

# Infectious Risk Prevention and Control Methods of Small Open Space in Post-Epidemic Era

## Risk Analysis of Airborne Transmission of Respiratory Infectious Diseases Based on CFD Wind Environment Simulation

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### Abstract

*The close contact in small open space poses a great risk of airborne transmission infection in post-epidemic era. But we still don't have a good model to estimate the risk quantitatively and decide what we can do to reduce infection rate in small open space design. In this study, CFD wind simulation is applied to predict the airflow distribution and virus transmission in different small open space scenarios, and the infectious probability of different positions is assessed by using the Wells-Riley equation. We found that the infectious probability is less than 0.0002% in small open space. But in poorly ventilated scenarios, areas with high-level infection risk are large, and there are aggregation areas of virus pollutant even at positions far from infectors. Reversing leeward environment to windward environment and moving the infectors to high wind speed position are two effective solutions to reduce infectious probability in small open space. The preliminary analysis can not only provide some reference for infectious risk in small open space, but also be of great significance to improve the air removal efficiency and provide places for residents to breathe freely.*

### Keywords

*small open space; COVID-19; CFD wind stimulation; Wells-Riley equation*

## 1. Introduction

In 2020, the COVID-19 broke out, the world adopted strict home quarantine to control the spread of respiratory infectious diseases. The confirmed transmission routes of COVID-19 are droplet transmission and contact transmission, but as we learn more about the pathology of the virus, the airborne transmission was added in the guidelines on epidemic prevention (CDC, 2021; Research, 2021). Recently, some studies have shown that COVID-19 probably transmitted through air (or aerosol) in confined spaces (Morawska and Cao, 2020; Morawska et al., 2020). Efficient air distribution is crucial to the containment of the virus through airborne transmission. However, due to the small size of virus particles, it is difficult to measure (Liu et al., 2020). The method based on CFD simulation provides a good visualization solution (Peng et al., 2020). The Wells-Riley equation is a classic model for quantifying the risk associated with airborne transmission of respiratory disease, revealed the relationship between transmission probability

and ventilation rate (RILEY et al., 1978), this equation has been used to analyze many outbreaks (Wu and Niu, 2017; Harrichandra et al., 2020; Shao and Li, 2020).

However, these studies are all in indoor spaces, and poorly ventilated spaces also appear in outdoor spaces, but there are few studies at present. Open space is defined as any open piece of land that is undeveloped and is accessible to the public (EPA, 2021). Small open space discussed in this paper, is surrounded by buildings and usually do not have a specific purpose, which is largely diversified, widely distributed and easily accessible, has become the first choice of recreation for urban residents during the epidemic (Dominski and Brandt, 2020; Gehl, 2021). Spaces with higher openness will be likely to undertake more activities, like as small live shows, vaccination sites and entrance queuing spaces.

The airborne transmission of respiratory infectious diseases is greatly affected by airflow (Qian et al., 2010). In addition to long transmission distance, the virus concentration measurement is difficult in small open spaces. There are many gathering activities with high population density and frequent face-to-face interactions. Plus, people's awareness of disease prevention in the outdoors is lower and they may not able to keep social distancing as indoor. We still don't have a good way to estimate the risk of infections quantitatively in these small open spaces. Therefore, in this paper we have proposed a solution for this problem. During the first part of the 20th century, it was widely accepted that urban planning should be responsible for dealing with public health issues. Our paper also offers some valuable insights into the problem - in this special time, how should urban planning respond to Covid-19?

In this study, CFD wind simulation is applied to predict the airflow distribution and pollution transmission in different small open space scenarios, and the infection probability of different positions is assessed by the Wells-Riley equation. The main objective is to estimate the association between space configuration and infectious probability, enhancing public awareness of the infection risk in small open space. At last, strategies, including space configuration and activity organization, are proposed for different small open spaces.

## 2. Methods

### 2.1. Calculation method of the infection probability

Based on the assumption of a well-mixed air space and steady-state conditions, the Wells-Riley equation is used to evaluate infection probability as follows:

$$P = \frac{c}{s} = 1 - e^{-Iqt/pQ}, \quad (1)$$

Here  $P$  is the infection probability in an infection scenario,  $c$  is the number of new infections,  $s$  is the number of susceptible people,  $I$  is the number of infectors,  $q$  is the quantum generation rate by one infected person (quanta/h),  $p$  is the pulmonary ventilation rate ( $m^3/h$ ),  $t$  is the total exposure time (h), and  $Q$  is the room ventilation rate ( $m^3/h$ ).

Wells-Riley equation has been confirmed in different indoor infection scenarios, and it demonstrates that increasing indoor ventilation is able to reduce the infection probability. However, outdoor air is not well mixed, in which wind speed, and virus concentration are different among positions. Based on Wells-Riley equation, there are a lot of non-uniformity models developed, such as exposure risk index, personal exposure effectiveness (PEE) (Melikov et al., 2002), intake fraction (IF) (Ai and Melikov, 2018). Shao and Li proposed "dilution ratio (DR)" to calculate difference of the virus the quantum concentration between positions in confined spaces (Shao and Li, 2020). But in outdoor wind simulation, relative concentration (RC) is more commonly used, which haven't received much attention and be correlated with infection risk in previous researches. RC is defined as the ratio of the quantum concentration at the susceptible position to that at the exhaled breath of infectors,

$$RC = \frac{C}{C_0} = \frac{qt/Qt}{qt/pt} = \frac{p}{Q} \tag{2}$$

here  $C$  and  $C_0$  are the quantum concentration in the inhaled of the susceptible person and the exhaled breath of infector respectively (quanta/m<sup>3</sup>). If the quantum concentration in the exhaled breath of infector is set as 1, the quantum concentration in the inhaled breath of susceptible person is RC.

The infection probability can be modified by combining Eq. (1) and Eq. (2) as

$$P = 1 - e^{-RCIqt} \tag{3}$$

The introduction of the RC provided an efficient way to analyse the risk of infection in the non-uniform outdoor environment. In small open spaces, activity time would be shorter than that in indoor places, but large number of people would attend. Besides, the natural ventilation would be very poor in some open spaces without any mechanical ventilation. Through this way, infectious probability can be easily evaluated in small open space.

## 2.2 Case setup

### 2.2.1 Study scale

There are many types of small open spaces, we should choose a scale which is not only suitable for common small open space but also convenient for calculation by CFD wind simulation.

Take a real urban form as an example in Yangpu district, Shanghai (Fig. 1). The size of small open space is around 1 hm<sup>2</sup> (100 m\*100 m), but the buildings surrounding this open space affect wind environment, therefore a larger scale (300 m\*300 m) is set as study scale. Afterwards, ArcGIS and Sketch up are used as tools to build the small space model.

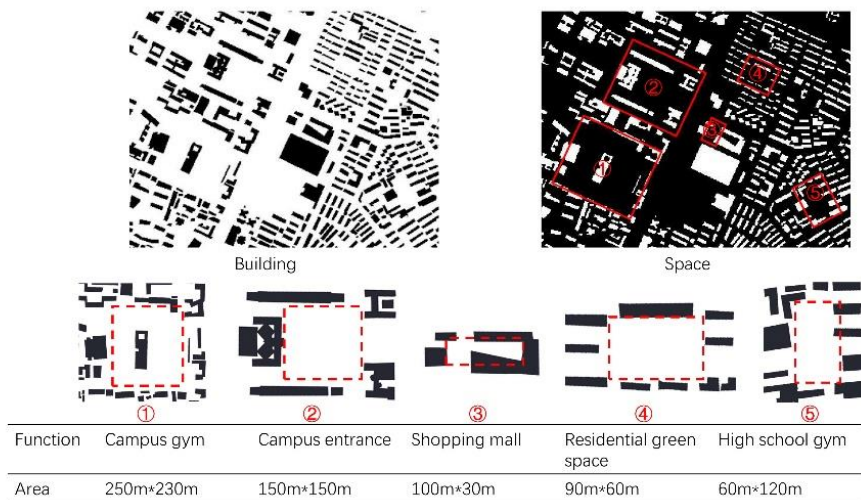


Figure 1. Urban form in Yangpu district, Shanghai. Source: the author.

### 2.2.2 CFD simulation

Computation fluid dynamics (CFD) numerical simulation is employed to analyze the wind environment of the small open space, which is calculated using the WindPerfect software (Hsieh et al., 2010). As for setting of boundary condition for simulation, the velocity inlet is set to be the gradient wind (4). The land surface is set to be a no-slip condition.

$$\frac{U(z)}{U_0} = \left(\frac{z}{\delta}\right)^\alpha \tag{4}$$

Here  $U_0$  is wind speed (m/s) outside of boundary layer,  $U(z)$  is the wind speed at the height of  $Z$  (m/s),  $\delta$  is the reference height (m),  $Z$  is the gradient height (m),  $\alpha$  is power law value (index).

In accordance with relevant research practices, the power law value was set as 0.22 and the gradient height was set as 450 m, which are the value for Land surface roughness: C (urban area with dense buildings). The wind was set as normal weather in winter in Shanghai (EnergyPlus, 2021).

The geometric model of the different small open scenarios is built up, as shown in Fig 2. For the surrounding area, the mesh size gradually becomes coarser with distance from the centre to the outside. Detail settings are provided in Tab. 1. The number of grids varies a little from different typical scenarios.

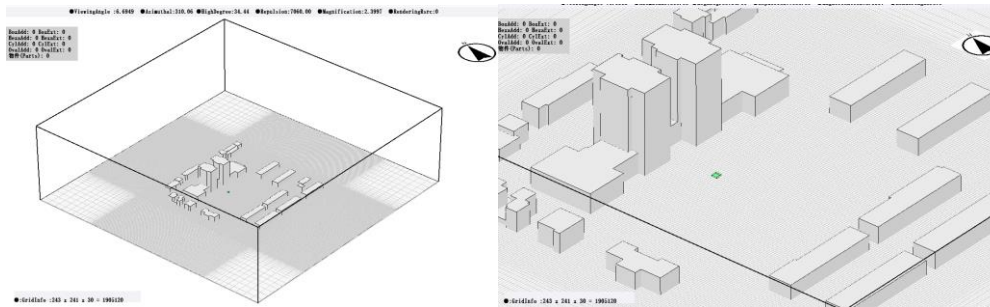


Figure 2. The geometric model and pollutant Source: the author by Windperfect.

Table 1. Parameters of boundary condition settings.

Items	Setting
Wind direction	NW
Wind velocity (m/s)	3.1
Governing equations	zero equation model
Boundary volume (X × Y × Z)	600 m × 600 m × 55 m
Spatial discretization	Minimum grids: 2 m × 2 m × 1 m
Grid number	Around 2,000,000
Reference height ( $\delta$ )	10 m
Gradient height ( $Z$ )	450 m
Power law value ( $\alpha$ )	0.22

Because small open space is much bigger than a person, the grids is coarse in the model and an infector is simplified as a hexahedron (4 m × 4 m × 1 m) at 1 m height, that is because the distance of droplets falls to the ground in a violent respiratory is around 1-2 m, long-distance airborne transmission begins after 2 m. But actually, the size of nose is just  $10^{-6}$  m<sup>3</sup>(diameter 0.01 m). Therefore, in this circumstance, we propose the assumption that the quantum concentration of an infector is set as 1 dimensionless unit and it is uniform distribution in the hexahedron, so the real relative concentration is  $\frac{RC}{16 \times 10^6} = 6.25 \times 10^{-8} \times RC$ .

In addition, the air temperature, pollution gravity and the pulmonary ventilation rate of the person are ignored, pollution diffusion only base on natural wind in these scenarios.

### 3. Results and discussion

#### 3.1 Spatiotemporal difference of infectious risk

According to the Eq. (3),  $q$  needs to be determined, which varies significantly because of inhalation rate, type of respiratory and activity level. Our aim is to analyze the light exercise activity without any movement, which represents the typical characteristic of infectors in small open space. The  $q$  reported by Dai and Zhao is  $14-48 \text{ h}^{-1}$  for COVID-19 in confined spaces (Dai and Zhao, 2020; Buonanno et al., 2020). In addition, the reproductive number of COVID-19 would decrease in outdoor space. Thus, we applied a  $q$  value of  $14 \text{ h}^{-1}$  for latter analysis.

Fig.3 shows the estimated exponential relationship between the infection probability and relative concentration(infectior=1), exposure time(infectior=1), number of infectors(time=1) respectively, which should be controlled to reduce the infection risk. There is still a very high infectious probability when staying a long time in a place with high virus concentration. Especially for small open space, some gather activities often happen, which would further increase the risk of infection.

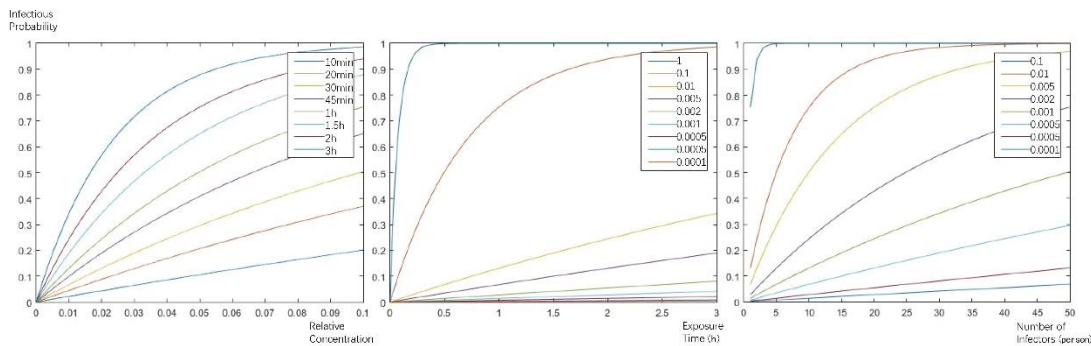


Figure 3. The association between the infectious probability(large scale) Source: the author.

But the relative concentration is less than  $6.25 \times 10^{-8}$  in two meters away from infectors, the relationship is close to linear in the small open space (Fig.4), and the infectious probability is less than 0.001%, whereas around 0.1% indoors. It is true that the risks are much lower in outdoor space. But there are lots of gathering activities and the participants are complex, it is hard to trace the source of the infectors and isolate potential patients in small open area. From this perspective, although the probability is very low, evaluation of risk positions and application of control measures are still necessary.

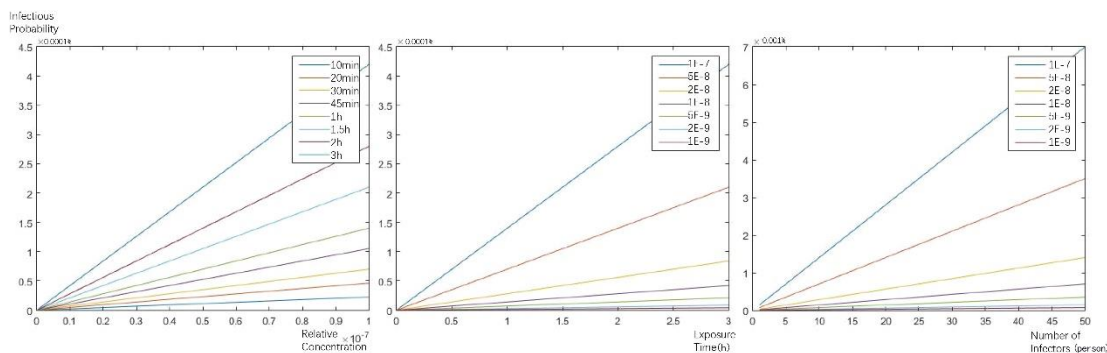


Figure 4. The association between the infectious probability(small scale) Source: the author.

Based on the above discussion, the infection probability of different positions in small open space was graded as Tab.2, "RC" means the result read in the CFD simulation model based on the assumptions above,

“real RC” means the real relative concentration in this position. Different infectious probability corresponds to different exposure time, this grade is in the case when exposure time is 1 h. Then we evaluated the probability of infection, base these grades.

When the level is high, the risk of infection in this position is as high as within two meters from infectors, which is extremely dangerous. When the level is medium, the probability is cut by half. When the level is low, people could safely stay and participate in activities at the position where “RC” is less than 0.2482.

Table 2. Different level of infection probability.

Level	Infectious probability	real RC	RC
high	0.0002%	6.20E-8	0.9927
medium	0.0001%	3.10E-8	0.4963
low	0.00005%	1.55E-8	0.2482

### 3.2 Infectious risk of typical scenarios

Campus space and commercial space, as two typical scenarios of small open space, have a high degree of space publicity and rich activities. Next, separate modelling is built for simulation. We select the urban space with a range of 300 m\*300 m, and ensure that the small open space is located in the middle of the range.

#### 3.2.1 Campus space

##### A. The entrance square of Tongji University

The entrance square space of Tongji University is symmetrically distributed. Combining with the central library, it emphasizes the solemnity of the entrance space. The space covers an area of about 150 m\*150 m, which is divided into multiple areas in actual use as shown in Fig. 5. People are mainly concentrated in the entrance of the library, who queue up for entering the library and raise the national flag in there. Meanwhile, as a landmark space of the campus, it is often used for gathering. The green hexahedron is in the position of the assumption infector, where wind speed is 0.494 m/s.

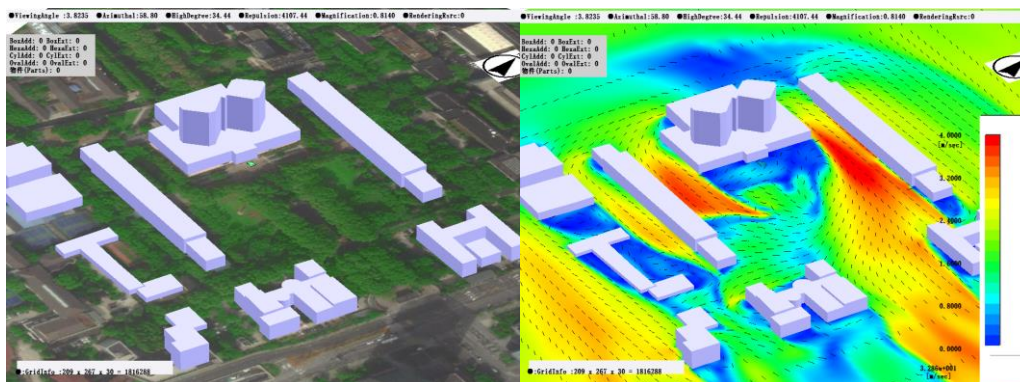


Figure 5. The space configuration and the result of wind show at breathing height 1.25 m (the entrance square of Tongji University) Source: the author by Windperfect.

Based on the simulation results Fig. 6, it can be seen that the high-level space is not only limited to the space around infectors. Due to the leeward environment of the huge library, the overall wind speed of the space is low, and virus pollutant will continue to deposit in the downstream space, resulting in aggregation. In the high-level area, 2 m was added to the social distance of 2 m, so we need to keep 4 m distance in this position. And the downstream area of virus deposition was about 25 m\* 5 m, it is far away from infector, and easy to be ignored.

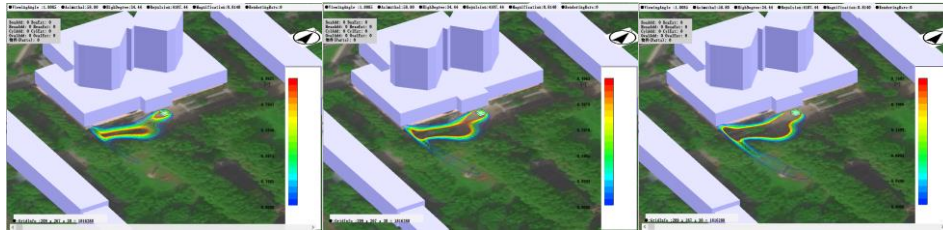


Figure 6. The result of relative concentration, high, medium and low respectively show at breathing height 1.25 m (the entrance square of Tongji University) Source: the author by Windperfect.

B. The lawn space in front of Guanghua Building, Fudan University

As the landmark building of Fudan University, the 142-meter-high Guanghua Building has become the tallest university skyscraper in Asia and the third tallest in the world, and also causing strong convection in the nearby air. The lawn space in front of Guanghua Building is an important place for students to communicate and participate in activities, as shown in the picture Fig. 7.

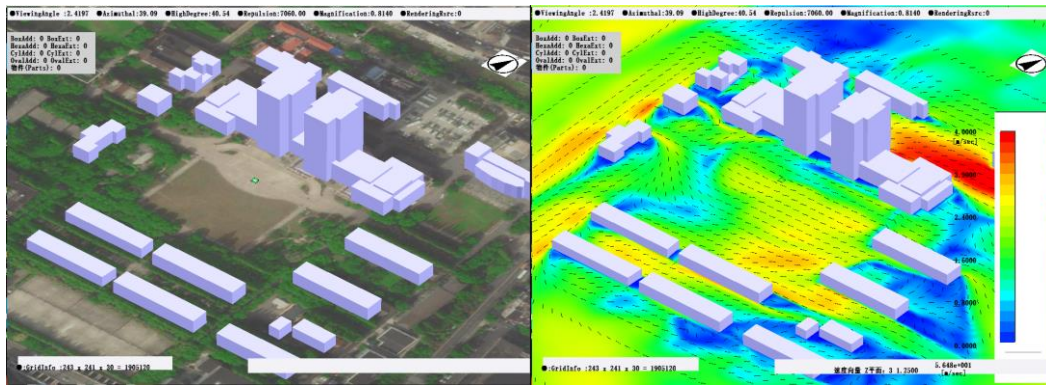


Figure 7. The space configuration and the result of wind show at breathing height 1.25 m (the lawn space in front of Guanghua Building, Fudan University) Source: the author by Windperfect.

The ventilation is good and the wind speed is fast in this space, 2.270 m/s. However, due to Leeward Environment, aggregation area far from infectors still appears (Fig. 8). And because of the fast wind speed, the high-level area is relatively small and farther away from infectors, making it more difficult to control.



Figure 8. The result of relative concentration, high, medium and low respectively show at breathing height 1.25 m (the lawn space in front of Guanghua Building, Fudan University) Source: the author by Windperfect.

3.2.2 Commercial space

A. The small square of Wanda Plaza

Wanda Plaza in a commercial complex, located in the prosperous business district, and the business model it adopts is indoor and outdoor interconnection. So, the external space is often used as temporary stores, exhibition space and performance space, as shown in Fig 9 The green hexahedron is in the position of the assumption infector, where wind speed is 1.913 m/s.

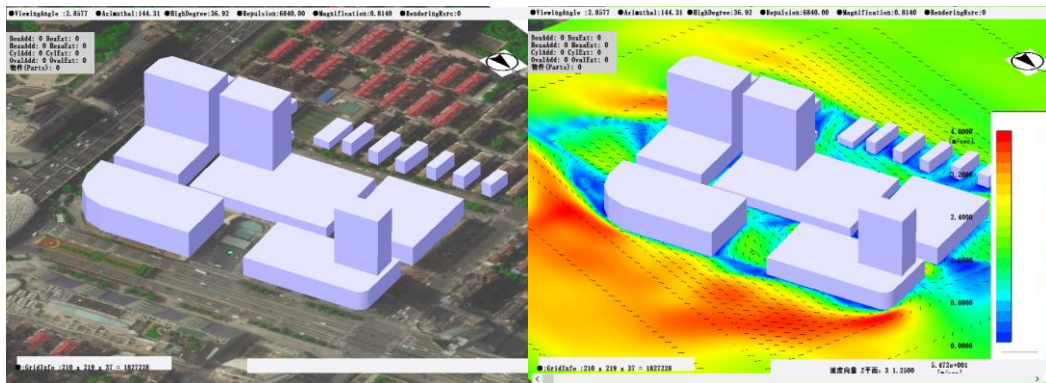


Figure 9. The space configuration and the result of wind show at breathing height 1.25 m (the small square of Wanda Plaza) Source: the author by Windperfect.

The wind speed is much faster in this square than the other scenarios, thus the high-level area is much smaller, even shorter than 2 m social distance (Fig. 10). The wind speed is slow at the edge of space, maybe it is not very suitable to stay for a long time there, but the centre of it is better.



Figure 10. The result of relative concentration, high, medium and low respectively show at breathing height 1.25 m (the small square of Wanda Plaza) Source: the author by Windperfect.

B. The atrium in Tongji Union Plaza

Tongji Union Plaza is a small commercial complex which is closely integrated with the residential area. The atrium space is often used for outdoor dining and coffee shop, especially as a vaccination space for nearby communities during the epidemic period. And the green hexahedron is in the position of the assumption infector, where wind speed is 0.401 m/s.

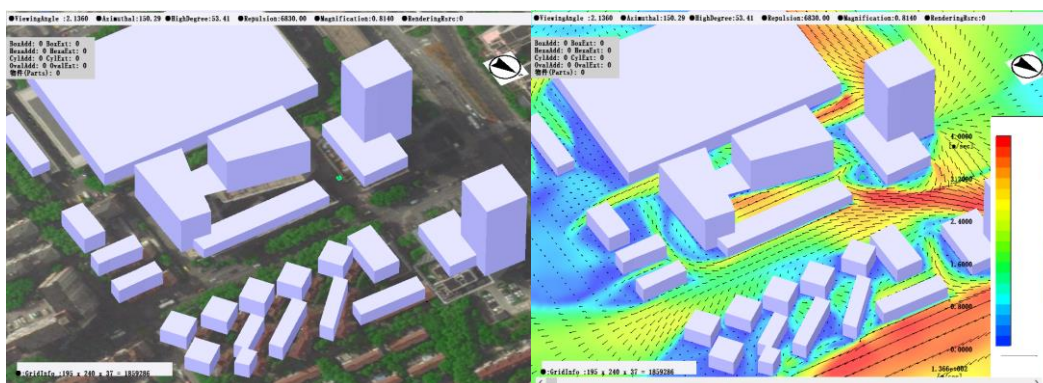


Figure 11. The space configuration and the result of wind show at breathing height 1.25 m (the atrium in Tongji Union Plaza) Source: the author by Windperfect.

Based on the above simulation results, natural wind forms an area with low wind speed behind the building. Similarly, low wind speed is difficult to dilute virus pollutant quickly. The high-level area is basically consistent with the social distance of 2 m, but the medium-low probability area, which is the area of outdoor coffee shop in actual use, has a high risk of infection.



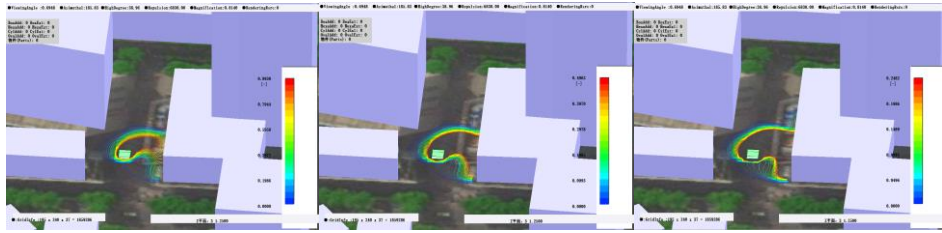


Figure 12. The result of relative concentration, high, medium and low respectively show at breathing height 1.25 m (the atrium in Tongji Union Plaza) Source: the author by Windperfect.

## 4. Summary and conclusions

### 4.1 Discussion

After exploring the possible reasons leading to virus pollutant aggregation in the typical scenarios, two alternative small open space design plans were proposed, and a CFD simulation was used to evaluate the effects of each plan. By considering consumer demand, and the influence of building on wind environment, two refined alternative plans were provided: one in change the position of infectors, and the other is a reverse leeward environment to windward environment.

The above mentioned two scenarios were taken for example. The first one is the entrance square of Tongji University, we talked about the direction between building and wind in this scenario. And the second one is the atrium in Tongji Union Plaza, we talked about the impact of infectors position, this is a very low-cost way to optimized space allocation in the post-epidemic period.

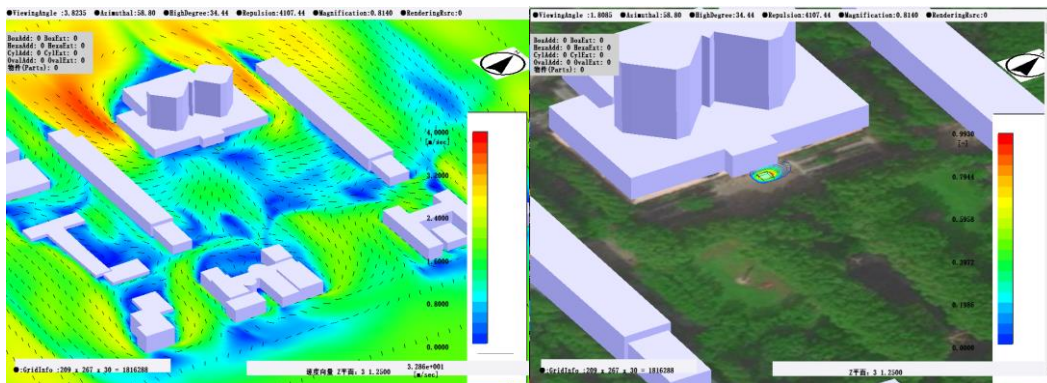


Figure 13. The result of wind and high-level concentration area show at breathing height 1.25 m (the entrance square of Tongji University) Source: the author by Windperfect.

Fig. 13 shows that a windward environment in the small open space, and the wind speed was slightly increased to 0.713 m/s (0.494 m/s before), so the virus pollutant can be carried away quickly by the wind. According to the high-level result, there is only one aggregation area, and it is smaller than before. The wind speed is around 1 m/s in the whole open space, which is also comfortable to do outdoor activities. From this perspective, return leeward environment to windward is really a good solution, not only for decreasing the infectious probability but also for a comfortable wind environment.

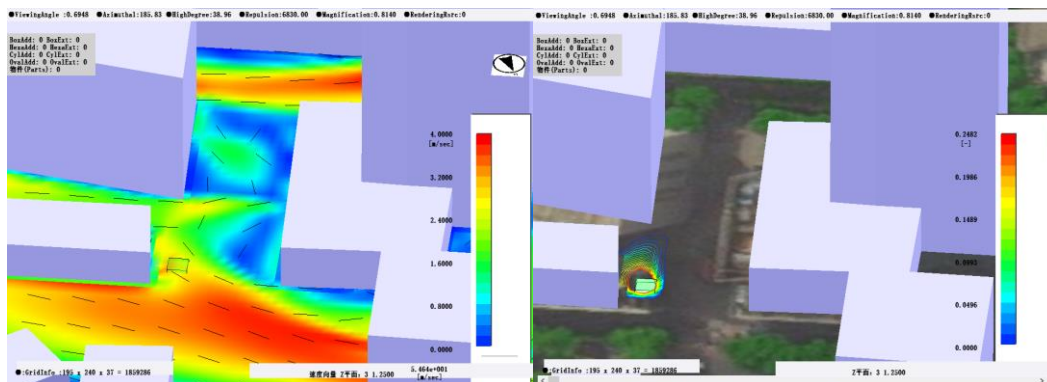


Figure 14. The result of wind and high-level concentration area show at breathing height 1.25 m (the atrium in Tongji Union Plaza) Source: the author by Windperfect.

Fig. 14 shows that a results of changing infectors position in the small open space and the wind speed is significantly improved to 2.50 m/s in this position (0.401 m/s before). The high-level area is much smaller than before, and would not influence the outdoor coffee shop, but the wind speed is too fast, therefore making any outdoor space very uncomfortable. Another advantage is that this solution has a low degree of spatial intervention and a small change cost, but requires a detailed analysis of the wind environment of space.

The influence of urban form on the wind environment has been proved many times. The natural wind environment of a city cannot be changed by the local climate, and the architecture and spatial form become the only influencing factors on the wind environment. Some studies have improved the wind environment by changing the urban form, aiming at optimizing the comfortable wind speed(Jiang and Gao, 2021). There was little wind environmental assessment study aimed at obtaining fresh air. The dilution ability of space wind environment is very important for isolating air pollutant and maintaining people's respiratory health(Hassan et al., 2020). In this paper, virus is used as pollutant to study the removal efficiency of wind environment in small open space. In fact, pollutant removal efficiency is discussed, which is similar to the concept of "Air Age"(Ramponi et al., 2015). We hope our study is not limited to the infectious diseases, but to give everyone a fresh breathing environment.

#### 4.2 Research conclusions

This study employed Wells-Riley equation to predict infection probability in some typical small open space scenarios based on CFD wind simulation. The main conclusions are as follows:

- (1) Keep social distance of 2 m is able to reduce infectious probability in small open space, which is less than 0.0002%. However, the number of infectors in outdoor spaces is much larger than in indoor spaces, so the probability of infection cannot be ignored.
- (2) In well-ventilated scenarios, the high-levels area is small, and the social distance can even be less than 2 m; Whereas, in poorly ventilated scenarios, mainly is leeward environment, the high-level areas are large, and even aggregation areas far from infectors would appear, which could be extremely dangerous.
- (3) Windward environment has higher pollutant dilution ability; whereas leeward environment not only has larger heigh-level area, but also cause the aggregation area which is far from infectors, increasing the difficulty of control.
- (4) Moving the infectors to high wind speed position is a little cost solution to reduce infectious probability, but the high precision wind environment simulation is needed.

### 5. Achievement and future outlook

Given the large uncertainties associated with each of the parameters, we relied on three assumptions in an attempt to link the wind environment in small open space to infectious disease risk models. First, the

concentration of viruses was assumed to be homogeneous within two meters of the infectors. This concentration must also have a dilution process, which could be simulated by finer grid. Other assumptions are that the exposure time was assumed to be 1 h, and the number of infectors was assumed to be 1 person. However, the activity scenarios are sophisticated, we need to further explore the impact of these differences on the infectious probability.

Current measures, strict screening of potential infectors, wider nucleic acid tests, and isolation have already ensured that there few infectors in indoor space. Furthermore, the indoor space is filled with familiar people, such as classmates, colleagues and relatives. On the contrary, there is no entry and exit control requirement in the outdoor space, people are mixed and people's awareness of disease prevention in outdoor open space is lower, thus the risk of infection cannot be ignored.

Respiratory infectious diseases mutate very quickly nowadays, so far there are alpha, beta, gamma and delta variants which are highly contagious, the value of  $q$  is more than we assumed in this research. Considering this point, the corresponding infection probability would be higher. Two years have passed since COVID-19 first outbreak in Wuhan, China, and we have also kept doing research on it for almost two years, but the number of confirmed cases in the whole world is over 600,000 every day. The COVID-19 have actually changed our lifestyle a lot. Now that many countries have relaxed the control of the epidemic, it is true that strong measures do not keep a long time, Maybe only changing the way we live and city develop can fundamentally solve this problem. It is hoped that urban designers and architectural designers can fully consider the importance of respiratory health and provide places for residents to breathe freely.

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