The Study of the Effects of Building Arrangement on Microclimate and Energy Demand of CBD in Nanjing, China

Ji-Yu Deng\textsuperscript{a*}, Nyuk Hien Wong\textsuperscript{b}, Xin Zheng\textsuperscript{a}

\textsuperscript{a}School of Architecture, Southeast University, No.2 Sipailou, Nanjing 210096, China
\textsuperscript{b}Department of Building, National University of Singapore, 4 Architecture Drive, Singapore 117566, Singapore

Abstract

This study aims to investigate the impact of building arrangement on the urban microclimate and energy consumption of buildings in central commercial and business district by using simulation tools, including ENVI-met and HTB2. In order to achieve this goal, a series of numerical calculations and building energy simulations are utilized to evaluate a total of 12 urban scenarios with various building arrangements. The results indicate a quantitative correlation between building arrangement and the microclimate and building energy performance at urban design scale. Furthermore, several recommendations have been provided for urban planners and designers as strategies and methods to mitigate the UHI effect and to reduce the energy consumption.

Keywords: Urban heat island; Building arrangement; Urban microclimate; Energy consumption; Plot ratio

1. Introduction

The urban heat islands (UHI) is known as the significant differences in microclimate between urban and rural areas [1]. Especially in the central area of city, the microclimate parameters in outdoor spaces, including the air temperature, wind speed, relative humidity, solar radiation etc., are significantly influenced by various configurations of urban texture, such as plot ratio, site coverage, building height, and building arrangement etc. Consequently, the microclimate parameters affect the outdoor thermal comfort and building energy demand considerably and correspondingly.

\* Corresponding author. Tel.: +86 153 8098 5151.
E-mail address: jiuyudeng@gmail.com (Ji-Yu Deng).
Over the past few decades, a large number of studies have been carried out to investigate the impact of urban morphology on microclimate condition. Basically, some researches were conducted by numerical models [2–4], while some others were based on field measurements [5–7]. These studies have validated how the urban geometry had certain effects in relation to urban microclimate condition.

Due to the climate change, building energy consumption will become increasingly sensitive to the effects of surrounding buildings. Therefore, building energy performance analysis should be considered in neighborhood context instead of an isolate building [8]. Moreover, most of the correlative studies were conducted to validate the relationship between urban morphology and building energy consumption by using an energy simulation tool [9–11].

Reference to above literature review, the parameters of urban morphologies involved in most of the studies are concerned with the street geometries, including aspect ratios, orientations, plot ratios and density. However, only a few literatures focused on the effects of building arrangement which create the various streets and canyons [12, 13].

This study aims to detect the effects of building arrangement variations on outdoor thermal conditions and building energy performance in CBD area under the local climate of Nanjing city. In order to achieve this goal, a series of numerical simulations were conducted to evaluate several urban scenarios with various building arrangements derived from two building prototypes and different parameter combinations. Finally, comprehensive and effective solutions for optimizing the guidelines and strategies of urban planning and design have been proposed.

2. Site Description

This study is carried out for typical summer conditions in Nanjing city located at 32.05°N, 118.48°E, and 22 m altitude above sea level. This city is characterized by a humid subtropical climate which is hot and humid in summer with an average maximum temperature of 32°C and a humidity of about 75%. The prevailing winds are from east and southeast, with average speed ranging from 2 to 3 m/s. All these climate conditions contribute to the typical climate of the middle and lower reaches of Yangtze River region.

![Fig. 1. The location of the reference site.](image)

The study area is located in the central area of the city, called Xinjieckou, which is a famous CBD with a dense urban morphology, as is shown in Fig. 1. The reference site is characterized by high-rise buildings, narrow streets and less vegetation. The block shape in this area can be classified into two types: point one and slab one. In addition, most of the streets have the E-W and N-S orientations, and some of them are with intermediate orientations while the terrain of the site location is flat. The outdoor space formed by variations of building arrangements has been adopted as the object of analysis in this research for the microclimate simulation.
3. Methodology

3.1. Development of urban setting scenarios

In this part, a total of 12 urban scenarios with various building arrangements have been developed by referring to the existing urban planning and building regulations of Nanjing city. As mentioned before, two block shapes, the point one and slab one, can be abstracted to be the representatives of the building typologies in urban context of Nanjing. For this paper, a total of 36 duplicated buildings for each building prototype were placed on a standard site of 504 m x 504 m which is suitable for a typical CBD estate. The horizontal dimensions of these two building prototypes were fixed, one for the point blocks is 48 m x 48 m while another for the slab blocks is 24 m x 96 m. Due to the square shape, the layouts of the whole site were arranged to be 6x6 blocks matrix for point type and 4 x 9 blocks matrix for slab type respectively. However, the distances between blocks are 24 m constantly in each scenario (Fig. 2).

![Fig. 2. The layouts of the whole site for point blocks (a) and slab blocks (b).](image)

For comparison purpose, the plot ratios of these scenarios were fixed to be a constant while a total of 36 buildings with various heights were arranged in 6 different ways to form 6 different urban scenarios for each building types. There is not explicit regulation to restrict the stories and heights of commercial and business buildings in Xinjiekou CBD. Accordingly, the building stories for point blocks in pre-set urban scenarios were set to be 10, 16, 22, 28, 34 and 40, and each value was assigned to 6 blocks. As a result, the corresponding building heights are 36 m, 57.6 m, 79.2 m, 100.8 m, 122.4 m and 144 m respectively if the story height is 3.6 m. Meanwhile, for slab blocks, the building stories were set to be 13, 16, 19, 22, 25, 28, 31, 34 and 37, and each value was assigned to 4 blocks. Correspondingly, the building heights are 46.8 m, 57.6 m, 68.4 m, 79.2 m, 90 m, 100.8 m, 111.6 m, 122.4 m and 133.2 m respectively.

It is necessary to note here, due to the constant value of plot ratio and site coverage, the total building volumes of the urban scenarios also keep a fixed value, and the average building heights (Av. H) of the scenarios are 90 m for 25 average stories (Av. ST) constantly. Both for two types, one of the 6 urban scenarios, which is full of buildings with 90m high and 25 stories, was regarded as a comparison benchmark. Therefore, the other 5 urban scenarios with various building heights were arranged in the way of center-high, center-low, high-to-low, low-to-high and random respectively, as is shown in Fig. 3 and Fig. 4.

The urban texture parameters of all the 12 scenarios are listed in Table 1, including the plot ratio, site coverage, building height (H), building storey (ST) and sky view factor (SVF) which has been validated as a key variable to contribute to the UHI [2, 14, 15]. The SVF values were calculated by using Skyhelios [16].

![Fig. 3. The perspectives of group one for point blocks: (a) Point-avg; (b) Point-center-high; (c) Point-center-low; (d) Point-high-low; (e) Point-low-high; (f) Point-random.](image)
Fig. 4. The perspectives of group two for slab blocks: (a) Slab-avg; (b) Slab-center-high; (c) Slab-center-low; (d) Slab-high-low; (e) Slab-low-high; (f) Slab-random.

Table 1. Urban texture parameters of all the 12 urban scenarios.

<table>
<thead>
<tr>
<th>Urban Scenarios</th>
<th>Plot Ratio</th>
<th>Site Coverage H (m)</th>
<th>Av. H(m)</th>
<th>ST</th>
<th>Av. ST</th>
<th>SVF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point-avg</td>
<td>90, 90, 90, 90, 90, 90</td>
<td>25, 25, 25, 25, 25, 25</td>
<td>0.2569</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Point-center-high</td>
<td>36, 57.6, 79.2, 100.8, 122.4, 144</td>
<td>10, 16, 22, 28, 34, 40</td>
<td>0.2479</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Point-center-low</td>
<td>36, 57.6, 79.2, 100.8, 122.4, 144</td>
<td>10, 16, 22, 28, 34, 40</td>
<td>0.2841</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Point-high-low</td>
<td>36, 57.6, 79.2, 100.8, 122.4, 144</td>
<td>10, 16, 22, 28, 34, 40</td>
<td>0.2673</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Point-low-high</td>
<td>36, 57.6, 79.2, 100.8, 122.4, 144</td>
<td>10, 16, 22, 28, 34, 40</td>
<td>0.2673</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Point-random</td>
<td>36, 57.6, 79.2, 100.8, 122.4, 144</td>
<td>10, 16, 22, 28, 34, 40</td>
<td>0.2667</td>
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<td></td>
<td></td>
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<tr>
<td>Slab-avg</td>
<td>90, 90, 90, 90, 90, 90, 90, 90, 90, 90</td>
<td>25, 25, 25, 25, 25, 25, 25, 25, 25, 25</td>
<td>0.2546</td>
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<td></td>
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<tr>
<td>Slab-center-high</td>
<td>46.8, 57.6, 68.4, 79.2, 90, 100.8, 111.6, 122.4, 133.2</td>
<td>13, 16, 19, 22, 25, 28, 31, 34, 37, 25</td>
<td>0.2522</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Slab-center-low</td>
<td>46.8, 57.6, 68.4, 79.2, 90, 100.8, 111.6, 122.4, 133.2</td>
<td>13, 16, 19, 22, 25, 28, 31, 34, 37</td>
<td>0.2688</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Slab-high-low</td>
<td>46.8, 57.6, 68.4, 79.2, 90, 100.8, 111.6, 122.4, 133.2</td>
<td>13, 16, 19, 22, 25, 28, 31, 34, 37</td>
<td>0.2593</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slab-low-high</td>
<td>46.8, 57.6, 68.4, 79.2, 90, 100.8, 111.6, 122.4, 133.2</td>
<td>13, 16, 19, 22, 25, 28, 31, 34, 37</td>
<td>0.2593</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slab-random</td>
<td>46.8, 57.6, 68.4, 79.2, 90, 100.8, 111.6, 122.4, 133.2</td>
<td>13, 16, 19, 22, 25, 28, 31, 34, 37</td>
<td>0.2601</td>
<td></td>
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</table>

3.2. Microclimate simulation by ENVI-met

For present study, ENVI-met was used to simulate the microclimate conditions of the proposed urban models. The ENVI-met software, developed by Bruse [17], has been well documented in a large number of studies about the urban microclimate and thermal comfort analysis [13, 18, 19]. In this study, 28th and 29th of July 2013, 48 hours in total, were selected as the typical hottest days of summer for the simulations based on the climate characteristics of Nanjing city. For this consideration, the meteorological data of 28th July 2013, as the initial input data, were input in the simulation configuration file. The typical input configuration for ENVI-met simulations is shown in Table 2. The outputs were obtained at the points of 2 m above the ground level in the centers of the street canyons.

Table 2. Conditions used in the simulations with ENVI-met.

<table>
<thead>
<tr>
<th>Location</th>
<th>Nanjing, China. 32.05°N, 118.48°E, 22 m a.s.l.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start Simulation at Day (DD.MM.YYYY):</td>
<td>28.07.2013 (Typical summer day)</td>
</tr>
<tr>
<td>Start Simulation at Time (HH:MM:SS):</td>
<td>06:00:00</td>
</tr>
<tr>
<td>Total Simulation Time in Hours:</td>
<td>48</td>
</tr>
<tr>
<td>Wind Speed in 10 m ab. Ground [m/s]:</td>
<td>2.6 m/s</td>
</tr>
<tr>
<td>Wind Direction (0:N..90:E..180:S..270:W..):</td>
<td>135</td>
</tr>
<tr>
<td>Initial Temperature Atmosphere [K]:</td>
<td>301K</td>
</tr>
<tr>
<td>Specific Humidity in 2500 m [g Water/kg air]:</td>
<td>9</td>
</tr>
<tr>
<td>Relative Humidity in 2m [%]:</td>
<td>75%</td>
</tr>
<tr>
<td>Inside Temperature [K]:</td>
<td>297K</td>
</tr>
<tr>
<td>Heat Transmission Walls [W/m² K]:</td>
<td>0.72 W/m² K</td>
</tr>
<tr>
<td>Heat Transmission Roofs [W/m² K]:</td>
<td>1.74 W/m² K</td>
</tr>
<tr>
<td>Albedo Walls:</td>
<td>0.3</td>
</tr>
<tr>
<td>Albedo Roofs:</td>
<td>0.4</td>
</tr>
</tbody>
</table>

It is important to note that the simulation starting time was set to be 6:00 due to the slow physical process and thermal interactions at the sunrise time. Besides, the simulation duration was set to run for 48h. In this way, the physical process and thermal interactions can take place completely after the first 24h cycle. As a result, all of the environmental components were in more stable status which can make the calculation more accurate in the second
24h cycle. Therefore, each urban scenario was simulated for 48h from 6:00am on July 28th to 6:00 on July 30th while the results for discussion were obtained from the second 24h cycle, 6:00 on 29th to 6:00 on 30th.

3.3. Building energy simulation

In this step, a series of building energy simulation were conducted based on the simulated microclimate data by using the HTB2 model which proposes a simple and accurate method in predicting the building energy demand [20, 21]. HTB2 can take the influences of complex and dynamic conditions into account for the calculations, including the ventilation, solar gain, shading, and time varying weather conditions.

In order to enable the analysis and simulation at urban scale, the Virvil plugin for HTB2 developed by Low Carbon Research Institute (LCRI) at Cardiff University links SketchUp 3D models with HTB2 and implements the calculation of annual solar radiation levels with the consideration of shading effect on building façades with the resulting shading mask in an urban context [22]. Thus, the proposed urban scenarios with various configurations can be created to be 3D models easily in SketchUp for the energy simulation at urban and regional scale.

4. Results and Discussion

4.1. Microclimate at street level

4.1.1. Air temperature (\(T_a\))

As discussed before, the comparisons were conducted in two groups respectively according to the two different building prototypes. The variations of the hourly average air temperatures \(T_a\) between the six urban settings with point blocks in group one are shown in Fig. 5. The average \(T_a\) in each urban scenario increases rapidly from 7:00 to 13:00, then reaches its maxima at 14:00 with a slow speed, and lasts for one hour until 15:00 in the afternoon, then begins to decline at 16:00 in the afternoon. The difference in average \(T_a\) between the various profiles is small in the morning until 9:00 and in the evening from 18:00.

![Fig. 5. Average air temperature (\(T_a\)) of the urban scenarios in group one obtained from pedestrian level.](image)

Among the six urban scenarios, the maximum peak value of \(T_a\) has been found at 14:00 in Point-center-low scenario, while the minimum peak value of \(T_a\) is observed in Point-center-high scenario. The peak values of \(T_a\) in Point-low-high and Point-avg scenario are slightly lower than the maximum \(T_a\) in Point-center-low scenario while the maximum \(T_a\) in Point-high-low and Point-random scenario are of medium value. The variations of \(T_a\) indicate that three urban scenarios, including Point-center-low, Point-low-high and Point-avg, are the warmest while Point-center-high scenario is the coolest.
Taking the influence of SVF into consideration, a positive relationship between $T_a$ and SVFs of the urban settings has been found in the results, since the air temperature decreases as the SVF decreases. As is shown in Table 2, among the six urban scenarios in group one, the average SVF of Point-center-low scenario is the maximum while the SVF of Point-center-high scenario is the minimum. However, it can be found that the SVFs of Point-high-low and Point-low-high scenario are the same whereas the $T_a$ of Point-high-low scenario is lower than Point-low-high. One possible reason is that the total area of the building surfaces exposing to the direct solar radiations in Point-high-low scenario is smaller due to the shading effects of the highest buildings in the south part of Point-high-low scenario.

As for the urban scenarios with slab blocks in group two, the differences in $T_a$ between them are smaller than point blocks in group one, as is shown in Fig. 6. Accordingly, the slight differences ($\Delta T_a (\text{max}) < 1^\circ C$) in $T_a$ between various urban scenarios maybe also because of the slight differences in SVFs of these urban scenarios.

Fig. 6. Average air temperature ($T_a$) of the urban scenarios in group two obtained from pedestrian level.

4.1.2. Mean radiant temperature ($T_{mrt}$)

The results show that $T_{mrt}$ are greatly influenced by the presence of solar irradiations and the availability of overshadowing at pedestrian level. Fig. 7 and Fig. 8 show the evolutions of $T_{mrt}$ that observed from the midpoints of street canyons at pedestrian level for two groups respectively. For both of the two groups, the durations of the extreme $T_{mrt}$ in all of the 12 urban scenarios begin at 8:00 and last for 8 hours until 16:00. During this period, the $T_{mrt}$ values fluctuate from hour to hour.

Fig. 7. Average $T_{mrt}$ of the urban scenarios in group one obtained from pedestrian level.
Fig. 8. Average $T_{mrt}$ of the urban scenarios in group two obtained from pedestrian level.

For group one, the $T_{mrt}$ in most of the urban scenarios reach to the peaks at 9:00, 12:00 and 16:00 respectively except the $T_{mrt}$ in Point-avg scenario which reaches to its peaks at 9:00, 12:00, 14:00 and 16:00. As for group two, $T_{mrt}$ in all of the six urban scenarios reach to the peaks at 9:00am, 13:00pm and 16:00pm respectively. Making a comparison between the peak values in two groups, the $T_{mrt}$ at peaks in group two are higher than group one. This is due to the larger building surface areas exposing to the solar radiation for the slab blocks in group two. Another point needed to be noticed is that the peak values at 13:00 are extremely lower than the values at 9:00 and 16:00 for group two while the peak values at the peak time points are similar for group one. This may be caused by the great shading effects of the slab blocks at noon when the solar angle approaches the zenith.

Both for the two groups, the urban scenarios of Center-low and Low-high produce the warmest condition at pedestrian level while the scenarios of Center-high and High-low are the coolest, and the Random scenarios are the intermediate one. Taking the $SVF$ values into consideration, the possible reason is that the total areas of the building surfaces exposing to the direct solar radiations in scenarios of Center-low and Low-high are larger than the other scenarios owing to the higher $SVF$ values. It is necessary to note that the $SVF$s of Low-high and High-low scenarios are the same whereas the Low-high scenarios are warmer than High-low scenarios. The reason can be also explained as discussed previously in the $T_o$ section.

4.1.3. Wind conditions

Fig. 9 shows the daily average wind velocities from the midpoints of street canyons at pedestrian level for the two groups. It can be clearly found that the maximum wind velocities observed are in Center-low scenarios while the minimum wind velocities are in Center-high scenarios both for two groups. This is owing to the open space in the central area of the Center-low scenarios which can contribute to the wind flow. On the contrary, the high buildings in the central area of the Center-high scenarios block the wind movement. Comparing the wind velocities between the two groups, one may observe that the wind velocities of all the urban scenarios in group two are generally higher than group one. The possible reason is that the slab blocks form a series of wind channels which can conduct the wind flow.
As for the distribution of the wind velocities, the arrangement of building heights and volumes plays a distinguish role in affecting it. Fig. 10 and Fig.11 are captured at pedestrian level at 21:00 for group one and 20:00 for group two, and show the distributions of the maximum wind velocities in the urban scenarios of the two groups respectively.

For group one, the distributions of wind velocities in four cases are symmetrical along the SE-NW direction except Point-high-low and Point-low-high scenarios. Nevertheless, the isotachs in the leeward area of Point-center-high scenario show a linear distribution while the other three symmetrical scenarios show a nonlinear distribution, and the gradients of the isotachs are increasing in order of Point-random, Point-avg and Point-center-low. The linear distribution may be caused by the gradually increasing building heights from the border to center area of the urban model, and the obstructive effect of this kind of building arrangement on the wind flow reduces gradually from the center to border area of the urban model.
As for the two asymmetrical distribution scenarios, the isotachs in the west leeward area of Point-high-low scenario are distributed in a wider range than the isotachs in north leeward area. The possible reason is that the highest buildings are in the first row in the south, and the variation range of the wind velocity is larger in the west leeward area where is near the lee surfaces of the buildings. Conversely, the isotachs in the north leeward area of Point-low-high scenario are distributed in a wider range than the west leeward area. Similarly, because the highest buildings are located in the northernmost row, and the area behind the buildings becomes the main leeward area where is near the lee surfaces.

For group two, the distributions of wind velocities in all scenarios are asymmetrical, as is shown in Fig. 11. Furthermore, the distribution ranges of the isotachs in the west leeward areas are wider than the other areas except the Slab-low-high scenario. This is probably owing to the wind channels formed by the slab blocks arrangement which conduct the southeast winds from east to west, and the west leeward areas become the buffer zones of the bottle-neck wind. Different from the other cases, the main leeward area of Slab-low-high scenario is located in the north area just behind the highest buildings which are placed in the northernmost row. Accordingly, both the north leeward area and bottle-neck wind effect result in the difference of the isotachs distributions of Slab-low-high scenario.

In addition, it is necessary to notice that the isotachs distributions are extremely intensive around the northeast and southwest corners of the urban models both for two groups. This is possibly because these corners are the critical areas between the windward and leeward, and the variations of wind velocities in these areas are rapider than other areas.

4.2. Energy consumption

The energy performance of each scenario has been detected by comparing the cooling demand. Fig. 12 shows the daily average cooling load per square meter ($kWh/m^2/day$). The results show some similarities and differences in energy performance among the modelled urban scenarios in two groups.
It can be clearly found that the urban scenarios with slab blocks in group two generally consume more energy in cooling the rooms than urban scenarios with point blocks in group one. The differences range from 0.004 kWh/m²/day for the random scenarios to 0.008 kWh/m²/day for the avg scenarios. This is probably because that the urban scenarios with slab blocks in group two have larger building surface areas exposing to the solar radiation than the point blocks in group one. Furthermore, both for two groups, the energies consumed by cooling load in Center-low and Random scenario are 0.003-0.008 kWh/m²/day higher than the other scenarios. The possible reason is that the heat produced by solar radiations is trapped in urban settings owing to the obstruction of the high buildings around the central area for Center-low scenarios and the complicated heat dissipation routes formed by the random building arrangement for Random scenarios. However, the energy consumed for cooling in Point-avg scenario is the lowest in group one while the cooling demand of the Slab-center-high scenario is the lowest in group two.

5. Conclusion

The following conclusions can be drawn from the results of the microclimate and energy simulations.

1. There is an association between the building arrangement and microclimate conditions. However, the effects of the building arrangements on Tmrt and wind condition are more significant than the effects on the Ta.

2. The sky view factor determined by the building height arrangement shows certain effects in relation to the air temperature and mean radiant temperature.

3. The wind potential is also affected by the building shape and its arrangement. The results show that the slab blocks arranged parallel will form wind channels which can benefit the urban ventilations.

4. The critical area between the windward and leeward is a key factor in connection with the isotachs distribution.

5. The building shape and arrangement in urban context affect the energy demand in cooling the rooms. On one hand, the building with point shape shows more potentials of saving energy. On the other hand, buildings in random and center-low arrangements have a worse performance in energy use while the buildings in avg and center-high arrangements show a better energy performance.

The outcomes reveal that more compact arrangement of the buildings can help to better the microclimate conditions and reduce the building energy use at urban scale. And this study fills the gap which has hitherto existed in urban microclimate studies based on the geographical and climatic conditions of Nanjing city.

There are also limitations pertaining to this study. Firstly, only N-S orientation is considered. The other orientations, including E-W, NE-SW and NW-SE, are not taken into account. Secondly, the present study only focuses on the urban scenarios with buildings in aligned arrangement, without the consideration of the staggered arrangement which is more complicated for the wind flow. These points will be discussed in future studies.
References

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