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Very high-resolution remote sensing-based mapping of urban residential districts to help combat COVID-19

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ABSTRACT

Urban residential districts (URDs) are a major element in the formation of cities that are essential for urban planning. Regarding the COVID-19 virus, which remains variable in aerosols for several hours, airborne transmission tends to occur in areas of poor ventilation and high occupant density. Thus, ventilation capacity is an important factor influencing airborne transmission in URDs, which should be evaluated as part of efforts to fight COVID-19 and guide healthy city planning and implementation. Here, we develop and test systematic methods to map URDs in a typical city in northern China and quantify their ventilation capacity using very high-resolution remote sensing images. Four fundamental spatial forms of URD are identified in the research area: the point-group form, parallel form, enclosed form, and hybrid form. Our analyses indicate that the integrated ventilation capacities for well-designed URDs are nearly twice those of poorly designed URDs. Large variations in ventilation capacity are also observed within URDs, with up to 13.42 times difference between the buildings. Therefore, very high-resolution remote sensing data are fundamental for extracting building height and generating precise spatial forms, which can improve the micro-scale URD ventilation planning for the prevention of COVID-19.

1. Introduction

Since December 2019, the coronavirus disease (COVID-19) has spread around the world, with over 255.1 million confirmed cases worldwide and more than 5.12 million deaths, involving more than 200 countries and regions (as of November 17, 2021) (Johns Hopkins University, 2021). As such, the world is paying increasing attention to the prevention and control of COVID-19 outbreaks (Dong et al., 2020; Dowd et al., 2020; Komarova et al., 2020; Wu & McGoogan, 2020). Many countries have entered a state of emergency and begun to upgrade and strengthen their prevention and control measures, including the United States, Argentina, Peru, Colombia, etc. in the Americas, Italy, Spain, and Serbia in Europe, South Africa and Zimbabwe in Africa, and Kazakhstan and the Philippines in Asia (Adhikari et al., 2020; Wang et al., 2020). Although the specific measures adopted by different countries are diverse (Wang et al., 2021), current prevention and control strategies can be classified into two major categories according to their prevention and control logic and basic characteristics (Dees, 2020; Tang et al., 2020). The first is the containment strategy, such as that adopted by China and South Korea, and the second is the mitigation strategy, such as that adopted by the United States, Germany, and the United Kingdom (Liu, 2020). Fighting the COVID-19 outbreak remains the greatest issue facing the world today (Alamoodi et al., 2021; Indolfi & Spaccarotella, 2020; Rasappan et al., 2020).

According to the World Health Organization (WHO), current evidence shows that the main mode of transmission of COVID-19 is through
respiratory droplets between people in close contact with each other. Aerosol transmission is assumed to occur in specific environments, especially indoors, among crowds, and between people in an insufficiently ventilated space (World Health Organization, 2020). Although the aerosol transmission of COVID-19 is still a topic of debate, several studies have proven this phenomenon. For example, in an open letter to the WHO written in July 2020, 239 scientists reported that COVID-19 aerosols “can stay in the air for several minutes to several hours” (Katie Kerwin McCrimmon, 2020). Moreover, the Centers for Disease Control and Prevention (CDC) in the United States revised its guidelines for responding to COVID-19 in 2021, clearly stating that the spread of COVID-19 and subsequent infections can occur through the inhalation of very small respiratory droplets and aerosol particles (Rachel Nania, 2021). Additionally, Vietnamese media have reported cases of COVID-19 infection occurring in meetings 10 m apart, providing further evidence that the virus can be transmitted through aerosols (Tencent, 2021). The prevention and control plan issued by the Chinese Health Commission states that COVID-19 may be spread through aerosols when people are exposed to high concentrations of aerosols for a long time in a relatively closed environment (National Health Commission, 2020).

Furthermore, Fears et al. (2020) concluded that COVID-19 can survive in aerosols for 16 h and has the ability to infect cells (Fears et al., 2020), Marc G. Wathelet used eight pieces of evidence to prove that aerosols are an important vector for COVID-19 (Marc & Wathelet, 2020), and Zhang et al. (2020) found that virus-carrying aerosols are inhaled and deposited directly along the human respiratory tract (Zhang et al., 2020). Thus, the importance of COVID-19 aerosol transmission is now widely recognized (Bazant & Bush, 2021).

Aerosol transmission involves the long-distance transfer of droplet nuclei, composed of residual protein and pathogens from potentially infectious aerosols, which remain after the evaporation of water during the air suspension process (Feng et al., 2020). Aerosols can remain in the air for several hours as tiny particles (Fears et al., 2020; Gowtham & Padma, 2014; Timonen et al., 2013), and the distance and range of aerosol transmission are significantly greater than those of direct transmission (Davis et al., 2009), which can occur in the indoor space of buildings or in outdoor urban spaces (Poydenot et al., 2021). Therefore, controlling the spread of COVID-19 aerosols should involve promoting urban ventilation by rationally designing and optimizing urban morphology. Specifically, effective urban ventilation helps prevent virus-containing aerosols and other pollutants from accumulating in outdoor spaces and instead promotes their dissipation (Constantinescu et al., 2016; Johnson et al., 2018). Moreover, the natural ventilation capacity of a building indirectly contributes to preventing the direct transmission of viruses in indoor spaces (Shi, 2020). Considering the ventilation environment of an urban residential district (URD), natural ventilation should be adopted as much as possible in order to reduce the concentration of COVID-19 aerosols per unit space and lessen the probability of infection (Liu, Wei, et al., 2020).

Urban planning policies about ventilation have been put forward since the 1970s. Germany is the first country to formulate policies related to the concept of urban ventilation (Knoch, 1951; Liu et al., 2015; Ren et al., 2011). Germany carried out cross-disciplinary researches (e.g., urban climate potential, ventilation effect of landscape structure, big data, etc.) and planning practices about improving urban ventilation corridor (Weber et al., 2013). In addition, the Committee of the German Society of Engineers compiled the “VD13787” guidelines in the 1990s to guide the urban ventilation assessment and construction. At present, the urban ventilation corridor is aroused attention increasingly in large and medium-sized cities in Germany, such as Stuttgart, Calif. Sale and Freiburg (Salcedo Rahola et al., 2009). Japan is the first country in Asia to start the practice on urban ventilation corridor (Sundell, 2017). The Japanese government conducted research on urban climate environment and planning application in the 1990s, and incorporated relevant norms into the planning indicators. In 2007, eight major prefectures in the Tokyo Bay metropolitan area jointly completed urban

Fig. 1. Map showing the location of the study area in Central China and four typical types of URD of Zhengzhou.
ventilation corridor project of “Wind Way”. In addition, in order to alleviate the urban heat island effect, the “Sea Forest” project was carried out to increase more prevailing monsoons (Kitao et al., 2012). Cities such as Manchester in the United Kingdom, Sao Paulo in Brazil, and Wroclaw and Warsaw in Poland have also carried out the ventilation corridor planning. Hong Kong is one of the earliest cities in China to recognize urban ventilation corridor (Ren et al., 2012). In 2003, for the first time Hong Kong City-wide Clean Planning Group published “Environmental Hygiene Improvement Measures in Hong Kong” for the government to consider the ventilation corridor as one of the urban planning factors (Ng et al., 2011). The “Recommendations on Residential Building Standards Design and Research Institute along with experts from relevant departments, also confirm the need for an effective ventilation. Indeed, three of the 15 specified prevention and control measures note the importance of urban ventilation (Liu, Feng, et al., 2020).

From above mentioned studies it can be seen that many cities all over the world have explored the macro-scale urban ventilation by focusing on a cities’ overall spatial form designing. However, under the new crown epidemic the micro-scale URD ventilation is more likely to affect public health because residents have their activities most often and most conveniently in URD which is the most important unit of the city. At the micro-scale, well ventilated URD can make a crucial contribution to prevent the aerosol transmission by promoting the aerosol diffusion and reduce its concentration in the air. As a result, the micro-scale URD ventilation capacity evaluation is of great significance for COVID-19 epidemic prevention and control, which is the research aim of the paper.

Although URD, which is the basic and important unit of the city, plays an important role in residents health during the COVID-19 era in term of aerosol transmission prevention, there are a few studies on the micro-scale URD ventilation compared with the above-mentioned studies on macro-scale urban ventilation. In addition, early researches on the prevention and treatment of COVID-19 were mostly from other environmental factors such as (i) temperature, humidity, and sanitation (Han et al., 2021; Hu et al., 2021; Meyerowitz et al., 2021; Muhammad et al., 2020; Qu et al., 2020), (ii) the transmission route, transmission range, epidemic trajectory and other infectious risks (Bai et al., 2020; He, Lau, et al., 2020; Lauer et al., 2020; Liu, Gayle, et al., 2020; Paules et al., 2020) and (iii) the various stages of infection intervention and treatment measures (Bialek et al., 2020; Gautret et al., 2020; Grasselli et al., 2020). This research fills the gap from certain fundamental aspects of a general framework for the micro-scale URD ventilation assessment: data selection and URD identification, ventilation model development and construction of ventilation evaluation system. In terms of data, we utilize very high-resolution remote sensing images to obtain the micro-scale representative URDs based on the stratified sampling methodology to ensure completeness and representativeness. In terms of modeling, we introduce the ecologic model of the least-cost distance model to simulate the ventilation capacity with high accuracy at the micro-scale. In terms of the evaluation system, we assess the COVID-19 spread resistance level based on the URD ventilation capacity to provide new ideas for global epidemic prevention and control, and also has practical significance for future urban planning and construction.

2. Methodology

2.1. Research area

Zhengzhou is a mega city in China and one of the national-level central cities approved by the State Council. Zhengzhou is located in the southern part of the North China Plain, in central and northern Henan Province, and in the lower reaches of the Yellow River, between 112°42′E–114°14′E and 34°16′N–34°58′N (Fig. 1). Under the combined effects of solar radiation, topography, geology, atmospheric circulation, and other factors, Zhengzhou has a climate characterized by a short spring and autumn, a long winter and summer, and four distinct seasons. The region belongs to a typical northern temperate continental monsoon climate. Meteorological data show that the summer wind direction in Zhengzhou is predominantly southeast and south, whereas the winter wind direction is predominantly northeast and northwest (Zhao, 2012). As a typical monsoon area, Zhengzhou has frequent heating and cooling periods with strong winds in winter and spring.

As the capital city of Henan Province, Zhengzhou is a global hub city of China's north-south and east-west traffic arteries, and the gateway to the new Eurasian Continental Bridge (Wu, 2020). In 2018, Zhengzhou's GDP exceeded one trillion yuan, ranking 15th in the country. In 2018, the permanent resident population of Zhengzhou exceeded 10 million, (10.136 million), the floating population increased to 3.4 million, and the urban population density reached 1362 people/km².

Zhengzhou and Wuhan are both in the hinterland of the Central Plains, with a small geographic distance, convenient transportation, frequent population flow, and close socioeconomic ties between the two cities. Therefore, Zhengzhou has also become a high-risk area for COVID-19 (Zhao et al., 2020). Since the first confirmed case was discovered on February 1, 2020, as of 00:00 on February 10, 2020, the Zhengzhou Municipal Health Commission has reported a total of 132 confirmed cases. Among these, 94 cases (71.21%) occurred within two weeks (January 20 to February 2); thereafter, the numbers began to decrease. Significant differences are observed in the spatial distribution of the COVID-19 outbreak within Zhengzhou. At the county level, there have been more confirmed cases in Jinshui District, Guancheng District, Erqi District, Zhongyuan District, and Gongyi City. At the urban street scale, the population is mainly distributed within the third ring road of the central city area, while areas with higher COVID-19 risk levels are mainly distributed in the urban areas of Zhengzhou, including Jinshui District, Erqi District, Zhongyuan District, and Guancheng District. Areas with lower risk levels are mainly distributed in Xinmi City, Xinzhen City, and Zhongmu County (Zhao et al., 2020). These outbreak characteristics have made Zhengzhou's urban area a key target for COVID-19 outbreak prevention and control.

2.2. Data used in the research

2.2.1. Very high-resolution remote sensing data

High resolution remote sensing images have a wide range of applications in the URD identification. Studies can be roughly divided into two categories. One is directly based on image characteristics. Hui et al. pointed out that the extraction of URDs from high-resolution remote sensing images has been widely studied because of its importance in obtaining urban information (Hui et al., 2019). Wu and Liu proposed a model to identify URDs based on the GF-4 high resolution satellite data (Wu & Liu, 2018). Zhao et al. classified and identified fine features based on their color, texture, and shape in buildings in a URD (Zhao et al., 2012). Based on aerial remote sensing imagery and SPOT-6 images, Liu et al. used multi-scale segmentation and multi-rule combination methods to automatically extract residential building information with the accuracy of 0.76 according to the complex underlying surface structure of URDs (Liu et al., 2016). The other is based on object-oriented method. Wang used rule-based object-oriented classification technology to obtain green space information in a URD (Wang, 2014). He used object-oriented technology to extract URD, commercial service area, medical and health area, industry area, education area and government agency area based on high resolution remote sensing images (He, 2020). Zhao et al. adopted the morphological building and shadow (im) age features multi-scale optimized segmentation and object-oriented classification technology to achieve the rapid extraction of URDs and shadow information (Zhao et al., 2015). Liu et al. proposed an object-oriented building shadow extraction method to overcome similarities between the dark lands (e.g., water, road, and soil) and shadows (Liu, Ning, et al., 2020). Based on multi-scale fusion model and object-
The product level of the ZY-3 image data selected in this article is 1120367, and the geographic area is 113°-114°E, 34°-36°N. The image band includes panchromatic (450–800 nm), blue (450–520 nm), green (520–690 nm), red (630–690 nm), and near infrared (770–790 nm).

2.2.2. Wind data

Wind data were primarily downloaded from the National Meteorological Science Data Center (National Meteorological Science Data Center, 2021). Wind data for the study area are shown in Table 1. The frequency comparison shows that the dominant wind directions in Zhengzhou over the past 10 years (2010–2020) are southwest (SW), northwest (NW), northeast (NE) and southeast (SE).

2.3. Evaluating the integrated ventilation capacity using very high-resolution remote sensing images

Many factors have a significant impact on URD micro-scale environment. These can be divided into two categories: (i) the natural factors such as wind, temperature and humidity; (ii) the man-made factor such as URD spatial form. This research only focuses on the assessment of ventilation capacity of URD based on two important factors of spatial form and stable wind to provide suggestions for improving the ability to prevent COVID-19 transmission.

2.3.1. Identification of spatial forms for urban residential districts

The preprocessing methods include atmospheric correction, orthorectification, image registration, image fusion, and image cropping. The multi-spectral ZY-3 image data has very good spatial resolution and breadth so we used the absolute radiation correction method to perform atmospheric correction. In short, this had three steps: (i) data calibration, in which the absolute radiometric calibration coefficient was used to convert the DN value of the multi-spectral image into a radiance image; (ii) spectral response function production; (iii) Fast Line-of-sight Atmospheric Analysis of Hypercubes (FLAASH). Image registration is based on the panchromatic image, and the multispectral image is registered by automatic point selection and manual modification. The Gram-Schmidt (GS) fusion method (Grochala & Kędzierski, 2017; Kong et al., 2021; Yilmaz et al., 2020), which not only maintains the spectral information of the original image but also retains the spatial texture of the panchromatic band image to the greatest extent, was employed to fuse panchromatic and multispectral image data. The spatial resolution of the multispectral bands was 2.1 m after GS fusion. This method does not limit the number of fusion bands and can be performed for all multispectral bands in a single fusion process, which reduces workload and improves work efficiency. Therefore, manual interpretation and analysis of very high-resolution remote sensing images was performed to obtain the buildings, green spaces, and roads of URDs using administrative divisions.

Building height is an important factor that affects the spatial form of URDs, and is also the main factor determining the wind resistance coefficient of a URD. In very high-resolution remote sensing images, shadows are a unique type of noise. Although they affect the image classification effect, the shape and size of building shadows depend on the building itself, the sun’s azimuth, the sun’s altitude, and the satellite’s azimuth. Satellite height angle and other information can therefore be used to invert the height of buildings. The geometric relationship between the sun, satellites, and buildings in the study area is shown in Fig. 2, where $\alpha$ is the height of the sensor, $\beta$ is the height of the sun, $\epsilon$ is the azimuth of the sun, $\delta$ is the azimuth of the sensor, $\gamma$ is the clockwise angle formed by the direction of the building and its shadow projection, $\theta$ is the height of the building, $\beta$ is the shadow length of the actual building, and $\gamma'$ is the shadow length observed on the image. In this schematic, the difference between the azimuth of the sun and the azimuth of the satellite is 56.61°, indicating that the sun and the satellite are located on the same side of the building. At this time, part of the shadow of the building cannot be detected by the satellite (Chen et al., 2016; Fang, 2019; Huo et al., 2018; Jingfeng & Yinpu, 2014; Xu et al., 2016). Therefore, the following equations are used to retrieve the height of the building.

According to the trigonometric function of a right-angled triangle, in the triangle $\Delta OAC$, the following is true:

\[
OA = AC \times \tan \beta
\]  
\[
\text{In the right triangle } \Delta OAB:
AB = OA \times \cot \alpha
\]

\[
\angle CAB = \epsilon - \delta
\]

Therefore, in $\Delta FBA$, $FB/|AE|$: 

| Table 1 |
|-----------------------------|
| Wind direction | Number of days | Frequency | Wind grade |
|-----------------|----------------|-----------|------------|
| SW              | 205            | 0.19      | 2.25       |
| NW              | 209            | 0.19      | 3.25       |
| NE              | 440            | 0.40      | 3.14       |
| SE              | 240            | 0.22      | 2.05       |

Fig. 2. Schematic of the geometric relationship between the sun, satellites, and buildings in the study area.
\[ \angle FBA = 180^\circ - \gamma - \angle CAB = 180^\circ - (\gamma + \epsilon - \delta) \] (3)

In \( \Delta FBA \), the law of sines is used:

\[ \frac{FA}{\sin (180^\circ - (\gamma + \epsilon - \delta))} = \frac{BA}{\sin \gamma} \] (4)

The length of the shadow in the image is \( FC = AC - AF \), and the height of the building is \( OA \). Combining Eqs. (3) and (4), we obtain

\[ \frac{OA \times \cot \beta - CF}{\sin (180^\circ - (\gamma + \epsilon - \delta))} = \frac{OA \times \cot \alpha}{\sin \gamma} \] (5)

Thus, the formula for calculating the height of the building is

\[ OA = \frac{CF \times \sin \gamma}{\cot \beta \sin \gamma - \cot \alpha \sin(\gamma + \epsilon - \delta)} \] (6)

By integrating the relationship between the shadow of a building and its height, we find that the height of the building is related to the length of the shadow on the remote sensing image and the fixed parameters of the satellite and the sun at the time of image capture. In other words, the height of the building is directly proportional to the length of the shadow detected on the image, as shown in Eq. (7):

\[ OA = CF \times K_1 \] (7)

\[ K_1 = \frac{\sin \gamma}{\cot \alpha \sin \gamma - \cot \beta \sin(\gamma + \epsilon - \delta)} \] (8)

In this study, the building shadow was extracted by manual interpretation based on the ZY-3 image data. The calculation of shadow length is key to using shadows to invert the height of buildings (An et al., 2014). In order to improve the accuracy of the shadow length calculation, we used the fishing net method to extract the shadow length (Fig. 3). The fishing net method generates a series of parallel lines according to the azimuth direction of the sun, such that the shadow plane intersects the parallel lines. We then performed overlay analysis on the shadow vector and parallel lines, and cropped the parallel lines in the shadow plane. In the study, the number of pixels was multiplied by the image resolution to calculate the length of parallel lines in each shadow plane (Tian et al., 2008). In order to reduce the error and improve the efficiency of screening, we used the box plot mathematical model to automatically identify and delete the abnormal value of the line segment in each shadow surface, then calculate the average value of the remaining effective line segments, which provides the length of the shadow surface.

The box plot principle proposed by Tukey in 1977 is a classic data mining method (Tukey, 1977). Box plots do not require the sample data to strictly obey the statistical distribution, and the samples are processed directly; therefore, the sample data to be mined present strong robustness (Fig. 3). The criteria for assessing the changed objects based on the box plots are based on the interquartile range and interquartile range. The quartiles in the data are not dependent on extreme points but are only related to the data subject when they are selected. Therefore, they should not be disturbed by changed objects, and the data can be analyzed more objectively. The steps of the box plot mathematical model used to detect outliers are as follows:

1. Arrange the sample observation values \( X_1, X_2, X_3, \ldots, X_n \) in ascending order.
2. Perform the following calculation:

\[ X_p = \begin{cases} 
X_{(n \cdot p)} & \text{if } n \cdot p \text{ is not an integer;}
\end{cases} \]

\[ \begin{cases} 
\frac{1}{2} \left( X_{(n \cdot p - 1)} + X_{(n \cdot p)} \right) & \text{if } n \cdot p \text{ is an integer;}
\end{cases} \] (9)

where \( n \) is the number of samples and \( X_p \) is the \( p \)-quantile of the sample \((0 < p < 1)\). When \( p = 0.25, X_{0.25} \) represents the lower quartile; when \( p = 0.5, X_{0.5} \) represents the median; when \( p = 0.75, X_{0.75} \) represents the upper quartile.

3. Calculate the truncation point of the abnormal value of the box plot:

Truncation point 1: \( Q_3 + 1.5 \times \text{IQR} \); Truncation point 2: \( Q_1 - 1.5 \times \text{IQR} \);
IQR

When the sample observation value \( X_n < Q1 - 1.5\times IQR \) or \( X_n > Q3 + 1.5\times IQR \), \( X_n \) is an outlier. In this equation, \( Q1 \) is the lower quartile, \( Q2 \) is the median, \( Q3 \) is the upper quartile, and \( IQR \) is the distance between the upper quartile and the lower quartile, that is, \( IQR = Q3 - Q1 \).

2.3.2. Wind resistance coefficient

The wind resistance coefficient is predominantly affected by the height of the building. The horizontal wind speed of the URD satisfies the following formula, which provides the wind resistance coefficient (Wang, 2016):

\[
v = v_0 \left( \frac{Z}{Z_o} \right)^{0.25}
\]

(10)

where \( v \) and \( v_0 \) are the wind speed at height \( Z \) and \( Z_0 \), respectively, and \( Z_o \) is the reference height. The amount of ventilation from the ground elevation \( Z_0 \) (referred to the elevation of the ground or roof) to the control height \( Z_e \) is:

\[
Q_b = \int_{Z_0}^{Z_e} v_0 \left( \frac{Z}{Z_o} \right)^{0.25} dZ = \frac{v_0}{1.25} \left( \frac{Z}{Z_o} \right)^{1.25} |_{Z_0}^{Z_e}
\]

(11)

\[
Q_b = \frac{v_0}{1.25} \left[ \left( \frac{Z}{Z_o} \right)^{1.25} \right]|_{Z_0}^{Z_e} - \left( \frac{Z}{Z_o} \right)^{1.25}
\]

(12)

The unconstrained (free) ventilation rate is:

\[
Q_0 = \frac{v_0}{1.25} \left( \frac{Z}{Z_o} \right)^{1.25}
\]

(13)

Then, the ratio of the influence of a building with height \( Z_e \) on the ventilation is:

\[
e_b = \frac{Q_b}{Q_0}
\]

(14)

The wind resistance coefficient \( K_b \) can be obtained according to the reduction ratio of ventilation as follows:

\[
K_b = e_b = \left( \frac{Z}{Z_o} \right)^{1.25}
\]

(15)

Where \( Z_0 = 0, K_b = 1; \) when \( Z_0 \geq Z_o, K_b = 100,000 \). The above calculation formula can be used to determine the wind resistance coefficient of residential areas.

2.3.3. Integrated ventilation capacities based on the least-cost distance model

When wind encounters a building, a pressure difference forms on the windward and leeward sides of the building. In addition to the wind speed, factors such as the building form, the angle between the building and the wind, and the layout of the surrounding buildings also influence this pressure difference (Alshenaifi & Sharples, 2018; He, Schnabel, et al., 2020). Thus, different building layouts exhibit significantly different ventilation conditions (Li et al., 2016; Liu et al., 2018; Mei et al., 2018). The buildings in a URD and the surrounding physical environment form a micro-environment, in which the ventilation environment represents an important component, exerting a significant influence on outdoor pedestrian activities and their physical health (Cao & Wang, 2017; Gilani et al., 2016; Sun & Pan, 2016). Ventilation capacity depends on factors such as air quality, pollutant sources, temperature, humidity, building orientation, internal wind path distribution, etc. (Roulet et al., 2002). Studies on ventilation evaluation can be roughly divided into the following two categories. One is to simulate the ventilation through computational fluid dynamics (CFD) to evaluate the ventilation capacity in the environment (Ayata & Yildiz, 2006; Li & Nielsen, 2011; Mistrriotis et al., 1997; Ramponi et al., 2015). Tan & Deng conducted numerical model on the ventilation capacity of residential buildings through transient system simulation tool (Tan & Deng, 2017). The second is to evaluate the ventilation capacity through simulated wind channel based on wind resistance coefficient (Hsieh & Huang, 2016; Ren et al., 2018). The latter may be better due to avoiding the inaccuracy of some important parameters, especially suitable for the micro-scale URD ventilation assessment.

On the basis of determining the wind resistance coefficient of URDs, the source and target points were set based on the wind direction, the least-cost path from the source point to the target point was calculated according to the least-cost distance model (Ban, 2020; Casey et al., 2015; Chan et al., 2014; Duan et al., 2014; Qu et al., 2016; Wang et al., 2018; Xueyi & Ba, 2016), and the ventilation corridor of the URD was constructed. The raster path (\( P \)) is an ordered sequence composed of a group of adjacent raster pixels, i.e.:

\[
P = \{ p_i \}, i = 0, 1, 2, ..., n
\]

(16)

where \( p_i \) is the raster pixel, \( i \) represents the ordered sequence, \( p_0 \) is the source point, and \( p_n \) is the target point. The manifestation of \( P \) can be discrete point elements, line elements, or area elements. Neighboring elements are allowed, but the attributes cannot be the same. Both raster data and vector data can represent \( P \).

The nearest neighbor cost (\( C \)) is used to describe the difference between two adjacent raster pixels:

\[
C = | p_1 - p_2 |
\]

(17)

where \( p_1 \) and \( p_2 \) are the vectors of two raster pixels, \( | p_1 - p_2 | \) represents the modulus of the difference between the vectors of the two raster pixels, and \( K \) is a constant used to adjust the size of the neighboring cost. The cost can be understood as an obstacle to achieving a goal or destination, and the cost grid carries the cost of passing through a certain pixel. The path cost (\( D \)) is used to describe the cost accumulation of a raster path between the start point and the end point:

\[
D = \sum_{i=1}^{n-1} C_i = \sum_{i=1}^{n-1} f(p_i, p_{i+1})
\]

(18)

where \( C_i \) is the neighboring cost between each pair of adjacent raster pixels in the raster path, representing the lowest cumulative cost of any pixel to the nearest and lowest cost destination.

The least-cost (\( P^* \)) path is a raster path with the minimum path cost between the starting point \( p_0 \) and the end point \( p_m \):

\[
P^* = \text{argmin}_{P} \sum_{j=0}^{m-1} f(p_j, p_{j+1})
\]

(19)

where \( m \) is the number of grid paths between the start point and the end point, which represents the forward direction of approaching the target point along the least-cost path starting from any pixel. This forward direction is one of 1, 2, 3, 4, 5, 6, 7, or 8. In a set of \( 9 \times 9 \) squares, the central square has a value of zero, which is the target point. When the value is one, the square is to the east of the target point; when the value is two, the square is to the southeast; when the value is three, the square is to the south. In other words, the target rotates clockwise from the east by 45° each time; as the value increases from 1 to 8, the orientation of each grid changes accordingly.

As the wind direction determines the source and target points, the integrated ventilation capacity (IVC) of the URD is calculated as follows:

\[
V_p = \sum_{i=1}^{n} W_i \times W_i \times R_e
\]

(20)

where \( V_p \) is the IVC of the URD; \( W_i \) is the frequency of the wind; \( W_i \) is the intensity of the wind; \( R_e \) is the areal proportion of ventilation corridors in the URD; and \( i = 1, 2, ..., n \) is the wind direction in the area. \( R_e \) is calculated as follows:
where \( VC \) is the total area of ventilation corridors, and \( Area \) is the total area of the URD.

3. Results

3.1. Fundamental URD spatial forms in the study area

As a general rule, the URD spatial form (e.g., the orientation, the distance between buildings, the spatial relationship of buildings, etc.) is mainly affected by climate, landscape, folk culture and historical tradition (Cao, 2012; Iscioglu & Keles, 2011; Li et al., 2016; Wang et al., 2019; Yang & Goodrich, 2014). Zhengzhou is a typical city in northern China and its URD spatial forms are regarded as a representative of northern China (Min et al., 2018). For example, Zhengzhou has four distinct seasons and the direct sunlight in winter is short in northern China (Mi et al., 2016). As a result, most of the spatial forms are the parallel form which refers to the north-south orientation of individual building in rows for better sunlight. Secondly, the west of Zhengzhou is a hilly loess area and the terrain is slightly undulating (Lei, 2012). Therefore, some of the spatial forms are the point-group form which refers to the architecture of single-yard housing, multi-layer point housing or high-rise tower housing in order to make use of the micro-topographical features. Besides, Zhengzhou was regarded as “in the middle of heaven and earth” in ancient China (Mandova, 2017). Influenced by the traditional Chinese culture with 5000-year history, there are still a certain number of traditional enclosed form which refers to the buildings forming a closed or semi-enclosed inner courtyard space. Finally, with the development of modern Zhengzhou, the continuous increase of the population from outside has led to a hybrid form which is a combination of above three basic forms or deformation forms to meet

\[
R_A = \frac{VC}{Area} \quad (21)
\]

Fig. 4. The sample data and stratified sampling results.
Fig. 5. Building heights of different URD types derived from ZY-3 images in the study area: (a) point-group form, (b) parallel form, (c) enclosed form, and (d) hybrid form.
The four URD spatial forms determined in this study.

Table 3

| Characteristics of the four URD spatial forms determined in this study. |
|---------------------------------------------------------------|
| Spatial form         | URD                  | Built year | Architectural form | Latitude and longitude | Study area (m²) | Plot ratio |
|----------------------|----------------------|------------|-------------------|------------------------|-----------------|------------|
| Point-group form (a) | Weilaicheng          | 2010       | Apartments        | 113.71° E, 34.76° N   | 66,222.31       | 3.68       |
| Parallel form (b)   | Jiangnan Rongju      | 2008       | Apartments        | 113.65° E, 34.72° N   | 23,592.04       | 4.20       |
| Enclosed form (c)   | Yongwei Hanlin Ju    | 2008       | Apartments        | 113.75° E, 34.79° N   | 68,632.90       | 1.84       |
| Hybrid form (d)     | Wenbo HuaYuan        | 2002       | Apartments        | 113.68° E, 34.80° N   | 40,747.20       | 2.10       |

3.2. Assessment of the integrated ventilation capacity of URDs

3.2.1. Spatial distribution of ventilation corridors in URDs

The four URD spatial forms exhibit very different spatial distributions for their ventilation corridors (Fig. 6). The maximum ventilation length (m)  

Table 4

| The maximum height, minimum height, average height and standard deviation for each URD spatial form. |
|---------------------------------------------------------------|
| Spatial form         | Maximum height (m) | Minimum height (m) | Average height (m) | Standard deviation |
|----------------------|--------------------|--------------------|--------------------|-------------------|
| Point-group form (a) | 95.70              | 66.70              | 79.85              | 10.53             |
| Parallel form (b)   | 29.90              | 12.90              | 19.30              | 3.20              |
| Enclosed form (c)   | 26.04              | 16.78              | 21.33              | 2.40              |
| Hybrid form (d)     | 52.20              | 17.40              | 35.57              | 12.77             |

In order to ensure completeness and representativeness, the stratified sampling method was utilized in the study. Stratified sampling is to divide the sampling unit into different layers according to a certain characteristic or a certain rule, and then draw samples independently and randomly from different layers (Kim, 2005). Stratified sampling ensures that the sample data contains sampling units with various characteristics and sample structure is relatively similar to the overall structure, resulting effective improvement of the estimation accuracy (Wang & Tong, 2008; Trost, 1986). In this study, we take 2685 URDs in Zhengzhou as the sample units. Then the sample units are divided into 4 layers according to the above-mentioned spatial forms. The sample data and weight, mean and standard deviation from the stratified sampling method are shown in Fig. 4 and four representative URDs are shown in Fig. 5, Tables 2 and 3.

The point-group form is observed in Weilaicheng, which is located in Guancheng Huizu District in Zhengzhou, at 113.71° E and 34.76° N. This URD was built in 2010, with a total area of 66,222.31 m² and a floor area ratio of 3.68, the building distribution is scattered, and the majority of buildings are high rises. The parallel form is observed in Jiangnan Rongju which is located in Erqi District in Zhengzhou, at 113.65° E and 34.72° N. This URD was completed in 2008, with a total area of 23,592.04 m² and a plot ratio of 4.20. Buildings are arranged in rows in a north–south direction. The enclosed form is observed in Yongwei Hanlin Ju, which is located in Zhengdong Xin District in Zhengzhou, at 113.75° E and 34.79° N. This URD was built in 2008, with a total area of 68,632.9 m² and a floor area ratio of 1.84. The buildings are distributed along the streets in a closed manner and are typically low-rise ones. The hybrid form is observed in Wenbo HuaYuan, which is located in Jinhui District in Zhengzhou, at 113.68° E and 34.80° N. The total area is 40,747.2 m² and the plot ratio is 2.10. There is no obvious regularity in the distribution of buildings, and the building heights are mixed. The architectural style in all four typical URD apartments is house designs (Fig. 4 and Table 3). The building height data for each URD spatial form are shown in Table 4, which indicate that the difference in building height was large for point-group and hybrid forms but small for parallel and enclosed forms.

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Figure 4: Distribution of buildings and ventilation corridors in URDs. The four URD spatial forms exhibit very different spatial distributions for their ventilation corridors (Fig. 6). The maximum ventilation length (m)
density value in point-group, determinant, and enclosed and hybrid forms is 31.98–39.14, 39.14–47.58, and 47.58–65.24, respectively. Furthermore, the maximum ventilation density value differs with wind direction. In the point-group form, the area of maximum ventilation density with a northeast wind is small and concentrated between building 3 and building 13, whereas that with a southwest wind is relatively scattered on the east sides of building 8 and building 12. The maximum ventilation density area with a northwest wind direction is distributed among building 8, building 11, and building 12. Finally, the area of maximum ventilation density is the smallest with a southeast wind direction, where it is limited to between building 11 and building 12. The minimum ventilation density value for the point-group form is between 4.86 and 9.72. The strength and spatial distribution of ventilation corridors according to wind direction are similar in the parallel form URD. With a northeast and southwest wind direction, maximum ventilation density areas are concentrated between building 3, building 5, and building 6 as well as between building 1 and building 2. With a northwest wind direction, the area of maximum ventilation density is small and concentrated between building 6 and building 7. Finally, with a southeast wind direction, maximum ventilation density is concentrated between building 3 and building 4, with a small area between building 6 and building 7. The minimum ventilation density value for the parallel form is 4.86–9.72.

In the enclosed form, the area of maximum ventilation density is relatively large with a northeast wind direction, and concentrated between building 10 and building 11. With a southwest wind direction, the area of maximum ventilation density is relatively small, concentrated between building 13, building 14, and building 10. The area of maximum ventilation density is the smallest with a northwest wind direction, and only part of it is concentrated between building 10 and building 11. Finally, a small area of maximum ventilation density is observed between building 7 and building 8 with a southeast wind direction. The minimum ventilation density value for the parallel form is between 4.86 and 9.72. The areas of maximum ventilation density are more numerous and scattered in the hybrid form. With northeast and southwest wind directions, three areas exhibit maximum ventilation density, which are distributed between building 5 and building 9, between building 7 and building 14, and between building 3 and building 6. With northwest and southeast wind directions, the areas of maximum ventilation density are similar on the east side of building 11, between building 2 and building 9, between building 3, building 5, and building 6, and between building 7 and building 14. The minimum ventilation density value for the parallel form is between 4.86 and 9.72.

### 3.2.2. Assessment of IVCs

As shown in Fig. 7, the areal proportion of ventilation corridors varies between the four URD spatial forms and with wind direction. Although variations with wind direction are minimal, the point-group form consistently has the largest proportion of ventilation corridors by area, whereas the parallel form consistently has the smallest proportion of ventilation corridors by area.

According to Eq. (20), the IVCs of URDs with various spatial forms are shown in Fig. 8. The IVCs differ between the four URD spatial forms, being largest for the point-group form (0.67), followed by the hybrid form (0.65), with the lowest IVCs for the enclosed form and parallel form (0.36 and 0.30, respectively). The IVC also differs with wind direction.
Ventilation capacity is highest with a northeasterly wind and lowest with a southwesterly wind for all spatial forms.

4. Discussion

(1) Our study fills the gap in the micro-scale URD ventilation assessment in term of aerosol transmission prevention using a general framework, which is profound and complementary to previous macro-scale urban ventilation studies (e.g., the macro-scale urban ventilation corridor in German was built through planning action space, compensation space and urban air guide channels, and controlling the space width and length at different levels; Hong Kong government evaluated the air circulation via wind tunnel tests and measurements for the establishment of urban macro-scale wind field) (Ng et al., 2011; Werner, 1979) and other environmental factors studies. Based on the micro-scale URD ventilation assessment, we provide new policy recommendations for the URD planning and design for controlling aerosol transmission of COVID-19. Although it is quite different in regions such as tropical/frigid zone or mountain/plain area, certain URD patterns are formed as the complex impacts of climate, landscape, folk culture and historical tradition (e.g., the simple URD pattern in northern China vs. the flexible URD pattern in southern China, the enclosed URD pattern in China vs. the open space URD pattern in Europe and the United States) (Giridharan et al., 2004; Guo et al., 2021; Liu et al., 2013; Yan, 2017). During the COVID-19 era it has been a very important and urgent issue to evaluate the micro-scale ventilation capacity of such representative URDs for coping with the virus spread since URD is the main living site and a city process space for residents. As a result, the general framework of data selection and representative URD identification, ventilation model development and construction of ventilation evaluation system in this paper will benefit local planning officers and policymakers all over the world. For example, it is generally believed that the symmetry of the spatial form will affect the ventilation capacity of the URD under different wind directions. The initial result from the general framework has shown that the maximum difference in the ventilation capacity relative to wind direction between enclosed and hybrid URD forms with poor symmetry is 0.20, indicating a significant difference. However, the ventilation capacity relative to wind direction between point-group and parallel URD forms

![Fig. 7. Areal proportion of ventilation corridors for different URD spatial forms and wind directions: (a) point-group form, (b) parallel form, (c) enclosed form, and (d) hybrid form URDs.](image-url)
with strong symmetry also exhibits substantial differences. Therefore, the ventilation capacity of a URD relative to the wind direction is unrelated to the symmetry of the spatial form, but may instead be related to the building orientation of the URD. These results could help urban planners to predict how COVID-19 virus are likely to spread at the micro-scale, and contribute to improve URD design to avoid aerosol transmission.

(2) Daylighting, noise prevention, and safety are the traditional goals for URD planning policy (Kennedy & Buys, 2010; Omer, 2008). However, our research shows that ventilation capacity should also be an important one. Since the global epidemic will not end in the near future (Balli, 2021; Microbe, 2021), a well-ventilated URD can help to suppress the spread of the coronavirus. Therefore, the policy makers should pay attention to the URD ventilation for planning and construction. For example, most of the URDs in the research area are the parallel form, which is only half of the point-group form in term of IVC but 8 times as many as the point-group form. In fact, the research area has faced the rapid movement of COVID-19 viruses since the outbreak. The improperly ventilated URD space could also be a factor. In addition, our research also shows that certain spatial forms of URDs can effectively improve ventilation, thereby enhancing the ability of URDs to prevent COVID-19 transmission. Since there are still many cities around the world that are still plagued by the epidemic, we think it is appropriate to formulate policies related to the improvement of URD ventilation in future urban planning.

(3) Remote sensing has been widely used in studies of the earth’s surface due to its real-time and high-efficiency characteristics (He et al., 2014), along with its capability to handle large volumes of data and a wide range of observations. As such, it has been widely used for mapping COVID-19 outbreaks, risk analysis, and planning the resumption of work and production. In response to the COVID-19 outbreak in India, Shruti et al. integrated satellite remote sensing, GIS, and expert knowledge to effectively address the spread of the disease and defined various risk areas and activities in space (Kanga et al., 2020). Therefore, this field of research provides new solutions for managing COVID-19 outbreaks worldwide. The ZY-3 satellite provides high-resolution remote sensing images with richer surface information for more accurate identification of feature types, particularly the height of buildings and the spatial form of URDs. As these parameters are important for evaluating the IVCs of URDs, ZY-3 very high-resolution remote sensing imagery is expected to play an increasingly important role in the prevention and control of COVID-19 outbreaks.

(4) However, there exist some deficiencies of the study and further researches are needed in the future, as following: (i) This paper mainly focuses on the micro-scale URD ventilation. As a practical matter, the micro-scale URD ventilation and the macro-scale urban ventilation should be combined properly for setting up one integral framework for ventilation evaluation, while tools of synthesis will need much further development. Such integral framework will help to cut off possible routes of aerosol transmission and thus contribute to control the epidemic spread. (ii) Big geodata such as street view images and points of interest (POIs) can be used to obtain voluminous URDs to increase the samples from a variety of sources besides very high-resolution remote sensing images (Berawi et al., 2020; Kontokosta & Malik, 2018; Yan, 2017; Yang et al., 2021). Some of its impacts are evident for adding representative URDs (including the extension of classification and increasement of hierarchy) and improving the computing accuracy of wind resistance coefficient. (iii) Nowadays one of the biggest threats facing our world is global warming. The direct consequence of a warming world is an increase in the intensity and frequency of extreme weather events (Mors et al., 2011; Owusu & Yiridomoh, 2021; Schiermeier & Quirin, 2011; Yan, 2017). For example, weaken surface wind speeds and the changed wind directions may lead to much uncertainty in the ventilation capacity. As a result, for controlling COVID-19 virus aerosol transmission it is necessary to incorporate such climatic consequences into the ventilation assessment in future micro-scale URD designing.

5. Conclusions

In this study, we use very high-resolution remote sensing images from the ZY-3 satellite to analyze samples of URD. The four representative spatial forms in northern China shows the complex impacts on URDs from regional physical, environmental and social elements. We evaluate the IVCs of four identified spatial forms based on the least-cost distance model and found that wind direction has a minimal influence on the ventilation capacity of URDs but the spatial form of the URD leads to substantial differences in the ventilation capacity. For example, IVCs are consistently higher for the point-group and hybrid URD forms than for the enclosed and parallel URD forms; the ventilation capacity within the URD is also significantly different between the buildings. Locally, we recommend, then, that in northern China the policy makers should give a prior consideration to point-group form and hybrid form in URD planning to improve the resistance against airborne viruses. Internationally, although there are great differences in URD forms around the world, the significance of the ventilation should be in focus for the governments’ planning policy, especially during COVID-19 era.

In the 1980s, the WHO proposed the “Urban Health Promotion Plan” and began implementing the regional “Healthy Cities Project,” which is a long-term sustainable development project with the goal of putting health issues on the agenda of urban decision-makers and prompting local governments to formulate corresponding health plans, thereby improving the health of residents. Urban planning is an important method of achieving a healthy city, and the global outbreak of COVID-19 has provided an important opportunity to improve urban living environments. An appropriately designed URD can significantly improve urban ventilation capacity and reduce the risk of COVID-19 transmission. Our research shows that the IVC of well-designed URDs is 2.23
times that of poorly designed URDs, and the difference in ventilation capacity between different URD spatial forms can reach 13.42 times. The difference in ventilation capacity between different URD spatial forms can reach 13.42 times.

Declaration of competing interest
The authors declare no conflict of interest.

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