although opening windows mitigates viral load levels, it may cause increased airborne particle accumulation in certain areas. In *Scenario 5*, the cross-ventilation by opening all windows reduces viral particles at most points to a lesser extent, although it increases concentration by more than twenty times ($0.8926 \text{ quanta/m}^3$) at S8, which is near the 'patient' as shown in **Fig. A.7**.

3.3.3 Comparisons

Comparing **Table 3** with **Table 4**, four experimental scenarios exhibit similar trends in impacting CO₂ and viral particle concentration, suggesting that window and door ventilation are effective strategies for improving IAQ and mitigating infection risks. Specifically, opening doors effectively reduces CO₂ and viral particle concentration in the Eastern Studio by diluting the two elements into corridor spaces. On the other hand, the open of windows significantly redistributes indoor airflows, which can most effectively optimize the indoor environment conditions.

3.4 Quanta emission and transmission route by scenarios

The simulated viral concentration across the classrooms on the 3rd floor is visualized in **Fig. 13**, illustrating the airborne transmission route and viral load, resulting from viral particles emitted by the patient investigated in *Section 3.3*.

In *Scenario 1*, with doors and windows closed, the virus originates from the Eastern Studio and diffuses into the Southern Studio, with a viral load of $10^{-2} \text{ quanta/m}^3$ observed in more than 90% of the space. A relatively minor virus spread occurs in the Hallway room, indicating the effectiveness of a large supply of fresh air dilution. In *Scenario 2*, with doors opened, the viral load increases to $10^{-2} \text{ quanta/m}^3$ in the corridor spaces, while less virus accumulates (a reduction to $10^{-3} \text{ quanta/m}^3$) in the Southern Studio, making the corridor a 'relief area.' However, infection risk heightens near the infected person with a $10^{-1} \text{ quanta/m}^3$ virus load. *Scenario 3*, with windows opened and doors closed, significantly reduces infectious areas in the Eastern Studio. The 'fresh air wall' functions efficiently, as the virus is contained and removed through the nearest windows. In *Scenario 4*, with extra doors opened, the virus is driven by airflow to the window areas and outdoors. Opening doors

reshapes indoor airflow distribution but does not significantly impact the effect of diluting the virus by opening windows. Compared to *Scenario 1*, in a cross-ventilation condition of *Scenario 5* by opening all windows, the infection stress is relieved in the southern part of the Eastern Studio and the Southern Studio, where the viral load dropped to 10^{-3} *quanta/m³* level or even lower from *Scenario 1*'s 10^{-2} *quanta/m³*, however, the virus at the 10^{-3} *quanta/m³* load spread more widely in the Hallway.

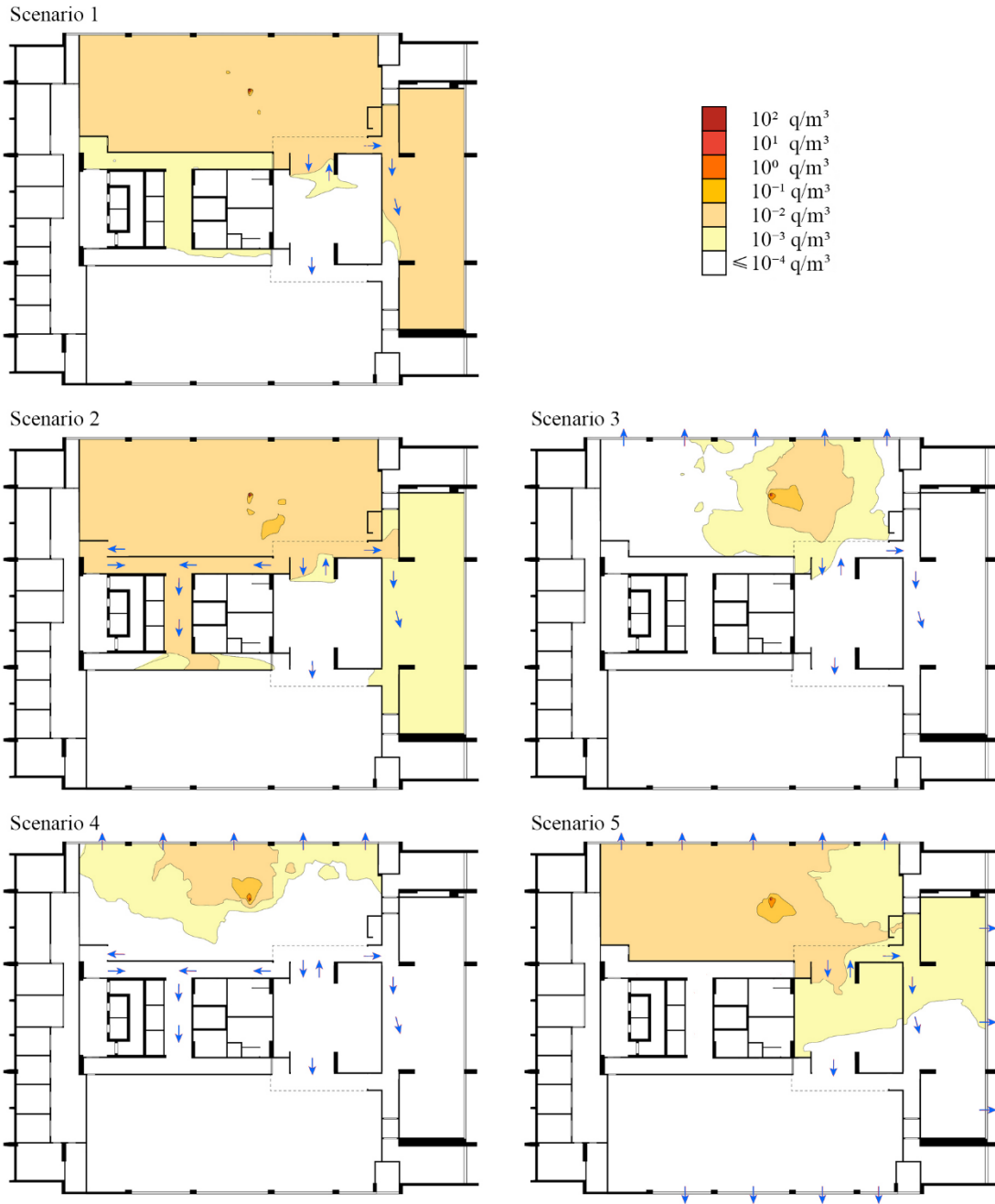


Fig. 13. Predicted transient viral concentration at room level in five scenarios.

According to **Fig. 13**, opening windows and doors generally provides a ventilation advantage,

facilitating the dilution of viral air, which exhausts through windows. However, excessive use may prove counterproductive, as demonstrated in *Scenario 2* and *5*, posing a threat to staff in the office area and weakening the effectiveness of opening windows in the Eastern Studio, respectively. Higher viral loads (10^{-1} quanta/ m^3) and infection probabilities in the areas around the ‘patient’ have been observed in all four experimental scenarios, which can be explained by airflow reconfiguration due to the opening of windows and doors leading to downdrafts of particles (**Fig. A.7**).

3.5 Infection risk by scenario

Understanding the transmission patterns of viral particles, particularly those originating from infectious sources, in enclosed environments is essential for enhancing public health measures and infrastructure modifications. In addition to the transmission route and dynamics, the viral load serves as another critical factor for analyzing indoor infection risks. Risk evaluation of transmission and infection risk calculations are required to assess the probability of infection. The infection risk model utilized in this study adopts the widely recognized Wells-Riley-like approach [57] which is extended in the Gammaitoni-Nucci (GN) model [58] that considers the temporal evolution of the viral load.

3.5.1 Calculation of probability

By introducing the assumption that quanta are emitted at a constant rate throughout the experiment, and that the infectious quanta can be transported and removed by ventilation systems, integrated with the Wells-Riley (WR) model [59], the probability of infection p , can be calculated:

$$p = 1 - e^{-n} \quad (1)$$

where

p the probability of infection for susceptible person

n quanta inhaled (quanta).

The quanta inhaled (n , quanta) is the product of the time-average quanta concentration (C_{avg} , quanta/ m^3), the volumetric breathing rate of an occupant (Q^b , m^3/h) and the duration of the occupancy (D , h) [60], which is expressed as:

$$n = C_{avg} Q_b D \quad (2)$$

The air and viral particles were assumed to be well-mixed, following the assumption of the WR

approach. Given that architecture students have extended working hours throughout the week [61], three types of schedules—8 hours, 4 hours, and 1 hour—were defined in this study to represent usage scenarios (one day, half day, and a lecture period) in daily studio work. Based on the quanta emission rates, the results of the probability of infection over 8 hours are depicted in **Fig. 14**, where more than 95% probability of infection risk is estimated in areas with a viral load of 10^0 quanta/ m^3 or higher.

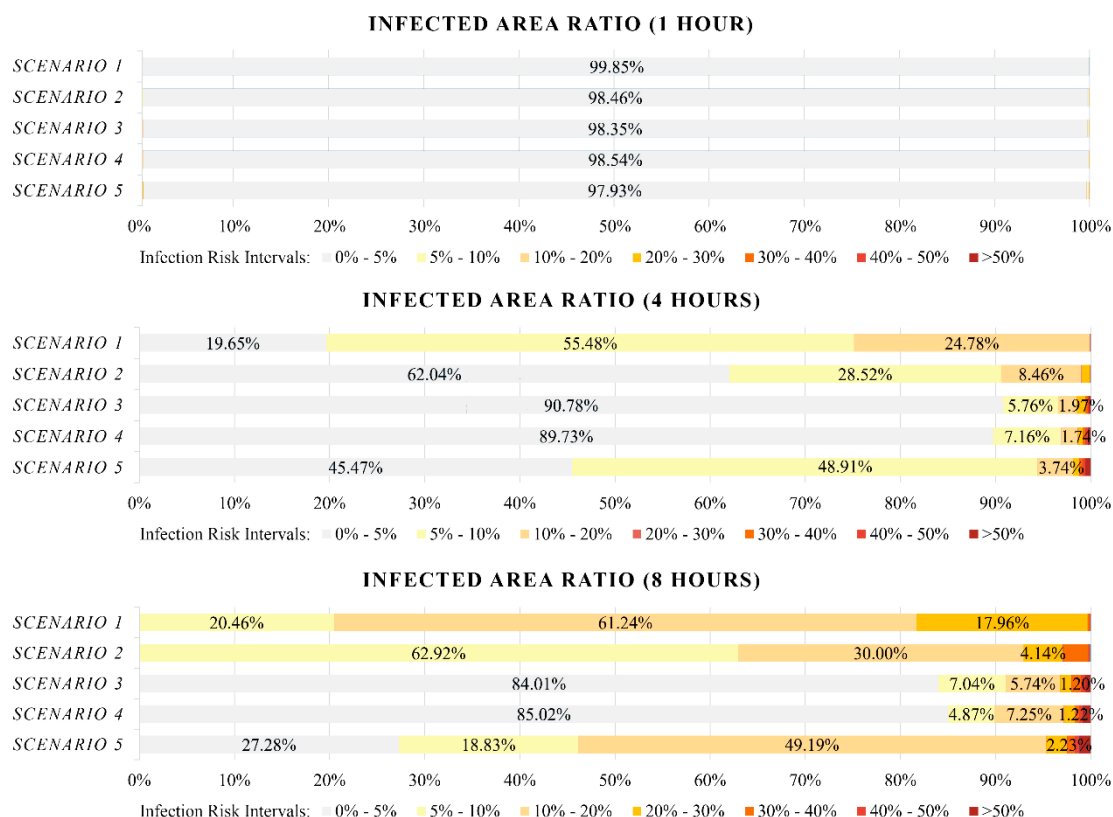


Fig. 14. The proportion of the total area of the Eastern Studio with certain ranges of infection risks of exposure in 5 different scenarios in 1 hour (*top*), 4 hours (*middle*), and 8 hours (*bottom*).

3.5.2 Three durations

The factor "Area Ratio of certain probability" is introduced in this study to depict the macroscopic state of infection risks in the Eastern Studio under various scenarios. **Fig. 14** shows the estimated infection probabilities were divided into seven intervals, and it demonstrates the variations in area proportions of each risk interval across five scenarios in three different durations (1h, 4h, and 8h), which quantifies the impacts of the distinct behaviors related to opening windows and doors. For the 1-hour duration, low infection probabilities (0%-5%) are observed in substantial areas (exceeding 97%) of the Eastern Studio across all scenarios. Opening windows or doors does not

significantly mitigate infection risks for this duration. For the 4-hour duration, classrooms with open windows (*Scenarios 3, 4, and 5*) consistently exhibit larger regions of lower infection risk (probabilities of 5% and below). However, in the meanwhile, classrooms with open windows display a more extensive area with high infection risks (probabilities of 30% and above), with the area ratio increasing to 1.22% (*Scenario 5*). For the 8-hour duration, opening windows or doors substantially reduce infection risk and decreases infectious areas. Opening windows (*Scenario 3, 4, and 5*) dramatically increases the area ratio with statistically insignificant infection risk (probabilities of 5% and below). In *Scenario 4*, adding door-opening measures to *Scenario 3* only marginally impacts the area ratio across all probability intervals, reaffirming the dominant role of opening windows.

An enhanced ventilation mode, cross-ventilation, by opening additional windows on the southern and the western sides of the floor (as depicted in *Scenario 5*) may potentially accelerate air circulation. However, as observed in the study, this approach significantly reduces the area ratio with low infection risk (probabilities of 5% and below) by approximately 50% for both 4-hour and 8-hour durations. These findings underscore the need for consistent and appropriate window ventilation in classrooms for extended periods and the significance of a balanced approach for opening windows to optimize airflow and minimize infection risk.

4. Discussion

4.1 Open the window or open the door

The findings of *Sections 3.3, 3.4, and 3.5* emphasize the importance of window ventilation in maintaining air circulation, minimizing CO₂ and viral particle accumulation, and reducing infection risk in classrooms. Window ventilation is shown to be more beneficial in the condition of insufficient mechanical ventilation (ventilation rates of 2.51 l/s/person in this study). However, indoor airflow distribution is crucial for investigating airborne diseases, as opening windows and doors can increase infection risks in certain areas near the 'patient.' Therefore, infection risk analysis should consider the overall performance of each measure and local conditions within a limited area, selecting representative sampling zones when designing ventilation strategies.

In addition to *Scenario 3*, increasing ventilation rates by opening extra windows in nearby rooms

(*Scenario 5*) did not further mitigate the infection risk in the Eastern Studio. Instead, it increased the infection risk and significantly caused the virus to spread more widely. Therefore, the mitigation strategy of opening windows in mixed ventilation systems should be optimized, considering occupancy arrangements and airflow distributions. Opening more windows in large spaces potentially has a negative impact on mitigation performance and is not always recommended. This finding substantiates the imperative of monitoring airflow patterns and CO₂ concentrations, thereby highlighting the authentic requirement and significance of incorporating our SEN system within educational indoor spaces.

4.2 Roles of airflow

Fig. A.8 displays grey and blue dots representing viral particle concentration levels and speed at 1.5-meter elevations in the Eastern Studio, and **Fig. A.9** shows the effective areas of a fan coil unit. Grey dots form distinct clusters, including a blue dot cluster. Blue dots, with two corresponding trend lines, are grouped into two categories based on their viral particle concentrations (ranging from 0.015 *quanta/m*³ to 0.115 *quanta/m*³). Trend Line One and Line Two reveal that speed values can negatively and positively affect viral particle concentrations, suggesting that airflow can dilute and exacerbate viral load levels under different conditions. The 'Double Roles of Airflow' [30] refer to two mechanisms in air movements: the 'removal role' and the 'transport role.' The 'transport role' involves airflow carrying viral particles, while the 'removal role' entails fresh air from HVAC system inlets diluting infectious air. In **Fig. A.9**, Trend Line One demonstrates the 'removal role,' with higher airspeed values corresponding to lower viral load values. This suggests that low airflow speed (in those lampshade-blocked spaces, as shown in **Fig. 10(d)**) could cause increased viral infection risk. Conversely, Trend Line Two indicates the 'transport role', with higher speed values associated with increased viral load estimates. Viral particle concentrations under each fan coil unit exhibit similar distribution patterns, corroborating the findings of airflow distribution in **Fig. 10(a)** and *Section 3.1*.

4.3 Air leakage through door cracks into connective space

Door and door frame cracks are vital for analyzing indoor airflow and air quality [45]. These cracks enable excess indoor air to escape due to positive pressure maintained by the HVAC system's fresh air supply. Air leakage from classrooms to corridors, observed in on-site measurements and simulations, results from these cracks. Indoor connective spaces, such as corridors, significantly

influence architectural traffic streamline planning and design due to high pedestrian flow and potential exposure. Therefore, door cracks in such spaces should be considered when assessing infection risk.

This study found that air leakage into corridor areas at speeds around or below 1.0 m/s introduced low-level quanta emissions (10^{-3} quanta/m³) near office entrances and lifts, making corridors a "relief area" for air pressure and airborne diseases. Door opening increased viral loads in corridors to 10^{-2} quanta/m³, emphasizing the need to enhance corridor ventilation to mitigate airborne transmission and cross-infection in connective spaces, potentially preventing vertical transmission between floors via lifts [62]. Future research could investigate transmission mechanisms in traffic streamline spaces (both horizontal and vertical) within educational buildings.

4.4 Building codes and local regulations

Although early startup and operation of HVAC systems are recommended as pandemic response strategies in building codes and regulations worldwide [63], the implications of opening windows in mechanically ventilated rooms remain debatable. Window-opening behaviors may reduce HVAC system efficiency and increase energy consumption [39,63]. While local building codes and regulations do not explicitly prohibit window opening, they address indoor temperature, thermal comfort [64], and closed-window mechanical ventilation rates [65]. Hong Kong's local guidelines advise adjusting and controlling HVAC systems in unexpected situations to ensure proper functioning, prevent safety hazards, and develop alternative emergency management plans [66]. Future research could investigate the comprehensive impacts of opening windows and doors as emergency anti-epidemic measures, providing a scientific basis for potential amendments in local building codes and regulations.

4.5 Limitations

This study acknowledges several limitations. Firstly, due to architecture students' high frequency of university classroom usage, even during non-working hours, on-site experiments were conducted within a limited timeframe, yielding only two hours of valid CO₂ concentration results in a one-occupant condition (Section 2.3.2). Secondly, the CFD models assumed perfect airtightness for external windows and ignored air leakage through closed windows (no cracks between windows and window frames). Thirdly, the study did not consider the interactions between viral particles and

potential surface deposition. Lastly, the study did not account for vertical airflow driven by the buoyancy effect and thermal properties of building materials in order to simplify the CFD models, as they were not the primary focus of the research. Future investigations are recommended to delve into the impacts of a more intricate outdoor thermal and wind environment on indoor airflow dynamics.

This research is a case study of a crowded educational space in Hong Kong. The building elements, including classroom layout, doors and windows, HVAC systems, and other building components, are configured to suit the local sub-tropical climate, addressing thermal performance, which is crucial for the results obtained in this study. The research focuses only on window and door opening behaviors and their impact on airflow and infection risk. The findings of this case study provide both quantitative and qualitative evidence for future studies and benefit the investigation of the impacts of each factor mentioned above.

5. Conclusion

This study reveals that opening windows and doors can enhance ventilation rates. In classroom Eastern Studio, opening all windows and doors in Scenario 4 effectively optimizes the indoor ventilation, which reduces CO₂ concentration by 728 *ppm* (a 60.57% reduction) and lowers the viral load by as much as 0.0529 *quanta/m³* (a 97.60% decrease) over an eight-hour period. This process decreases the size and number of infectious zones. The analysis uses 5% as a minimum level of infection risk. The most significant performance achieved in the optimization strategy of pandemic prevention is also observed in *Scenario 4*, which substantially increases the area ratio of regions with low infection risks (below 5% probabilities) to 85.02% from below 0.5% over an eight-hour period. Such reductions in infection risk and infected areas are important, especially for cases where fresh air ventilation rates are relatively low in densely occupied spaces. Of course, higher design ventilation rates should be used in line with recommended standards, but this is often not the case.

However, those opening behaviors may redistribute indoor airflows, potentially increasing infection probabilities near the ‘patient’, which can be mitigated by social distancing policies. Moreover, cross-ventilation by opening more windows in large spaces in some conditions will cause a wider spread of viral particles and increase the infection risks. Therefore, opening windows should be

571 optimized, considering occupancy and indoor airflow; simply opening more windows without
572 considering indoor airflow redistribution should be avoided.

573 In addition, this study supports using CO₂ as a valid tracer for airborne respiratory disease aerosols
574 in analyzing transmission mechanisms in university classrooms. Introducing an array of CO₂
575 detector sensors into indoor spaces can effectively warn of potential hazards and prompt measures
576 such as window opening.

577 The findings of this case study can inform future university classroom operations, retrofitting, and
578 HVAC system optimization, highlighting the potential effectiveness of mixed ventilation modes and
579 the benefits of opening windows as an emergency strategy when active measures are insufficient for
580 diluting diseases. Future studies can explore implementing automated doors and windows with
581 optimization algorithms to ensure the effectiveness of infection-mitigation measures in various
582 indoor airflow distribution and occupancy scenarios while addressing energy efficiency issues.

CRedit authorship contribution statement

Xi Deng: Writing – original draft, Writing – review & editing, Literature review, Modelling, Validations, Methodology, Investigation, Formal analysis, Project administration. **Zhihao Bao:** Literature review, Validations, Investigation, Data curation, Formal analysis, Modelling. **Shuning Chen:** Investigation, Visualization, Formal analysis. **Eric Schuldenfrei:** Conceptualization, Resources, Funding acquisition, Supervision. **Jianxiang Huang:** Software, Methodology, Formal analysis. **Phil Jones:** Writing – review & editing, Methodology, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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785 **Appendix A. Supplementary Data**

786 **Table A.1.** Collected flow speed (m/s) and temperature (°C) data of each fan coil's outlet in the Eastern
787 Studio, the Southern Studio, and the Western Studio.

Fan Coil	Top (Air Outlet)	Left (Air Outlet)	Bottom (Air Outlet)	Right (Air Outlet)
E1	2.8 m/s, 15.3 °C	3.0 m/s, 14.0°C	2.8 m/s, 16.7°C	3.6 m/s, 16.0°C
E2	2.9 m/s, 20.6 °C	3.2 m/s, 19.7°C	3.0 m/s, 21.3°C	3.3 m/s, 20.3°C
E3	3.0 m/s, 24.0 °C	3.2 m/s, 24.1°C	3.1 m/s, 24.2°C	3.6 m/s, 24.1°C
E4	3.0 m/s, 24.0 °C	3.8 m/s, 24.0°C	3.2 m/s, 23.8°C	3.3 m/s, 23.9°C
E5	2.9 m/s, 23.4 °C	3.3 m/s, 23.4°C	3.1 m/s, 22.9°C	3.2 m/s, 20.6°C
E6	2.5 m/s, 24.0 °C	2.8 m/s, 23.8°C	2.4 m/s, 24.0°C	2.7 m/s, 23.8°C
E7	1.7 m/s, 11.1 °C	2.0 m/s, 12.4°C	2.0 m/s, 11.6°C	2.4 m/s, 10.8°C
E8	2.8 m/s, 11.6 °C	3.7 m/s, 11.5°C	2.6 m/s, 12.0°C	3.0 m/s, 11.1°C
E9	3.4 m/s, 23.9 °C	3.6 m/s, 24.0°C	3.3 m/s, 24.0°C	4.0 m/s, 23.7°C
E10	3.7 m/s, 23.6 °C	4.3 m/s, 23.7°C	3.7 m/s, 23.6°C	3.8 m/s, 23.8°C
S1	Closed	Closed	Closed	Closed
S2	3.0 m/s, 13.0°C	3.0 m/s, 12.4°C	3.6 m/s, 12.7°C	2.9 m/s, 11.5°C
S3	2.9 m/s, 13.5°C	2.7 m/s, 12.1°C	3.2 m/s, 11.2°C	2.5 m/s, 12.0°C
S4	3.0 m/s, 24.1°C	2.6 m/s, 24.0°C	2.9 m/s, 23.8°C	3.0 m/s, 24.1°C
S5	Closed	Closed	Closed	Closed
S6	2.1 m/s, 13.2°C	2.0 m/s, 13.0°C	2.5 m/s, 13.0°C	1.9 m/s, 12.2°C
S7	Closed	Closed	Closed	Closed
W1	Closed	Closed	Closed	Closed
W2	3.3 m/s, 16.0°C	3.8 m/s, 16.9°C	3.3 m/s, 17.3°C	3.6 m/s, 18.1°C
W3	2.3 m/s, 21.6°C	3.1 m/s, 21.0°C	2.8 m/s, 20.9°C	3.9 m/s, 21.1°C
W4	3.6 m/s, 12.9°C	4.0 m/s, 12.9°C	3.5 m/s, 13.2°C	3.6 m/s, 13.3°C
W5	2.9 m/s, 18.0°C	3.1 m/s, 18.6°C	2.9 m/s, 18.3°C	3.5 m/s, 17.9°C
W6	2.9 m/s, 12.5°C	3.1 m/s, 11.0°C	2.8 m/s, 12.6°C	2.8 m/s, 10.9°C
W7	3.0 m/s, 12.6°C	3.3 m/s, 13.8°C	3.2 m/s, 12.3°C	3.7 m/s, 11.2°C
W8	3.2 m/s, 24.2°C	3.3 m/s, 24.1°C	3.0 m/s, 24.3°C	3.0 m/s, 24.3°C
W9	Closed	Closed	Closed	Closed
W10	3.5 m/s, 23.8°C	3.7 m/s, 23.7°C	3.3 m/s, 24.0°C	3.5 m/s, 24.1°C
W11	Closed	Closed	Closed	Closed
W12	3.2 m/s, 19.8°C	4.0 m/s, 19.2°C	3.2 m/s, 19.4°C	3.4 m/s, 18.5°C
Fan Coil	Top (Air Outlet)	Center (Air Outlet)	Bottom (Air Outlet)	-
E-1	0	0	0	-
E-2	0.5 m/s, 19.0°C	0.8 m/s, 19.1°C	0.4 m/s, 20.2°C	-
E-3	0.4 m/s, 19.4°C	0.6 m/s, 19.2°C	0.6 m/s, 19.6°C	-
E-4	0.9 m/s, 16.9°C	0.6 m/s, 17.7°C	0 m/s, 18.3°C	-
E-5	0.5 m/s, 16.2°C	1.0 m/s, 17.5°C	0.6 m/s, 18.3°C	-
E-6	0 m/s, 22.3°C	0.9 m/s, 19.2°C	0 m/s, 20.1°C	-
W-1	1.2 m/s, 19.5°C	0.6 m/s, 20.9°C	0.4 m/s, 21.5°C	-
W-2	0.5 m/s, 18.1°C	0.4 m/s, 18.5°C	1.4 m/s, 18.8°C	-
W-3	0	0	0	-
W-4	2.0 m/s, 15.0°C	0.5 m/s, 17.1°C	0.9 m/s, 17.7°C	-
W-5	0.5 m/s, 16.1°C	0.7 m/s, 15.7°C	0.8 m/s, 15.8°C	-
W-6	0	0	0	-

788 Note: Rows from E-1 to W-6 are the fresh air supplier inlets.

Table A.2. Collected flow speed (m/s) and temperature (°C) data of each cylindrical air supply's inlet in the Hallway.

Supply	Outer Ring (Air Outlet)	Inner Ring (Air Outlet)
H1	1.6 m/s, 15.3°C	1.3 m/s, 14.6°C
H2	2.0 m/s, 15.0°C	2.2 m/s, 14.6°C
H3	1.9 m/s, 15.5°C	1.9 m/s, 18.0°C
H4	1.8 m/s, 20.3°C	1.7 m/s, 20.2°C
H5	2.2 m/s, 16°C	2.2 m/s, 15.4°C
H6	1.9 m/s, 15.8°C	2.2 m/s, 14.5°C
H7	3.3 m/s, 15.7°C	3.7 m/s, 19°C
H8	3.7 m/s, 20°C	3.4 m/s, 23°C
H9	2.7 m/s, 16.9°C	2.2 m/s, 17.4°C
H10	3.0 m/s, 17.6°C	3.2 m/s, 17.3°C
H11	2.8 m/s, 20.8°C	2.9 m/s, 20.5°C
H12	1.5 m/s, 23.4°C	2.1 m/s, 23.6°C
H13	2.1 m/s, 16°C	1.7 m/s, 16.3°C
H14	2.8 m/s, 17.5°C	2.7 m/s, 17°C
H15	2.6 m/s, 17.8°C	2.5 m/s, 18°C
H16	2.1 m/s, 20°C	2.2 m/s, 21.2°C

Table A.3. Collected flow speed (m/s) and temperature (°C) data of each fan coil's outlet in the Eastern Studio, the Southern Studio, and the Western Studio.

Fan Coil	Upper Left Corner (Air Inlet)	Upper Right Corner (Air Inlet)	Lower Left Corner (Air Inlet)	Lower Left Corner (Air Inlet)	Center (Air Inlet)
E1	0 m/s, 23.0°C	0 m/s, 23.2°C	0.5 m/s, 22.7°C	0.4 m/s, 24.1°C	1.5 m/s, 23.2°C
E2	0 m/s, 23.0°C	0 m/s, 23.1°C	0 m/s, 23.4°C	0 m/s, 23.4°C	1.5 m/s, 22.8°C
E3	0.4 m/s, 24.9°C	0.5 m/s, 24.3°C	0.5 m/s, 24.7°C	0.4 m/s, 24.8°C	1.4 m/s, 24.1°C
E4	0.6 m/s, 24.1°C	0.6 m/s, 24.0°C	0.5 m/s, 24.1°C	0 m/s, 24.1°C	1.5 m/s, 24.0°C
E5	0 m/s, 23°C	0 m/s, 23.5°C	0.5 m/s, 23.9°C	0.4 m/s, 23.9°C	1.4 m/s, 23.9°C
E6	0.5 m/s, 24.0°C	0.4 m/s, 24.0°C	0.4 m/s, 24.3°C	0 m/s, 24.5°C	1.1 m/s, 24.1°C
E7	0.4 m/s, 23.3°C	0 m/s, 23.7°C	0.3 m/s, 23.6°C	0.4 m/s, 23.8°C	1.0 m/s, 23.2°C
E8	0.4 m/s, 21.7°C	0 m/s, 21.9°C	0.4 m/s, 22.5°C	0 m/s, 22.5°C	1.5 m/s, 21.4°C
E9	0.5 m/s, 23.9°C	0.5 m/s, 24.2°C	0.6 m/s, 24.1°C	0.6 m/s, 24.0°C	1.6 m/s, 23.9°C
E10	0 m/s, 23.7°C	0.7 m/s, 23.7°C	0.4 m/s, 24.1°C	0.5 m/s, 23.9°C	1.7 m/s, 24.1°C
S1	Closed	Closed	Closed	Closed	Closed
S2	0 m/s, 23.5°C	0 m/s, 23.6°C	0 m/s, 23.8°C	0 m/s, 23.6°C	1.7 m/s, 24.7°C
S3	0 m/s, 23.6°C	0.5 m/s, 23.5°C	0 m/s, 23.4°C	0 m/s, 23.7°C	1.5 m/s, 23.2°C
S4	0 m/s, 23.7°C	0 m/s, 23.7°C	0 m/s, 23.7°C	0 m/s, 23.6°C	1.6 m/s, 24.1°C
S5	Closed	Closed	Closed	Closed	Closed
S6	0 m/s, 23.4°C	0 m/s, 23.6°C	0.3 m/s, 23.6°C	0 m/s, 23.6°C	1.1 m/s, 23.3°C
S7	Closed	Closed	Closed	Closed	Closed
W1	Closed	Closed	Closed	Closed	Closed
W2	0.7 m/s, 22.5°C	0.4 m/s, 23.3°C	0.6 m/s, 23.2°C	0.4 m/s, 23.0°C	1.7 m/s, 23.3°C
W3	0.5 m/s, 23.1°C	0 m/s, 23.4°C	0 m/s, 23.7°C	0 m/s, 23.6°C	1.5 m/s, 23.6°C
W4	0.6 m/s, 19.5°C	0 m/s, 20.2°C	0.4 m/s, 21.6°C	0.4 m/s, 21.5°C	1.6 m/s, 22.1°C
W5	0 m/s, 21.5°C	0 m/s, 21.9°C	0.4 m/s, 22.2°C	0.4 m/s, 22.5°C	1.4 m/s, 23.1°C
W6	0.4 m/s, 22°C	0.4 m/s, 22°C	0 m/s, 22°C	0 m/s, 22.4°C	1.5 m/s, 21.8°C
W7	0 m/s, 15.9°C	0 m/s, 16.5°C	0.4 m/s, 16.1°C	0 m/s, 21°C	1.5 m/s, 21.3°C
W8	0 m/s, 24.3°C	0.4 m/s, 24.6°C	0.5 m/s, 24.6°C	0.5 m/s, 24.5°C	1.4 m/s, 24.1°C
W9	Closed	Closed	Closed	Closed	Closed
W10	0.6 m/s, 24.1°C	0 m/s, 24.6°C	0 m/s, 24.5°C	0.5 m/s, 24.9°C	1.8 m/s, 24.5°C
W11	Closed	Closed	Closed	Closed	Closed
W12	0 m/s, 20.8°C	0.4 m/s, 22°C	0.4 m/s, 22.8°C	0.4 m/s, 22.7°C	1.6 m/s, 22.9°C

793 **Table A.4.** Specifications of Anemometers 3D (left) and 2D (right).

YOUNG Model 81000		YOUNG Model 86000	
WIND SPEED		WIND SPEED	
Range:	0 to 40 m/s (0 to 90 mph)	Range:	0-75 m/s (156 mph)
Resolution:	0.01 m/s	Resolution:	0.01 m/s
Threshold:	0.01 m/s	-	-
Accuracy:	±1% rms ±0.05 m/s (0 to 30 m/s) ±3% rms (30 to 40 m/s)	Accuracy:	0 to 30 m/s ±2% or 0.1 m/s 30 to 75 m/s ±3%
WIND DIRECTION		WIND DIRECTION	
Azimuth Range:	0.0 to 359.9 degrees	Azimuth Range:	0-360 degrees
Elevation Range:	±60.0 degrees	-	-
Resolution:	0.1 degree	Resolution:	0.1 degree
Accuracy:	±2° (1 to 30 m/s) ±5° (30 to 40 m/s)	Accuracy:	± 2 degrees

794 **Table A.5.** Specifications of CO₂ sensors.

Parameter	Conditions	Value
CO ₂ output range	-	0-40000 ppm
SCD40 CO ₂ measurement accuracy	400 ppm - 2'000 ppm	± (50 ppm + 5% of reading)
SCD41 CO ₂ measurement accuracy	400 ppm - 5'000 ppm	± (40 ppm + 5% of reading)
Repeatability	Typical	± 10 ppm
Response time	T63%, typical	60 s
Accuracy drift per year with automatic self-calibration algorithm enabled	Typical	± (5 ppm + 0.5 % of reading)

795 **Table A.6.** Specifications of the mobile CO₂ detector.

Type: 77535
CO ₂ Range: 0~9999ppm
Temperature c: -10-60°C (14~140°F)
Humidity Temperature Range: 0.1%~99.9%RH
Operation Temperature: -20.0~59.9 °C
Resolution: 1ppm,0.1°C /°F
CO ₂ Accuracy: ±30ppm ±5%(0~5000ppm)
Temperature Accuracy: ±0.6°C /±0.9°F
Humidity Accuracy: ±3%RH/±5%RH
Startup Time: 30 s

796 **Table A.7.** CO₂ readings at critical positions of the HVAC systems.

HVAC	CO ₂ (ppm)	HVAC	CO ₂ (ppm)
E Fan Coil Unit	411/418	L Ceiling1Speed (Vent)	441/454
E Supply	382/420	L Ceiling2 Speed (Supply)	435/435
E Fan Coil Unit Vent	433/434	L Ceiling3	OFF
S Fan Coil Unit	406/407	LCeiling4 Speed (Supply)	437/440
S Fan Coil Unit Vent	427/430	LCeiling5 Speed (Supply)	421/430
W Fan Coil Unit	413/433	-	-
W Supply	409/426	R Ceiling1 Speed (Vent)	440/445
W Fan Coil Unit Vent	426/427	R Ceiling2 Speed (Vent)	423/433
E Cylindrical Supply	398/416	R Ceiling3 Speed (Supply)	427/430
W Cylindrical Supply	400/411	R Ceiling4 Speed (Supply)	425/436
E F-Door	410/416	E B-Door	423/430
W F-Door	419/425	W B-Door	423/432

797 **Table A.8.** Measured Air flow volume of HVAC units.

Units	Volume Speed (m ³ /h)	Units	Volume Speed (m ³ /h)
L-Cylindrical Supply 1-3	902.5	R-Cylindrical Supply 1-3	1011.5
L-Cylindrical Supply 4-6	794.5	Cylindrical Supply 1-3	793.5
L-Cylindrical Supply 7-8	960	Cylindrical Supply 1-3	722.5
L-VENT	-742	R-VENT	609.5
E-Supply A	0	W-Supply A	149.5
E-Supply B	142	W-Supply B	135
E-Supply C	62	W-Supply C	0
E-Supply D	138.5	W-Supply D	188.5
E-Supply E	148	W-Supply E	143.5
E-Supply F	88.5	W-Supply F	145
L-Ceiling 1 Vent	-645.5	R-Ceiling 1 Vent	-488
L-Ceiling 2 Supply	271.5	R-Ceiling 2 Supply	152
L-Ceiling 3 Vent	0	R-Ceiling 3 Supply	401.5
L-Ceiling 4 Supply	175	R-Ceiling 4 Supply	147
L-Ceiling 5 Vent	0	R-Ceiling 5 Supply	67.5
-	-	R-Ceiling 6 Supply	95.5

798 **Table A.9.** The measured and simulated airflow speeds at 15 observation spots (at a height of 1.5m).

Validation Spots	S1	S2	S3	S4	S5	S6	S7	S8	SW
Measured (m/s)	0.018	0.047	0.034	0.028	0.064	0.061	0.033	0.108	0.048
Simulated (m/s)	0.017	0.027	0.058	0.05	0.066	0.03	0.047	0.059	0.04
Validation Spots	H1	H2	M	C1	C2	C3			
Measured (m/s)	0.054	0.076	0.098	0.037	0.01	0.087			
Simulated (m/s)	0.056	0.074	0.11	0.033	0.004	0.072			

799 **Table A.10.** The measured and simulated CO₂ at 24 deployed spots (at a height of 2.1m).

No. of Sensors	0	1	2	3	4	5	6	7	8	9	10	11
Measured (ppm)	414	416	419	413	417	402	424	420	414	424	417	426
Simulated (ppm)	411	411	410	411	411	410	411	413	413	419	415	413
No. of Sensors	12	13	14	15	16	17	18	19	20	21	22	23
Measured (ppm)	425	434	419	425	431	409	425	416	412	416	411	416
Simulated (ppm)	420	429	414	418	421	409	415	415	413	414	414	413



800

801 **Fig. A.1.** *Kestrel 4500* mobile weather meter.



802

803 **Fig. A.2.** *Testo 420* volume hood.



Features

- Photoacoustic sensor technology PASens®
- Smallest form factor: 10.1 x 10.1 x 6.5 mm³
- Reflow solderable for cost effective assembly
- Large output range: 0 ppm – 40'000 ppm
- Large supply voltage range: 2.4 – 5.5 V
- High accuracy: $\pm(40 \text{ ppm} + 5 \%)$
- Digital I²C interface
- Integrated temperature and humidity sensor
- Low power operation down to < 0.4 mA avg.
@ 5 V, 1 meas. / 5 minutes

Fig. A.3. Specification of the CO₂ sensor.

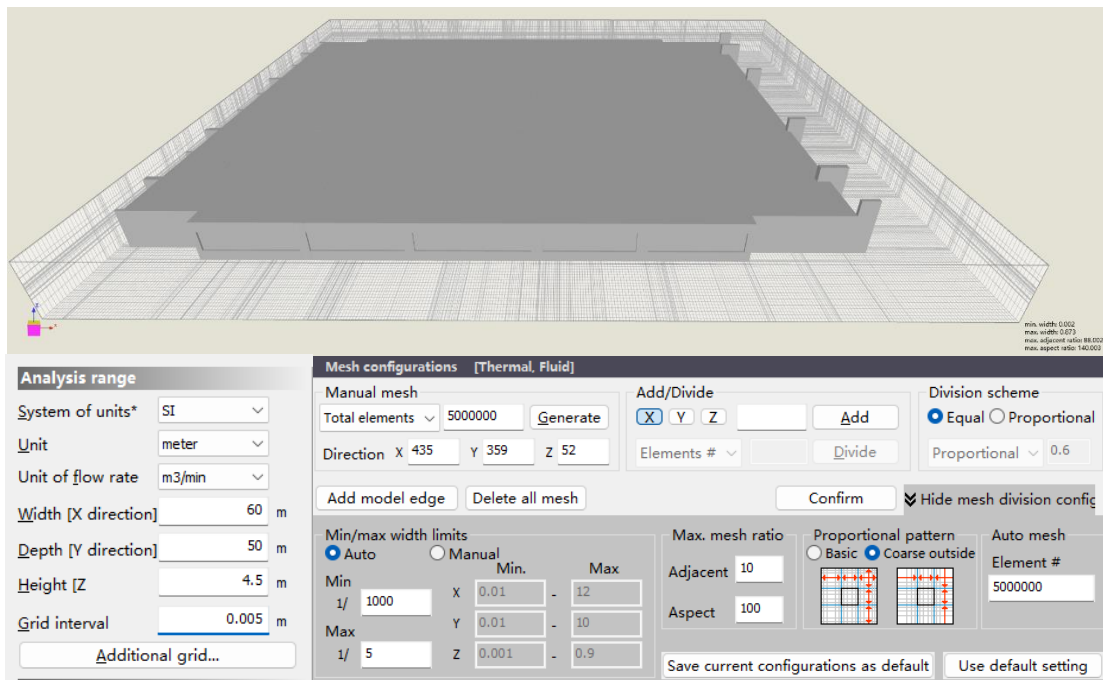
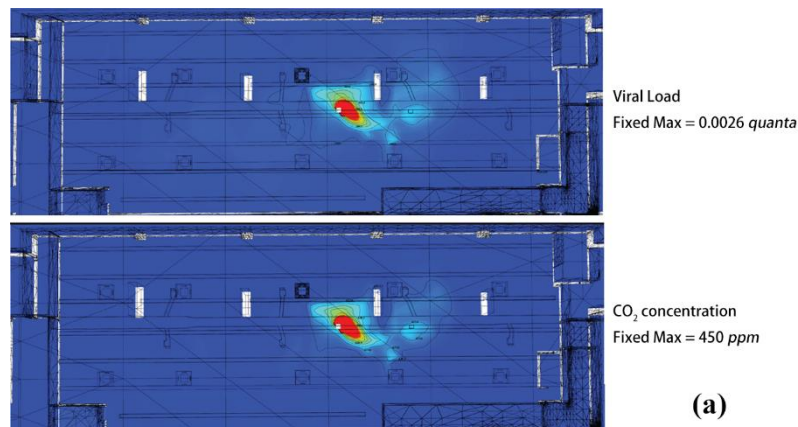


Fig. A.4. Grid and other settings.

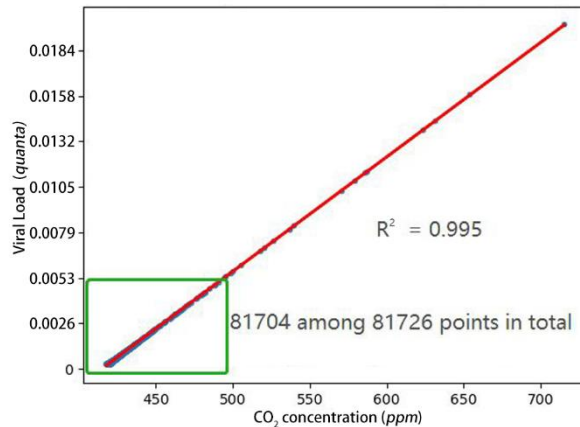


Fig. A.5. The predicted velocity field at a height of 1.5m.



(a)

Correlation of CO₂ concentration and viral load emitted from the 'patient'



(b)

Fig. A.6. Comparison (a) and correlation (b) between CO₂ concentration and viral load from the same 'patient'.

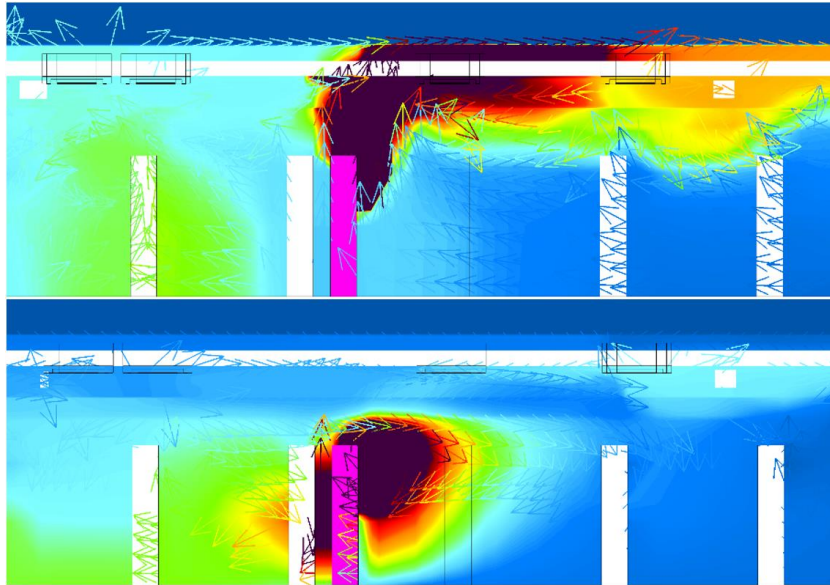


Fig. A.7. Sections of simulated airflow distribution and viral particle concentration in *Scenario 1* (upper) and *Scenario 5* (down); the patient is pink.

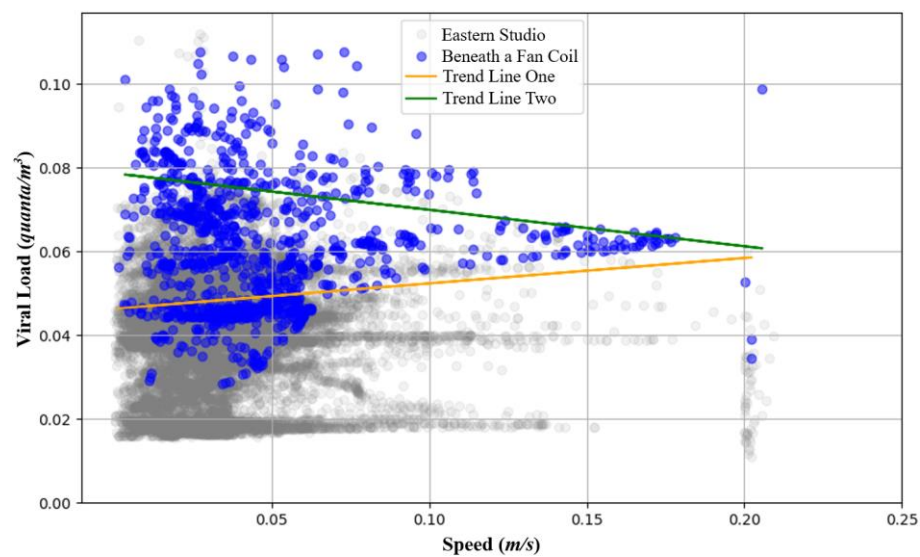


Fig. A.8. A scatter plot of the squared value of airspeed and viral load.

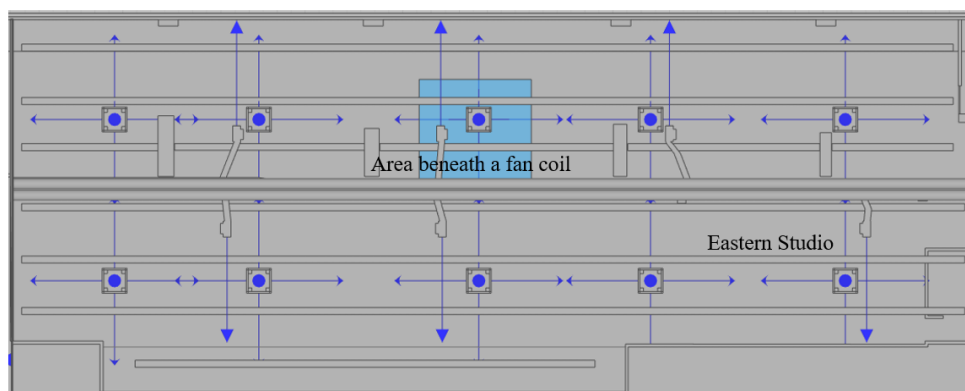


Fig. A.9. A 4-meter by 4-meter 'Effective Area' under a fan coil unit highlighted in blue.