



Article A Quantitative Study of Geometric Characteristics of Urban Space Based on the Correlation with Microclimate

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Abstract: With the sustainability of contemporary cities gaining more and more attention, interest in the correlation between urban geometry and urban microclimate is increasing. On this basis, this paper aims to investigate the quantification of geometric characteristics of urban space. Based on a combination of easily accessible software packages, a quantitative method composed of spatial partition, spatial characteristic indices (area, shape, and openness), and a spatial classification chart is proposed for the study of the correlation between urban spatial geometry and urban microclimate. Two blocks with different spatial geometric characteristics of the Xinjiekou central area in Nanjing are selected as the cases to verify the operability and effectiveness of this method. The results reveal that complex real urban space can be quantitatively described and classified by this spatial quantification method. In addition, a possible correlation between urban spatial geometry and urban wind environment is demonstrated by using the method, which may also be applicable to the correlation study between urban spatial geometry and other environmental issues.

Keywords: built environment; urban space; geometric characteristics; quantitative approach; urban microclimate

1. Introduction

Due to rapid urbanization in China, the spatial scale, construction capacity and building density of many cities have increased rapidly [1]. This dramatic transformation has improved the living standards of residents to a certain extent, but also increased the environmental burden, leading to increasingly serious urban environmental problems, such as air pollution, the heat island effect and ventilation problems [2,3]. Since urban microclimate affects human comfort and health, evaluating the effects of urban geometry on urban microclimate in urban planning and architectural design has become a significant issue for sustainable urban development [4].

The association between urban geometry and urban microclimate is widely considered to be the beginning of Oke [5]. Oke associates the aspect ratio (H/W) of the ideal street canyon with the airflow pattern inside and draws the interior of the canyon with different aspect ratios. There are several different forms of airflow, i.e., the isolated roughness flow regime (H/W < 0.3), the wake interference flow regime (0.3 < H/W < 0.67), the skimming flow regime with one main vortex (0.67 < H/W < 1.67), and multi-vortex flow regime (H/W > 1.67). Moreover, some correlated research has focused on urban-like configurations, and the plan area ratio (λ_p) and height variation (σ_H), which can represent the density and complexity, have also been added [6–9]. On the basis of urban-like geometry, some scholars have abstracted the model into a more representative real city and added more morphological parameters to investigate the relationship between morphology and microclimate. Through fixing the floor area ratio in urban planning and changing the building coverage, Peng conducted over 100

ideal urban plot configurations to investigate the relationship between the coverage changes and the local ventilation efficiency [10]. You studied the relationship between the length of the building, the distance between the buildings within residential community and the ventilation performance of the local space [11].

The quantitative description of urban space has been investigated by many researchers. Space syntax, proposed by Bill Hillier, is a theory and method to study space organization by quantifying spatial structure [12–15]. It pays attention to the relationship between human society and urban space, not to the geometry and actual size of urban space. As an analysis software of space syntax, DepthmapX divides the space into equal grids and calculates the connectivity, step depth, and integration of these regions. Based on the concept of 'isovist' and 'convex space', many analysis tools used to quantify the spatial characteristics have been developed [16]. In the initial analysis of isovist, Benedikt divided the space into a series of continuous grids, obtained the corresponding isovist shapes from the central points of each grid, and identified six geometric parameters—area, perimeter, occlusivity, variance, skewness, and circularity—to analyze the geometric characteristics of these shapes [17]. Batty proposed a usable computational method to measure isovist fields and explained how to visualize their spatial characteristics using maps and frequency distributions [18,19]. Ratti developed a method for quantifying the geometric characteristics of urban texture by using the raster-based model to evaluate the urban environment [20].

Despite numerous studies, there is a lack of an effective link between urban geometry and the quality of urban microclimate, which is partly attributed to the difficulty in quantitatively describing the complex real urban space [20]. Current quantitative research on urban space usually divides complex urban space into a series of small grids, and then quantify the spatial characteristics from each grid, ignoring the overall geometric characteristics of urban space. Geometric indices, such as spatial width and the aspect ratio, which are widely associated with the quality of microclimate, have limitations and are more suitable for ideal models or extreme urban space cases. Although some studies have attempted to correlate morphological parameters of real cities with microclimates, complex spatial features are still difficult to use with effective morphological parameters, and these real urban spaces are still idealized and use traditional morphological parameters [21–24].

The main purpose of this study is to investigate a quantitative method of spatial geometric characteristics that can be directly related to urban microclimate. For simplicity, as the basic unit of urban space, block space is focused on. In Section 2, blocks in the Xinjiekou central area in Nanjing, a typical rapidly urbanizing area in china, are selected as the study cases. Subsequently, the quantitative method of spatial geometric characteristics is described, including the spatial identification and partition, the quantification of spatial characteristic indices (area, shape, and openness), and the spatial classification based on the indices. A possible correlation method between spatial characteristic indices and the microclimate evaluation index is also proposed in this section. In Section 3, the case in Nanjing is used to verify the feasibility of the quantitative method and the possible correlation between the spatial characteristic indices and the microclimatic evaluation index. The spatial morphological classification chart based on the spatial characteristic indices and wind velocity distribution map is presented. Finally, we systematically discuss the effectiveness, limitations and future prospects of this quantitative method of the geometric characteristics of urban space.

2. Materials and Methods

2.1. Study Area

As the core area with dense buildings, overlapping functions, concentrated population and frequent outdoor public activities, the urban central area has a more significant impact on urban microclimate, and more prominent microclimate problems [25]. The Xinjiekou central area in Nanjing, a typical rapidly urbanizing area in China, has a variety of building types, including large commercial complexes, residential buildings and office buildings, which results in a complex urban spatial form.

The environmental and spatial conditions of this area have been studied by researchers in many fields from the simulation of the urban wind and thermal environment to the quantification of urban form [25–27]. Therefore, the study cases selected in this study are two blocks (block A and B) with different spatial geometric characteristics located in the Xinjiekou central area (Figure 1).



Figure 1. The location of the study area in Nanjing. Source: Google Earth.

2.2. Method

2.2.1. The Identification and Partition of Urban Space

The premise of quantifying spatial geometric features is to identify and divide the continuous space. To this end, we propose a method for identifying and partitioning the complex spaces based on the connectivity graph and Peponis' theory of surface partition, which proposes that the discontinuity of spatial information is caused by the discontinuity of the spatial boundary, such as building corners [28]. The connectivity graph can be generated by DepthmapX, which is a space syntax analysis software that can calculate the connectivity of the space by dividing the space into small grids [29]. Connectivity actually calculates the number of other points located in each grid's center that a particular point can see within its line of sight, which can be applied to quantify the spatial visibility to distinguish urban space [30]. Taking the ideal spatial model shown in Figure 2a as an example, the spatial partition method is demonstrated. Firstly, connect the building corners outside the space to define the scope of the whole space (Figure 2b). Secondly, connect the building corners of the whole space (Figure 2c). Finally, according to the connectivity graph generated by DepthmapX (Figure 2d), select the spatial partition lines (Figure 2e).



Figure 2. The spatial partition method: (a) the ideal spatial model; (b) connect the building corners outside the space to define the scope of the whole space; (c) connect the building corners of all space; (d) generate the connectivity graph by using DepthmapX; (e) select the spatial partition lines.

2.2.2. The Definition and Quantification of Spatial Characteristic Indices

Measurable spatial characteristic indices are very important for understanding and shaping the urban spatial environment and application to the urban design process [31]. There are various indices that can be used to measure the urban spatial geometric characteristics because of the complexity. For urban activities, the area of open space determines the function and carrying capacity of the space, and affects the physical environment of the space, which are all important factors for urban sustainable development [32]. On the condition of the same area, the shape of the space often determines whether a space is wide and spacious, or long and narrow [33]. Even if the area and shape of the space are the same, the enclosure degree of the space. Because the area, shape, and enclosure degree of space can distinguish different types of space and can be understood by urban designers and architects to design corresponding urban spaces, these geometric characteristics of space are further defined as spatial characteristic indices, including area, shape, and openness (Table 1).

Spatial Characteristic Indices	Area	Shape	Openness
Schematic diagram	• big	• spacious	• close
	• small	• narrow	• open

Table 1. The spatial characteristic indices and the corresponding schematic diagram.

Area is the size of the divided space. Shape is similar to elongation and can be measured by the ratio of the average horizontal distance to the maximum horizontal distance from the center of space to the boundary of space [33]. Openness is related to the number and size of openings in the space. On the basis of their respective calculation methods, in order to use computer programming to improve the computation efficiency, this study develops a new method of spatial data acquisition and proposes the calculation method for spatial characteristic indices based on the collected data.

Figure 3a illustrates a spatial plane graph and the isovist from point O. An isovist can be considered as the area that is not in the shadows cast from a point light source [18]. The point O shows the observer's location and the grey area shows the area visible from the location. Based on the concept of isovist, a spatial data acquisition method is developed. First, the buildings are scanned counterclockwise from the *X*-axis around point O and the horizontal distance from point O to the buildings is recorded every 1°, which is called r_i (Figure 3a). Second, the corresponding point-based spatial data graph is created based on the horizontal distance and scanning angle (Figure 3b). When the measuring point is at the centroid of space, the spatial characteristic indices can be calculated by analyzing the numerical changes of the point-based spatial data graph. Through analysis, a Python script is developed to calculate the spatial characteristic indices (see the Supplementary Material: Script S1). The mathematical development of the indices is shown below.



Figure 3. The spatial plane graph and the point-based spatial data graph: (**a**) scanning of the buildings counterclockwise from the X-axis around point O and recording of the horizontal distance from point O to the building every 1°, which is called r_i ; (**b**) illustration of the corresponding point-based spatial data graph.

Area measures the size of space, which is the basic characteristic of open space (Figure 4a). The equation used is as follows:

Area =
$$\sum \frac{r_i r_{i+1} \sin 1^\circ}{2} \qquad [m^2] \tag{1}$$

where r_i ($1 \le i \le 360$) represents the horizontal distance from a measuring point to the spatial boundary composed of the building walls and spatial partition lines.



Figure 4. The spaces with different geometric characteristics shown in a spatial plane graph and the corresponding point-based spatial data graph: (**a**) the spaces of different areas with the same shape and openness; (**b**) the spaces of different shapes with the same area and openness; (**c**) the space with two openings, which are marked in red.

Shape measures the narrowness of urban space, which can be used to distinguish short and wide spaces from long and thin spaces. Figure 4b illustrates that as the shape becomes longer and narrower, the ratio of maximum horizontal distance to average horizontal distance increases. Therefore, the equation used is as follows:

$$Shape = \frac{r_{ave}}{r_{max'}} \qquad [-] \tag{2}$$

where r_{ave} and r_{max} are the average horizontal distance and maximum horizontal distance from a measuring point to the spatial boundary composed of the building walls and spatial partition line. The shape value ranges from 0 to 1. The larger the value is, the wider the space is. The smaller the value is, the narrower the space is.

Openness is related to the number and size of the openings in urban space. The equation used is as follows:

$$Openness = \frac{N_o \times A_o}{360^\circ} \qquad [-] \tag{3}$$

where N_O is the number of openings in the space around the measuring point, and A_O is the angle of openings in the space around the measuring point. As shown in Figure 4c, openings in space have a direct relationship with the change of horizontal distance in the point-based spatial data graph. Therefore, a Python script is developed to calculate N_O and A_O by analyzing the change of horizontal distance (see the Supplementary Material: Script S1). The larger the value is, the more open the space is.

2.2.3. Spatial Classification Method Based on Spatial Characteristic Indices

The spatial morphological classification chart with area, shape, and openness as axes is proposed to classify urban space with different geometric characteristics. Figure 5a shows three groups of controlled trials with different spatial geometric characteristics: keeping the other two spatial characteristic indices unchanged, the area of a1 to a4 gradually increases, the shape of b1 to b4 gradually decreases, and the openness of c1 to c4 gradually increases. Figure 5b shows the distribution of a1 to c4 on the spatial morphological classification chart. Different spatial forms present different aggregation conditions on the spatial classification chart. By analyzing the distribution of density, urban space with different geometric characteristics can be classified.



Figure 5. Controlled experiments with different spatial geometric characteristics: (**a**) keeping the other two spatial characteristic indices unchanged, the area of a1 to a4 gradually increases, shape of b1 to b4 gradually decreases, and openness of c1 to c4 gradually increases; (**b**) the distribution of a1 to c4 on the spatial morphological classification chart.

2.2.4. The Correlation Method of Spatial Characteristic Indices and Microclimate Evaluation Index

In order to verify the feasibility of the correlation study between the above spatial quantitative method and urban spatial microclimate, computational fluid dynamics (CFD) was used to simulate the wind field of pedestrian height (h = 1.5 m) in the block. The standard k- ε model of the 3-D steady Reynolds Average Navier-Stokes (RANS) approach was employed for the numerical simulation [34]. The summer typical inflow wind in Nanjing was taken as the inflow wind speed (https://weatherspark.com/y/132872/Average-Weather-in-Nanjing-China-Year-Round). A validation study against the wind tunnel experiment has been performed in a previous study [11]. In order to better verify the applicability of the correlation study between space and local ventilation, the spatial wind velocity ratio (VR) was

employed as a quantitative evaluation index in this study. By comparing the three spatial characteristic indices (area, shape and openness) with VR, it can provide ideas for the study of the correlation between urban spatial geometry and urban microclimate. The equation of VR is as follows:

$$VR = \frac{U}{U_0} \qquad [-] \tag{4}$$

Here, VR donates the spatial velocity ratio, U is the specified velocity at a pedestrian level (h = 1.5 m), and U_0 is the reference velocity in the far upstream free flow.

3. Results and Analysis

3.1. Spatial Partition and Spatial Data Collection

According to the spatial partition method mentioned above, the space in block A and B is identified and divided (Figure 6a). As verification, the spatial partition is compared with the connectivity graph generated by DepthmapX (Figure 6b). The subspaces of block A and B are numbered, and there are 36 subspaces from A0 to A35 in block A and 17 subspaces from B0 to B16 in block B (Figure 6c). The measuring points are set in the centroid of these subspaces to collect information on the space (Figure 6d).



Figure 6. The partition, connectivity graph, numbers and measuring points of the space in block A and B: (**a**) spatial partition; (**b**) superposed spatial partition lines on the connectivity graph based on DepthmapX; (**c**) 36 subspaces from A0 to A35 in block A and 17 subspaces from B0 to B16 in block B; (**d**) the measuring points placed in the centroid of the subspaces.

3.2. Spatial Data Processing and Analysis

The spatial data processing flow is as follows. Firstly, the grasshopper program in Rhino software is used to collect the spatial data around the measuring points. Second, the python script is run with the collected spatial data to calculate the spatial characteristic indices. Finally, the values of these spatial characteristic indices are employed to quantify and classify the geometric characteristics of the block spaces.

Figure 7 shows the calculation results of the spatial characteristic indices of the blocks (the values of the spatial characteristic indices can be seen in the Supplementary Material: Table S2). It can be found that the range of area is from 25 m² to 13,394 m², the range of shape is from 0.04 to 0.99, and the range of openness is from 0.03 to 2.01. The numerical differences between different spaces are obvious. Moreover, by comparing the values of the spatial characteristic indices (area, shape, and openness), different spatial geometrical characteristics can be distinguished. Take the index values of spaces in block A and block B as an example, where the red frame in Figure 7 shows four different types of spaces (space A4, A6, A23, and B14) in the blocks with distinctly different spatial characteristic indices:

- The space with a small area, large shape, and large openness is a small, open and spacious space (such as space A4);
- The space with a small area, small shape, and small openness is a small, closed and narrow space (such as space A6);
- The space with a large area, small shape, and small openness is a large, closed and narrow space (such as space A23);
- The space with a large area, large shape, and large openness is a large, open and spacious space (such as space B14).



Figure 7. The spatial characteristic indices charts and four types of spaces in block A and B: space A4, A6, A23, and B14.

3.3. Urban Spatial Classification with Different Geometric Characteristics

According to the statistics of the spatial characteristic indices (area, shape, and openness) and the distribution of the statistics on the spatial morphological classification chart, the spaces in two blocks of the Xinjiekou central area can be generally classified into five categories as shown below (Figure 8a).

- Type 1 (large open spacious space) with a large area, shape, and openness (marked in red);
- Type 2 (large closed narrow space) with a large area and small shape and openness (marked in green);
- Type 3 (small closed narrow space) with a small area, shape, and openness (marked in blue);
- Type 4 (large open narrow space) with a large area and openness and small shape (marked in light purple);
- Type 5 (small open spacious space) with a small area and large shape and openness (marked in yellow).



Figure 8. Spatial morphological classification chart and the corresponding spatial distribution map: (**a**) Type 1 is a large open spacious space, Type 2 is a large closed narrow space, Type 3 is a small closed narrow space, Type 4 is a large open narrow space, and Type 5 is a small open spacious space; (**b**) the spatial distribution of the five spatial types on the map.

Figure 8b illustrates the spatial distribution of these five spatial types on the map to intuitively reveal the difference of the spaces, which is also validation of the above classification methods.

3.4. Comparison of the Spatial Average Wind Velocity Ratio and Spatial Characteristic Indices

We performed a simulation of the wind flow field of pedestrian height in block B according to the method mentioned in Section 2. The simulation results are shown in Figure 9a. In order to further compare them with the spatial geometry, the spatial partition lines are superposed on the wind velocity distribution (Figure 9b), and the spatial average wind velocity ratio of each subspace is calculated based on the spatial partition (statistics can be seen in the Supplementary Material: Table S3).



Figure 9. (a) The wind velocity at a pedestrian level (h = 1.5 m) in block B of summer; (b) spatial partition lines superposed on the wind velocity distribution.

According to the numbers of subspaces in block B, the calculated spatial average wind velocity ratio can be compared with the spatial characteristic indices of different subspaces to analyze the changing trend of its value (Figure 10). The bar chart with different colors represents the different spatial characteristic indices, and the line chart represents the spatial average wind velocity ratio. Complex and real urban space can be quantified into three spatial characteristic indices, which can be combined as different aspects of the whole space to compare with spatial average wind velocity ratio comprehensively.



Figure 10. A line chart with statistics of the spatial average wind velocity ratio and a bar chart with spatial characteristic indices (area, shape, and openness) of subspaces in block B.

4. Discussion

By comparing the spatial average wind velocity ratio of each subspace with the spatial characteristic indices of the area, shape, and openness of each subspace, the relationship between the wind environment and the spatial geometric characteristics could be inferred. It could be generally inferred

that the area and openness are related to the wind environment, but the shape is not. Taking space B0 and space B1 as examples, the area and openness of space B0 are larger than space B1, while the shape of space B0 and space B1 is similar, and the average wind velocity ratio of space B0 is larger than space B1. However, this relationship between area and openness and the wind environment is not absolute. For example, space B14 has the largest area and openness in all subspaces of block B, while the spatial average wind velocity ratio is not the largest. This phenomenon may be caused by the surrounding space environment or other spatial characteristics of the space.

It is worth noting that the north side of space B14 is another block, which is separated with block B by a street. At the beginning of the quantitative study of urban space, block space, as the basic unit of urban space, is taken as the research object. While the space outside the blocks, which is usually the street space between the blocks, is not taken into account. This space may have an impact on the microclimate inside the block, especially the wind environment. Therefore, the spatial partition method may need to be optimized according to different researching purposes and spatial conditions.

5. Conclusions

We proposed a new quantitative method of spatial geometric characteristics, including spatial partition, spatial characteristic indices (area, shape, and openness), and spatial classification, to provide ideas for the study of the correlation between urban spatial geometry and urban microclimate. The spatial partition and quantification methods proposed in this paper make the quantified spatial objects clearer, so as to make the objects of correlation study clearer. For urban planners and building designers, the specific urban space can be designed and improved according to the results of the relationship between the spatial geometry and the wind environment.

Three spatial characteristic indices, including area, shape, and openness, can effectively describe the complex urban space to a certain extent. In addition to area and shape, which are recognized as the basic spatial characteristic indices, openness is a very important index for describing the spatial form, which is usually calculated by obtaining the ratio of the spatial entity boundary perimeter to total spatial perimeter. In fact, the openness of space is not only related to the length of spatial openings, but also to the number and distribution of these openings. Therefore, this research optimizes the calculation method of openness and makes it more pertinent. In this study, the quantification of urban geometry focuses on the spatial plane geometry. However, for the wind environment, height is also an important morphological index. Therefore, how to incorporate height into the current quantitative methods and the relationship between all these indices may need further study.

Taking two blocks in the Xinjiekou central area in Nanjing as an example, the spatial average wind speed ratio and the spatial characteristic indices are compared and analyzed, and the effectiveness and practicability of the correlation research between the wind environment and urban spatial geometry have been verified. In the correlation research with the wind environment, the shape has little correlation, and the area and openness are correlated with the wind environment to some extent, but the correlation is not absolute. Further analysis is needed in combination with the specific space and its surrounding spatial environment. When the area, shape and openness are not correlated with the wind environment, other spatial characteristic indices may be needed. It is worth noting that when the shape is the same, if the direction of the shape and wind is different, although the visual perception of space is the same, the wind environment is different. Therefore, it is necessary to discuss the direction of shape in a future correlation study on spatial geometrical configurations and the wind environment. In addition, it is found that there may not be a unique spatial partition, which depends on different environmental issues. For example, when associated with the wind environment, the spatial partition can take into account the space outside the block. The spatial partition method will be further discussed for different microclimate problems in future research.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/11/18/4951/s1, Script S1. Python Script of Spatial Characteristic Indices; Table S2. Statistics of the Spatial Characteristic Indices of Subspaces in Block A and B. Table S3. Statistics of Spatial Average Wind Velocity Ratio of Subspaces in Block B.

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