Impact of Urban Morphology Parameters on Microclimate

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Abstract

Urbanization process has dramatically influenced urban climate and environment. In the urban planning and design practice, there are several important parameters such as sky view factor, floor area ratio, site coverage ratio and building stories. These parameters can determine the urban morphology. This study shows the impact of urban morphology parameters on urban microclimate. It aims at provide suitable ranges of parameters which are beneficial for the thermal comfort of urban pedestrians. As a result, recommendations are given for government agency and urban planners in the urban design process.

Keywords: parametric study; urban morphology; sky view factor; microclimate; thermal comfort

1. Introduction

According to the statistics from the National Bureau of China, the urban population accounted for more than half (54.78%) of the country’s population in 2014. Megacities in China, such as Beijing, Shanghai, Guangzhou, Shenzhen, are facing a significant pressure to extend their land to accommodate their increasingly high population. The urbanization process brings a lot of benefits. In the meantime, the highly densified urban development causes many problems related to urban climate, air pollution, ecosystems, energy consumption, traffic and health.

Urbanization provokes major modifications on natural landscape. For instance, soils have been transformed into roads and pavement. Consequently, greenery has been vastly reduced. Considering these major changes, weather conditions within the urban canopy layer exhibit the clearest signs of inadvertent modifications [1]. Urban morphology...
influences urban microclimate, and vice versa. Therefore, effective urban design with the consideration of local climate has become an important and urgent task for the cities with high building densities.

Climate responsive urban design requires comprehensive and vast knowledge in different fields. This includes climatology, geography, urban planning, architecture, energy engineering. This study tries to focus on links between microclimate and urban morphology. The latter has significant impact on Urban Heat Island (UHI) effect and energy use in buildings. The objective of this paper is to demonstrate microclimate analysis on a hypothetical district varying urban morphology parameters. And it aims at improve the efficiency of using urban space, enhance thermal comfort in cities and reduce energy consumption.

2. The Variables to Characterize the Building Environment

Problems related to urban climate are so complex that it is impossible to include every variable into the analysis to quantify the microclimate impact of the built environment. So, it is crucial to choose the right variables [2].

2.1. Sky View Factor (SVF)

The main reason of the UHI is the urban–rural temperature difference in the nocturnal cooling processes, which are primarily forced by outgoing long wave radiation. In urban areas the 3D geometrical configuration of the urban surface cover plays an important role in the restriction of long-wave radiative heat loss. It also contributes to intra-urban temperature variations below roof level [3] [4]. The highest UHI intensity is generally higher in the nighttime than daytime [5]. The Sky View Factor (SVF) is the most appropriate parameter describing the urban geometry [4]. The SVF is defined as the ratio of the radiation received (or emitted) by a planar surface and the radiation emitted (or received) by the entire hemispheric environment [6]. Therefore, it is a dimensionless measure between zero and one [7]. The regression analysis of field measurements indicates a strong negative relationship between SVF and UHI [8].

2.2. Urban density parameters

![Diagram of indicators included in 'space-mate']

Pont, M. B. established a comprehensive density indicators diagram tool to characterize urban geometry [9]. The tool is called ‘Space-mate’ (Fig.1). It makes possible to describe an urban environment by using a set of density variables (FSI, GSI, OSR and L). These quantities can be used both to describe and characterize, as well as prescribe different urban environments.
Four more variables which are included in ‘space-mate’ have to be introduced to demonstrate how the geometry of a site can be differentiated from others. They are useful when describing the Ground Space Index (GSI), the Open Space Ratio (OSR) and the Layer (L). The Floor Space Index (FSI), which is also called the Floor Area Ratio (FAR), expresses the intensity of a built area. The FAR is widely used in design briefing and development budgeting as it reflects the amount of floor area to be built. It can be used to estimate the balance of investment and returns. The Gross Space Index (GSI), or the Building Site Coverage (BSC), describes the proportion of built ground in an area. It also demonstrates the relationship between built and non-built space. The Open Space Ratio (OSR), or spaciousness, describes the intensity of the non-built ground. The number of stories (L) indicates the average number of floors in an area.

Fig. 2. The first group of scenarios with the same FAR

| FAR | BSC | L  | Gross Floor Area (m²) | Foot Print Area (m²) | Building length (m) |
|-----|-----|----|-----------------------|----------------------|---------------------|
| 3   | 11% | 27 | 6912                  | 256                  | 16                  |
| 3   | 17% | 17 | 6912                  | 400                  | 20                  |
| 3   | 25% | 12 | 6912                  | 576                  | 24                  |
| 3   | 34% | 9  | 6912                  | 784                  | 28                  |
| 3   | 44% | 7  | 6912                  | 1024                 | 32                  |
| 3   | 56% | 5  | 6912                  | 1296                 | 36                  |
| 3   | 69% | 4  | 6912                  | 1600                 | 40                  |

Table 2. The second group of scenarios sharing the same BSC

| FAR | BSC | L  | Gross Floor Area (m²) | Foot Print Area (m²) | Building length (m) |
|-----|-----|----|-----------------------|----------------------|---------------------|
| 2   | 25% | 8  | 4608                  | 576                  | 24                  |
| 3   | 25% | 12 | 6912                  | 576                  | 24                  |
| 4   | 25% | 16 | 9216                  | 576                  | 24                  |
| 5   | 25% | 20 | 11520                 | 576                  | 24                  |
| 6   | 25% | 24 | 13824                 | 576                  | 24                  |
| 8   | 25% | 32 | 18432                 | 576                  | 24                  |
| 10  | 25% | 40 | 23040                 | 576                  | 24                  |

3. Research Methodology

This study aims at discover the connection between the SVF and urban density. In additions, it is intended to analyze the impact of urban morphology parameters on microclimate variables such as Ambient Temperature ($T$) and the Mean Radiation Temperature ($T_{mrt}$). A parametric study [10] was conducted on interactions between urban morphology and microclimate. The building plots are hypothetical districts located in the urban area of Shanghai, China. All the scenarios are assumed to be on the same district configuration, where buildings are inside 9 plots (red color) of 48 m × 48 m. They are surrounded by rows of identical buildings as buffer area (white color). Proposed
buildings are designed with square plan. The impact of plants on microclimate is excluded. Therefore, there is no vegetation in all the scenarios. The scenarios are named by FAR-x_BSC-y, where x indicates their Floor Area Ratio and y the BSC in percentage.

In the process of the urban design practice, the FAR is usually arranged by the urban planning bureau to make the best use of the land. Although the plots share the same FAR value, their morphology could have many choices. For instance, their building site coverage, footprint area number of floors and the layout of buildings can vary dramatically. This parametric study includes two groups of scenarios. The first group share the same FAR value. However, the BSC and the number of floors (L) of each scenario vary (see Fig. 2). The analysis of this group aims at investigate the connection between the BSC and the SVF of scenarios with same the FAR value. Besides that, it is intended to discover the impact of BSC on microclimate when their FAR is constant. The second group shares the same BSC, while the FAR and floors (L) increase gradually. The purpose to analyze this group is to explore the relationship between the FAR and the SVF when the BSC is constant.

The SVF, T, the T_{mrt} of these two groups of scenarios were calculated with ENVI-met. The simulation starts at 0:00 am on June 22nd 2001. The simulation of each scenario ran for 24 hours. Initial temperature was set as 293 K. Relative humidity at 2 m was 50%. Wind speed and wind direction were 3.1m/s and southeast, respectively. The other variables were set to default values. All scenarios share the same boundary conditions.

4. Data Analysis

4.1. The connection between SVF and Density indicators

![Fig. 3. Relationship between Mean SVF and BSC with FAR of 3](image1)

![Fig. 4. Relationship between Mean SVF and FAR with BSC of 25%](image2)

The mean SVF of Group 1 can be seen in Fig. 3. The diagram shows that the mean SVF has a large range from 0.41 (BSC-11) to 0.17 (BSC-69), even though scenarios of each group shares the same FAR. It can be observed that the mean SVF significantly decreases. When the FAR remains constant and the site coverage increases, the building footprint area will increase although the height of buildings decrease (Fig. 2). Therefore, the building interval decreased due to the increased footprint area. Consequently, the SVF declines due to the decreased buildings interval. Although the decreased heights (caused by decreased number of story) can provoke an increase of SVF, the impact of the decreased building interval excesses the impact of decreased building height on SVF.

Fig. 4 illustrates the mean SVF for various scenarios of Group 2 with a BSC of 25%. Similar to what was observed in Fig. 3, the mean SVF decreases. The latter ranges between 0.48(SVF-2) and 0.21(SVF-8). The reason is that, in this group, the building site coverage is invariable. It results in the building footprint area of each scenario is constant. The varying parameters are number of floors (L) and building height. When the building height proportionally increases with respect to the FAR, the sky view was increasingly obstructed by the increased building height. Consequently, the SVF experience a declined trend with the increased FAR.
4.2. Impact of building density indicators on microclimate

In this section, the objective is to investigate how microclimate variables are affected by variations of the BSC with constant FAR of 3.

4.2.1. Impact of Building Site Coverage on mean radiant temperature

The mean $T_{mrt}$ profile of Group 1 for different scenarios is depicted in Fig. 5. The graph shows that at night the range of $T_{mrt}$ is very narrow (2-3.3°C). In the daytime, the $T_{mrt}$ range of different scenarios becomes wider. It reaches the maximum (20.7°C) when the time close to the noon. The gap tends to be narrow when the time close to sunset. According to Fig. 5, all scenarios in this group reach their peak at 12:00, and fall to the bottom at 5:00. Therefore, the average $T_{mrt}$ at 5:00 (Min. $T_{mrt}$) and 12:00 (Max. $T_{mrt}$) are picked to conduct further analysis.

Fig. 5. Averaged hourly $T_{mrt}$ of the Group 1 scenarios

The relationship between the minimum $T_{mrt}$ and the BSC can be observed in Fig. 6(a). It shows that the minimum $T_{mrt}$ presents a general growing trend with the FAR of 3 when the building site coverage increases from 11.67°C (BSC-11) to 13.68°C (BSC-69). According to the previous section, the SVF decreases when the BSC increases. It can be therefore deduced that the minimum $T_{mrt}$ increases when the SVF decreases. This outcome agrees with J. Unger’s research [8]. In the nighttime, urban areas with higher SVF have a lower radiant temperature due to their openness. However, it shows that minimum $T_{mrt}$ slightly decreases when the BSC is less than 17%. It can also be observed that the minimum $T_{mrt}$ reaches to its bottoms at 11%. This means that other urban morphology factors need to be considered apart from BSC and SVF.

Fig. 6(b) illustrates the maximum Mean Radiant Temperature (Max. $T_{mrt}$) at 12:00. When the FAR is 3, the maximum $T_{mrt}$ decreases when the BSC increases from 60.13°C (with a BSC of 11%) to 39.59°C (with a BSC of 56%). In the previous section, it was discovered that the SVF decreases when the BSC increases. Similar to what was observed in the research of Oke [1] and J. Unger [8], higher radiation occurs in areas with higher openness (i.e. with a high SVF) in the daytime. When the SVF declines, the shade of solar radiation increases. This causes the $T_{mrt}$ to decline. The only scenario that does not obey this trend is FAR-3_BSC-69. It is probably because the BSC reaches 56% when the shade of the buildings reaches the maximum. An increase in the BSC cannot lead to an increase of the shade anymore. In other words, the maximum $T_{mrt}$ cannot decline anymore.
A closer examination upon the 24 hours averaged $T_{mrt}$ ($\text{Avg. } T_{mrt}$) reveal the relationship between the $T_{mrt}$ and the BSC. Fig. 7 shows that the averaged $T_{mrt}$ decreases from 32.15°C (with a BSC of 11%) to 24.34°C (with a BSC of 56%). It means that the overshadowing of buildings in the daytime gives a dominant impact on $T_{mrt}$ and pedestrian comfort. Therefore, the layout with a large BSC (Low SVF) is beneficial to reduce the $T_{mrt}$ during summer season in Shanghai, when the FAR is constant and no vegetation is planted.

4.2.2. Impact of Building Site Coverage on ambient temperature

Another observation was made for ambient temperature of Group 1. Fig. 9 shows the mean hourly ambient temperature profile. It describes that ambient temperature of all scenarios falls to the bottom at 6:00 ($T_{min}$) and reaches the peak at 14:00 ($T_{max}$). This is quite different with the profile of $T_{mrt}$, because of the time lag of the radiation transform to heat of the air. At night, the graph (Fig. 9) shows that the gap of the minimum air temperature ($T_{min}$) of different
scenarios very narrow (0.78°C). On the other hand, in the daytime, the range of ambient temperature in different scenarios becomes distinct and reaches the maximum (4.12°C) when close to 13:00. The gap of difference scenarios doesn’t narrow dramatically as the $T_{mrt}$ when the night falls.

![Fig. 9. Hourly ambient temperature of the Group 1 scenarios](image)

Fig. 10 shows that mean ambient temperature of all the scenarios fall to the bottoms at 6:00 ($T_{min}$) and reach the peak at 14:00 ($T_{max}$), so a closer examination upon $T_{min}$ and $T_{max}$ were done to scrutinize the relationship between ambient temperature and the urban morphology.

![Fig. 10 (a) $T_{min}$ at 6:00; (b) $T_{max}$ at 14:00 of the Group 1 scenarios](image)

Fig. 10(a) illustrates the link between $T_{min}$ and the BSC. It can be observed that $T_{min}$ declines from 16.96°C of BSC-11. It hits the bottom at 16.02°C with the BSC of 25%. Then, it grows to 16.61°C of BSC-69. According to the previous analysis of the SVF, the latter decreases when the BSC increases. Consequently, the $T_{min}$ increases with respect to the BSC. This comes from the fact that an increase of the obstruction from surroundings provokes an
increase in the amount of heat released into the atmosphere. When the site coverage is less than 25%, the profile does not obey this tendency. (It means that other variables effect the $T_{min}$, which still need further research.) The curve demonstrates that the layout of BSC-25 is the best choice to alleviate UHI effect in summer nights of Shanghai.

Fig. 10(b) displays the impact of BSC on $T_{max}$ when the FAR is constant. It shows that $T_{max}$ increases with respect to the BSC from 23.75°C (of BSC-34) to 19.89°C (of BSC-69). This is similar to the previous study [1,5,8] where it was observed that urban areas with high openness (low BSC, high SVF) experience higher $T_{max}$ in the daytime. However, compared with the $T_{min}$ graph where the scenario of BSC-25 experiences lowest $T_{min}$ in the nighttime, the highest $T_{max}$ are achieved by BSC-25 in the daytime.

As the previous diagrams of $T_{min}$ and $T_{max}$ display different trends, the 24-hours averaged ambient temperature was conduct to scrutinize the abstract relationship between the average ambient temperature and urban morphology parameters (Fig. 8). The chart (Fig. 8) shows that the average temperature declines from 20.27°C of BSC-11 to 18.09°C of BSC-69. This is caused by the same reasons observed in the daily averaged $T_{mrt}$.

5. Conclusion

This study intended to analyze the relationship between urban morphology parameters and microclimate of two groups of scenarios. As a result, it was shown that urban morphology parameters have a significant connection with microclimate variables. In other words, urban morphology parameters have an obvious impact on microclimate.

In addition to this, two main findings were discovered. First, the SVF declines when the BSC increases and the FAR remains constant. In the case that the BSC is constant at 25%, the SVF also decreases when the FAR increases. Second, $T_{mrt}$ and $T$ are strongly correlated with urban morphology parameters when the FAR is constant. In the nighttime, minimum $T_{mrt}$ increases with respect to the BSC. The same thing can be observed with $T_{min}$. Based on these observations, BSC-25 was recognized as best choice to alleviate UHI effect in summer nights of Shanghai. In the daytime (12:00), maximum $T_{mrt}$ and $T_{max}$ decrease when the BSC increases. In other words, in the nighttime, urban areas with higher SVF (lower BSC) have a lower $T_{mrt}$ and $T$ due to their openness. On the other hand, in the daytime, higher radiation occurs in areas with high SVF (lower BSC). Moreover, the overshadowing in the daytime gives a dominant impact on the averaged $T_{mrt}$ and averaged $T$. When the FAR is constant and no vegetation is planted, the layout with a large BSC (Low SVF) is beneficial to reduce both $T_{mrt}$ and $T$ during summer seasons in Shanghai.

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