The impact of the spatio-temporal morphology of urban green infrastructure on urban building energy consumption: A case study in the hot-summer-cold-winter climate

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Abstract. Studies have confirmed that urban green infrastructure (UGI) profoundly impacts urban building energy consumption by regulating urban microclimate, providing shading to buildings, and other mechanisms. This impact is largely dependent on the morphology of UGI. Although this conclusion is widely accepted, there lacks a systematic approach to quantify the impact and thus the knowledge regarding its magnitude. This paper discusses the influencing mechanisms of UGI on urban building energy consumption. The city of Nanjing, a Chinese city in the hot-summer-cold-winter climate, is morphologically analyzed to extract prototypes of UGI forms. These prototypes are simulated for their microclimate and urban building energy consumptions using a co-simulation technique, which links ENVI-met to EnergyPlus. The simulation results are statistically analyzed to quantify the impact of UGI morphology on urban building energy consumption. The energy consumption of different morphological groups in summer and winter is compared to determine the impact of UGI morphological features on urban building energy.

1. Introduction

The urban areas account for 67 – 76% of the total energy consumption, and 71 – 76% of the greenhouse gases related to energy consumption are emitted[1]. The proportion of building energy consumption in the total energy consumption is about 40%, which is expected to increase due to population growth, economic growth and climate change[2]. It is necessary to improve building energy efficiency to reduce urban greenhouse gas emissions[3][4].

Urban green infrastructure (UGI) is an essential functional system to regulate the urban environment. In the past few decades, numerous studies have confirmed that UGI around buildings can reduce the energy demand of buildings for cooling and heating[5][6][7][8]. UGI affects building energy consumption mainly through several processes, including (a) shielding the solar radiation transmitted to the building surface[9][10][11], (b) preventing air infiltration[12], and (c) changing the microclimate around the building [7] [8] [13].
Urban form imposes significant impacts on building energy consumption[5][6]. The morphology of UGI is one of the critical factors. The size and location of vegetation affect the energy consumption of buildings[11]. Appropriate UGI layout (crown shape, type and relative location to buildings) improves solar radiation and wind, saving energy to a certain extent[8][14][15]. However, UGI does not always save energy. Improper tree layout blocks sunlight and ventilation, resulting in more energy being used for heating and cooling[16]. In most cases, the trees on the west and south sides of the building show the most energy-efficient in summer, while the trees on the north side of the house increase the energy consumption[6][9][17]. In winter, UGI in the upwind direction of the monsoon reduces heating energy[18]. In addition, the sun angle, tree shape and the distance between tree and building affect building energy use[11]. Seasonal morphological changes of UGI should also not be ignored. Solar irradiance in shadow on the south side of the building is reduced by about 80% in the non-deciduous season, reduced by nearly 40% in the deciduous season[14].

Although the impact of single plants on urban building energy has been proven, there is still a lack of understanding of how UGI forms reduce building energy demand and its impact degree[5][6], especially at the macroscopic level. Consequently, it is necessary to systematically quantify the energy efficiency based on morphological analysis of UGI.

2. Methodology

2.1. Case study area
The influence of UGI on urban energy largely depends on the climate and location [11]. In this study, Nanjing was selected as a case study area to demonstrate the proposed method. Nanjing is an important city in the Yangtze River Delta of China. It is typical hot-summer-cold-winter climate, characterized by distinct seasons and abundant rainfall. Figure 1 shows the geographic location of Nanjing. The meteorological data in typical meteorological year (TMY) of Nanjing were analyzed to select the typical climate day in summer and winter.

![Figure 1. The geographic location of Nanjing.](image)

2.2. Typical prototypes of urban form

2.2.1. The scale of urban form prototypes. The model's radius should not be less than 200m to ensure the adjustment part of the inner boundary layer of the model is wholly located in the region[19].
Considering the average area of the statistical blocks is 93697.93 m², the prototype's size was set as 600m * 600m, containing four blocks.

2.2.2. Classification of urban forms. The building and UGI forms of the blocks in the research area were analyzed to summarize the typical morphological prototypes. To classify the urban form, we investigated 952 blocks in the main urban area. The blocks without buildings (undeveloped areas or parks) were not included. The blocks with an average building height over 24m were defined as high-rise blocks, otherwise low-rise blocks. The median density of low-rise blocks was 0.28, which was taken as the boundary of high-density and low-density types. Thus, four types of classification based on building form were obtained, and the median density of each type was taken as the representative of each type.

The median of the UGI coverage ratio was 0.23, which was taken as the boundary of two types: high-UGI and low-UGI. The median UGI coverage ratio of the two types were 0.36 and 0.15. The average crown volume per area in 86 blocks was investigated to obtain the crown volume in the high-UGI and low-UGI types. Table 1 shows the eight basic urban form types combining the UGI quantity and building form and their proportion in the research area. Since the basic urban types accounted for less than 10% of the area, they were not covered in this research.

Table 1. The eight basic urban form types and their proportion

| Density | UGI     | Number of Blocks | Percentage |
|---------|---------|------------------|------------|
| Low     | High    | 246              | 25.84%     |
|         | Low     | 92               | 9.66%      |
| High    | High    | 107              | 11.24%     |
|         | Low     | 231              | 24.26%     |
| Low     | High    | 99               | 10.40%     |
|         | Low     | 39               | 4.10%      |
| High    | High    | 24               | 2.52%      |
|         | Low     | 114              | 11.97%     |

Furthermore, each basic type was divided into seven UGI spatial types including (a) south-concentrated type, (b) east-concentrated type, (c) north-concentrated type, (d) west-concentrated type, (e) middle-concentrated type, (f) surrounding type and (g) uniform type. By combining the basic block types with UGI spatial types, 35 UGI morphological prototypes were obtained for energy consumption simulation analysis.

2.3. Co-simulation technology combining UGI, microclimate and urban energy

2.3.1. Co-simulation of urban microclimate and urban building energy. ENVI-met was used in urban microclimate simulation and the output was used as input climate data in EnergyPlus to simulate the energy consumption of buildings under the influence of UGI [21]. However, in the urban energy simulation, it is time-consuming and labour-intensive to manually input the microclimate data of a large number of urban buildings individually.

We integrated the simulation and interaction processes of ENVI-met and EnergyPlus into the rhino and grasshopper platform to build automatic modelling and simulation programs to realize the automatic co-simulation of urban microclimate and energy. Modules share and transfer the model and non-geometric parameters. The building and UGI profiles in shapefile format are used as input. The ENVI-met running module is used to simulate the urban microclimate under the influence of a specific UGI form. The microclimate outputs are automatically extracted to analyze the microclimate data around each building through the GIS platform. Though a program, the EnergyPlus Weather (EPW) file of each building is automatically generated in batch. The EPW files are read in grasshopper and linked to the geometric model of each building. Finally, EnergyPlus runs the IDF file to obtain the CSV result files. Figure 2 illustrates the complete co-simulation workflow.

The thermal load of building heating and cooling was simulated under the ideal loads air system in EnergyPlus. The thermal conductivity of the exterior wall was 22W/(m·K). The temperature points of
cooling and heating were set as 26 °C and 20 °C, respectively. The time step of zone heat balance model calculation was 6/ hour. Infiltration rate per area was 0.00025m²/m³.

Figure 2. Co-simulation workflow based on rhino and grasshopper platform

2.3.2. **Transmittance of UGI model in EnergyPlus.** The influence of UGI on urban energy by shielding solar radiation should not be ignored. In the geometric modelling of EnergyPlus, the context geometries are surfaces with transmittance. In this study, a single plant was modelled as an independent surface in EnergyPlus, set with the corresponding transmittance. In order to obtain the canopy transmittance of representative tree species in Nanjing in different seasons, the canopy volume was converted into voxels [20]. Each voxel has different absorbance for solar radiation according to its leaf area density. The greater the optical depth of sunlight, the more light is absorbed by the canopy. The photosynthetically active radiation (PAR) absorbed by each voxel and the PAR transferred to the ground can be obtained, thus the approximate transmittance of the crown.

3. **Results**

3.1. **Output visualization**

Figure 3. Spatial distribution of daily energy consumption per unit building area (low-rise, low-density, high-UGI and south-concentrated type)

The energy simulation results are linked to the FID of the shapefiles to connect to each building. In this way, the 3D visualization of energy consumption spatial distribution, spatial analysis, database
construction and other functions on the GIS platform is achievable. Figure 3 shows the spatial distribution of building energy consumption of the prototype in summer and winter, taking the low-rise, low-density, high-UGI and south concentrated type as an example.

3.2. Impact of UGI spatial type on urban microclimate

The microclimate data around buildings extracted from ENVI-met was grouped by UGI spatial types. Friedman test was conducted among groups. Significant differences existed in temperature, relative humidity and wind speed in summer, as well as relative humidity and wind speed in winter. A significant difference in temperature in winter was shown among basic urban form types but not among UGI spatial types. It suggested that the temperature in winter is affected by the building form type rather than UGI spatial type.

In summer, the temperature was lower and the humidity was higher in the east-concentrated type and uniform type. The wind speed of the uniform type was relatively low. In winter, the humidity of the east-concentrated type was the highest, and the overall characteristics of temperature and humidity were similar to summer (Figure 4).

![Figure 4. Mean climate around buildings grouped by UGI spatial type](image)

3.3. Comparison of urban building energy consumption in different basic types

![Figure 5. Comparison of daily energy consumption per unit area of different basic urban form types](image)
Based on the basic types of urban form, 35 prototypes were divided into five groups, and their daily energy consumptions per unit building area were compared. As illustrated in Figure 5, there were significant differences among the groups. In summer, the high-rise, high-density and low-UGI type have the highest energy efficiency while the low-rise, high-density and low-UGI type performed the worst. In winter, the energy consumptions of high-rise types were markedly higher than others.

3.4. Comparison of building energy consumption of different UGI spatial types

To compare the impact of UGI spatial types on energy, the energy evaluation index was defined as the difference between the energy consumption of the prototype and the average of the basic urban form type. If the energy evaluation index is positive, the energy consumption is higher than the average level of the basic urban form. Figure 6 shows the difference in energy evaluation index in prototypes.

When comparing the energy consumption of four directions of centralized types, no significant difference was shown in the nonparametric test in summer. However, differences were significant in winter. The north-concentrated type was relatively energy saving, comparing with other directions, although the gap was not significant.

The side-centralized types consumed more energy in summer, and the middle-centralized types were close to the average level. The surrounding and uniform types were below the average level. The statistics suggested the opposite in winter.

![Figure 6. The energy evaluation indexes of UGI spatial types.](image)

4. Conclusions and Outlooks

Taking Nanjing as an example, the urban form and UGI form prototypes of the main urban areas were extracted. The time-saving, labour-saving and fully automated co-simulation method was proposed, which could be applied to different climate regions. The simulation results were statistically analyzed to quantify the impact of different UGI basic types and UGI spatial types on urban building energy consumption. The low-rise, high-density and high UGI prototype showed high energy-saving efficiency in both summer and winter. In UGI spatial types, the uniform type performed the best in summer, while the eccentric concentrated type consumed the least energy in winter. The relationship between UGI morphological quantitative parameters and urban building energy should be analyzed in future research to conduct low-energy-oriented UGI planning methods. Moreover, it will be worth studying expanding the method to a larger city scale and more extended time.

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