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Performance-driven Optimization of Urban Open Space Configuration in the Cold-Winter and Hot-Summer Region of China

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Abstract: Urbanization has led to changes in urban morphology and climate, while urban open space has become an important ecological factor for evaluating the performance of urban development. This study presents an optimization approach using computational performance simulation. With a genetic algorithm using the Grasshopper tool, this study analyzed the layout and configuration of urban open space and its impact on the urban micro-climate under summer and winter conditions. The outdoor mean Universal Thermal Climate Index (UTCI) was applied as the performance indicator for evaluating the quality of the urban micro-climate. Two cases—one testbed and one real urban block in Nanjing, China—were used to validate the computer-aided simulation process. The optimization results in the testbed showed UTCI values varied from 36.5 to 37.3°C in summer and from -4.9 to -1.9°C in winter. In the case of the real urban block, optimization results show, for summer, although the average UTCI value increased by 0.6°C, the average air velocity increased by 0.2m/s; while in winter, the average UTCI value increased by 1.7°C and the average air velocity decreased by 0.2m/s. These results demonstrate that the proposed computer-aided optimization process can improve the thermal comfort conditions of open space in urban blocks. Finally, this study discusses strategies and guidelines for the layout design of urban open space to improve urban environment comfort.

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Keywords: performance-driven optimization; urban open space layout; universal thermal climate index; urban design; cold winter and hot summer climate

1. Introduction

The effects of urban climatology increasingly call for more climate responsive environments in urban open spaces [1,2]. Environmental issues are gaining more attention due to their negative impacts on human satisfaction and urban sustainability. Meanwhile, the urban heat island (UHI) effect is of great severity [3,4]. Reportedly, the UHI phenomenon can increase temperature differences between urban and surrounding suburban areas [5,6]. Therefore, urban open space has become an important ecological factor in high-density and -intensity urban development, gradually becoming the focus of architects and planners. Urban open space can improve local air temperatures, alleviate the UHI effect, and improve air quality. It plays an irreplaceable role in improving the local ecology, recreation and landscape, and preferentially reflects the planning guideline of respecting nature in urban construction [7–10]. Therefore, local decision makers and researchers are continually focusing on implementing engineering methods to optimize the performance of urban open space.

Research methods have evolved from traditional on-site measurements [11] and questionnaire surveys [12] to current infrared remote sensing [13], digitalized simulation and geographic information system (GIS) data [14]. Meanwhile, computer-aided environmental simulation is widely applied in urban design research focused on urban open space comfort. The applied simulation software includes: 3D conceptual environmental design tools (Concept) [15], Computed Fluid Dynamic (CFD), ENVI-met, Ecotect, and EnergyPlus. For example, Zheng applied a GIS-based method to map the local climate zone (LCZ) in the high-density city of Hong Kong to show the spatial distribution pattern of LCZ classification [16]. Tsoka et al. applied a three-dimensional, non-hydrostatic, climate model using ENVI-Met to gauge the impact of cool materials and additional tree planting on the urban micro-climate [17]. Karakounos estimated the influence of a bioclimatic urban redevelopment on the outdoor thermal comfort on a hot summer day, using an ENVI-Met model [18].

When simulating urban open space, relationships between inter-buildings and between buildings and surroundings are also considered, such as overall layout relationship and form optimization of buildings, including cluster layout, orientation, the streets, open spaces between buildings, and so on. By using the Pareto optimal algorithm in the ModeFRONTIER software, Grifoni et al. analyzed the relationship between the specific urban form indices and the percentage dissatisfied in Ancona, Italy [19]. From this, researchers formulated a strategy of responding to the urban environment under climatic change [19]. Bajsanski analyzed the impacts of urban planning on the heat environment in Neoplanta, Serbia, using the Ladybug plug-in of the Grasshopper software [20]. Taleb et al. used Rhino and genetic algorithms to generate a building form cluster that adapts to a dry and hot climate, covering environmental factors—such as solar radiation, urban ventilation, building form and orientation—to achieve the best sustainable urban form [21]. Using a Grasshopper platform and genetic algorithm, Hu et al. studied low UHI in high-density cities and revealed the potential of urban form design in optimize the UHI effect [22]. Perini et al. modeled and simulated urban outdoor thermal comfort by coupling EVNI-Met and TRNSYS using Grasshopper [23].

In addition, some studies have started to research the relationship between the building volume and other factors, such as topography, greening and water ways. Using Rhino Grasshopper and Ecotect, Bajsanski et al. calculated the impacts of vegetation on improving the heat environment of parking lots, by optimizing vegetation locations and forms [24]. Similarly, Lgnatius simplified outdoor greening to turfs and trees, then calculated the leaf area index (LAI) and green plot-ratio (GnPR) to study how they impact the urban micro-climate in a tropical climate [25]. Yang took urban form and density as indicators for summertime outdoor ventilation potential and conducted a case study on high-rise housing in Shanghai to analyze the effects on wind [26]. Martins et al. proposed a methodology to identify and adapt existing urban typologies to assess urban design strategies and further, validated his methodology using a case study in Maceio, Brazil [27].

Such researches focus on the urban design of the micro-dimension—e.g. how street valleys [28] and courtyards [29] influence the improvement of the urban micro-climate—and merely analyzed single influential factors, such as the relationship between urban environment and surface albedo [30], or the building and underlying surfaces [31]. However, few studies integrate the impact of the multi-geometric form factors of open space to understand micro-climate comfort at the block dimension. On the other hand, with regard to thermal comfort, increasingly more studies have begun to predict human comfort by using bio-climatic indices [32]. Common indices include the Predicted Mean Vote (PMV) [33], the Physiological Equivalent Temperature (PET) [34], and the Universal Thermal Climate Index (UTCI) [20]. Based on the local climate, most studies explore the improvement of the realization approach of desirable outdoor micro-climate under extreme hot [35] and extreme cold [36] conditions.

However, how such performance analysis of urban open space contributes to guide urban planning and design with environmental impact needs further exploration. This study selects the open space of an urban block in Nanjing, Jiangsu province, China, which is located in a cold-winter and hot-summer region, and investigates performance-driven urban design optimization for the urban micro-climate. This study applies the Grasshopper tool and Ladybug plug-in as the simulation tool and a genetic algorithm integrated in the tool is applied for the urban block optimization. The outdoor mean UTCI index is selected as the performance index to analyze the urban micro-climate. Fig. 1 shows an example of urban block open space.

This study has the following objectives:

(1) Propose a computer-aided automatic optimization process with the Grasshopper tool and Ladybug plug-in for performance-based open space design strategies of urban block and use UTCI as the performance indicator.

(2) Apply a testbed and validation case of urban open space derived from a real urban site in Nanjing, China, to validate the optimization process strategies.

(3) Finally, explore guidelines on how to best utilize the urban open space layout at a city-block scale, to improve the thermal comfort of outdoor environment during summer and winter seasons.

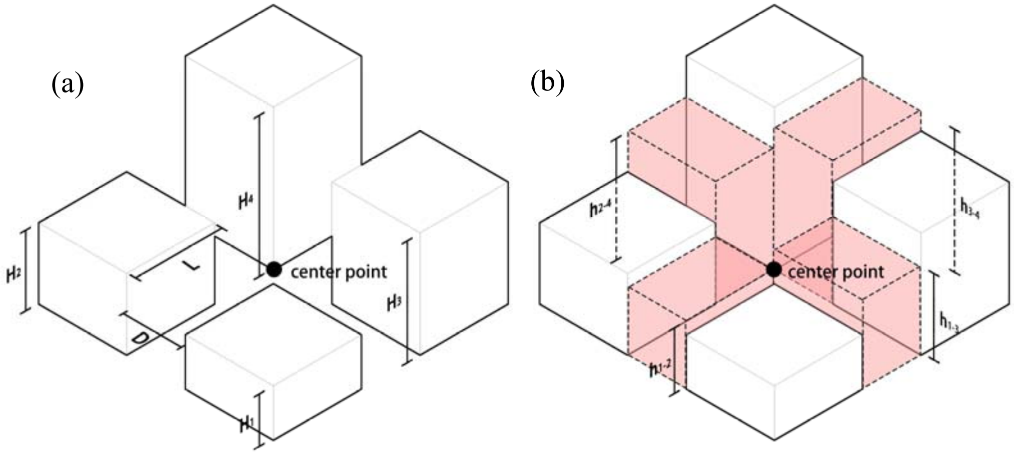


Fig.1. The open space schematic: (a) the white represents the building height and (b) the red represents the height of the open space.

2. Methodology

2.1 Overview of case study

The cold-winter and hot-summer region of China is selected in this study, and the region covers 16 Chinese provinces, accounting for about one-fifth of the total land area in China [37]. Therefore, studying such a region in China is necessary to evaluate the performance of urban open layout design. This study takes Nanjing city, representative of a typical city located in the cold-winter and hot-summer region of China, as an example. This city is also one of the climatic zones with the densest population and the fastest economic development in China. Demand for cooling and heating is persistent for year-round, which demands increasing electricity use in Nanjing. Therefore, the climatic urban design is not only important for improving the outdoor comfort and promoting urban vigor, but also potentially very significant for saving energy.

Performance-driven optimized design can be achieved via computer-aid automatic calculation to determine an optimal solution with a series of set rules and goals. Ultimately, the process transpires from disorderly to orderly generation and eventually obtains a design result [38]. This study selected the Ladybug plug-in on the Rhino Grasshopper platform, which allows architects to realize performance-driven optimization design. Specifically, the plug-in can evaluate the comfort of the human body by calculating the UTCI of the outdoor air environment. Further, the plug-in can also support the calculation of the outdoor air temperature distribution and the wind environment [39]. The emergence of the Ladybug tools has reduced barriers to using performance analysis and evaluation optimization, enabling architects to realize performance-driven optimization design on the Grasshopper platform.

2.2 Model configuration

2.2.1 Testbed for urban open space

This study focuses firstly on optimizing the location and height of a group of buildings with the goal to improve the thermal comfort between buildings. Therefore, during the parameter selection, the climatic parameters were highly important. The model is simplified because there is extreme complexity in city-scale input modeling, and too much detail detracts from the overall goal of the study. Therefore, the urban land parcel is taken as 350m × 350m and the site size of the actual research is set as 250m × 250m. On this site, buildings have the dimensions of 30m × 30m (length, width). Buildings were distributed regularly at an interval of 20m. Other parts can be regarded as the existing neighboring environment, with a building height of 25m. The plot ratio of this land parcel was set as 2.0 and the building density at 30%. A random value list, with the same number as that of the buildings, was established with the help of the Grasshopper platform, to serve as the gene dish. The listed values are exactly the number of floors of the various buildings in the experimental unit. This needed to satisfy the limitation placed on the overall building area and building density as a whole. After repeated experimentation, the least unit in the change of the number of building floors was set as 3; namely, the value field is 0, 3, 6, 9…27, 30, and the interval length is 11. After that, the obtained figure was multiplied by the coefficient to maintain the constancy of the plot ratio. In order to meet the building density requirement, the number of floors for four buildings in the experiment unit will be 0, as open space set aside (Fig. 2).

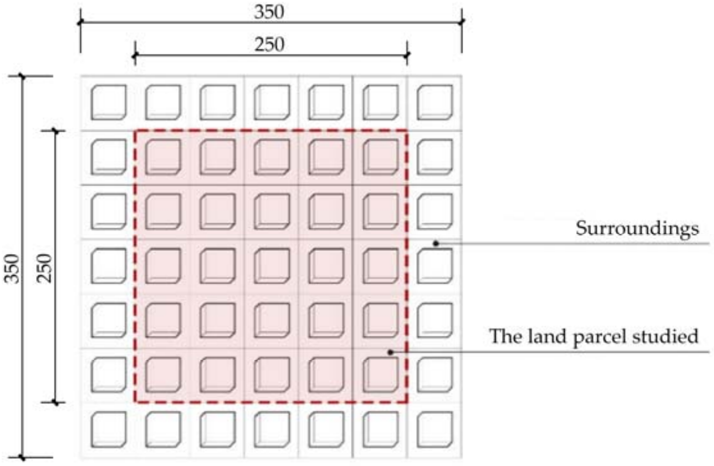


Fig. 2. Parameterized experiment model setup.

2.2.2 Validation case study

The testbed in the computer software offers the basic layout of the urban block unit, which can usually be referred to or transferred to an actual urban block model. This open space model can be modified by connections with other spaces (e.g., green space) to build its micro-climate system and reduce UHI effects; corridors around block can also serve as a buffer against the surrounding environment. While combining the open space model with actual urban cases, it is convenient and quick to build climate-adaptable urban open space by fine-tuning the volume, building density, layout and so on. This study selected one actual urban block from Nanjing to validate the automatic optimization process of the urban open space layout. Nanjing city is the provincial capital of Jiangsu province, China, with 31°14″ to 32°37″ north latitude and 118°22″ to 119°14″ east longitude. The urban block of the case study is located in the main urban area of Nanjing, and surrounded by Danfeng Road, Dashiqiao Road, Zhongshan Road, and Zhujiang Road, as shown in Fig. 3. The model inputs are based on the layout of Nanjing and the actual road network dimensions, while other geographic features of the city are abridged. The length and width are about 400 m and 250 m, respectively, and the area is about 114,293 m^2. The building functions vary from high-rise commercial, office buildings, to multi-story commercial buildings. There are also some dot-type high-rise and board-type low-rise residential areas located in the inner urban block. The plot ratio of this urban block is about 4.5, and the building density is 0.4.

Fig. 3. Validation case study of real urban block in Nanjing.

2.3 Climate settings

Meteorological data for the city of Nanjing was used to establish the climate settings for the model. Ladybug read the Nanjing epw weather data downloaded from the EnergyPlus website, which represents the typical weather year at that location. Nanjing belongs to a typical region with a hot summer, cold winter (HSCW), and year-round high humidity. It has an annual average air temperature of 15.4°C and plenty of rainfall. Summer highs reach 40°C, and winter lows reach -13°C. In the climatic data read by Ladybug, the period from August 5 to August 11 and from January 15 to January 21 are designated as the hottest and coldest weeks in the year, respectively. Therein, the hottest day, August 5, had a daily average temperature of 33.4°C, humidity of 63%, and a southeastern wind at 2.5 m/s. The coldest day, January 15, had a daily average temperature of 0.8°C, humidity of 89%, and a northern wind at 2.5 m/s. Table 1 shows the experimental arrangement and parameter settings used in the study. The nomenclature is such that "OLS" represents the optimization layout in summer, and "OLW" represents the optimization layout in winter.

Table 1. The experimental arrangement and parameter settings

Typical Climate Information of Nanjing			
Annual Average Air Temperature			15.4°C
Maximum air temperature			40°C
Minimum air temperature			-13°C
Hottest period			August 5th to 11th
Coldest period			January 15th to 21st
Simulation Climate Settings			
	Season	Climate data conditions	Optimization target
OLS	Summer (S)	Temperature: 33°C Humidity: 68% wind speed: 2.5 m/s	Outdoor average UTCI minimum
OLW	Winter (W)	Temperature: 1°C Humidity: 89% Wind speed: 2.5 m/s	Outdoor average UTCI maximum

2.4 Performance index

Over the past 50 years, researchers have developed a series of universal indices to characterize the human perception of the thermal environment. Some of these indices include the predicted mean vote (PMV), the standard effective temperature (SET), the physiological equivalent temperature (PET) and the universal thermal climate index (UTCI). Each has its respective scope of application. Therein, the UTCI was proposed by the German International Biological Meteorological Society in 2009. UTCI is acknowledged as a comprehensive index [40]. The index provides an overall consideration of the outdoor thermal comfort of humans driven by factors such as outdoor air temperature, radiation temperature, relative humidity and wind speed.

Further, the index's evaluation uses a classification that is divided into 10 grades. Table 2 shows the stress classification of UTCI under different ranges [40]. Therein, 9°C to 26°C is considered the standard comfort interval, with varying degrees of comfort associated with each temperature range. UTCI is applicable and useful for key applications in human thermal comfort in public climate impact research. Additionally, Zare et al. studied and compared UTCI with PMV, SET, PET, and so on with a 12-month dataset in year 2016, ultimately finding that UTCI can have significant correlations with other indices and can be a better indicator of thermal comfort [41]. Therefore, the UTCI was selected as the main evaluation index in this study since it is deemed more suitable for predicting the comfort of the human body in a climatic region such as Nanjing, China.

Table 2. Stress classification of the outdoor thermal environment following the UTCI ranges.

The range of UTCI (°C)	stress classification
>46	Extreme heat stress
+38 to +46	Very strong heat stress
+32 to +38	Strong heat stress
+26 to +32	Moderate heat stress
+9 to +26	No thermal stress
+9 to 0	Slight cold stress
0 to -13	Moderate cold stress
-13 to -27	Strong cold stress
-27 to -40	Very strong cold stress
< -40	Extreme cold stress

2.5 Simulation tool

This study used the Ladybug plug-in as part of the Rhino Grasshopper, which is one of the most popular simulation tools for architecture and urban design. The Ladybug includes four important functions: (1) Ladybug for urban climate analysis and visualization; (2) Honeybee for building energy, solar, and thermal simulation; (3) Butterfly for wind environment simulation; and (4) Dragonfly for micro-climate simulation. Meanwhile, the Ladybug plug-in can read weather data files in EnergyPlus epw format; the weather data for the city of Nanjing (see Section 2.2) was used. After the weather data was read, an iterative calculation was conducted to generate the vector data of the urban wind environment. The Grasshopper Ladybug module was then used to simulate the solar radiation and export the solar radiation distribution. The UTCI module in Grasshopper Ladybug was used as the evaluation index for the outdoor environment simulation and visualization. The visualization of the UTCI distribution results was exported and the mean value of UTCI was calculated with the input of the outdoor air temperature, humidity, the wind speed (generated by simulation) and the solar radiation (generated by simulation).

2.6 Optimization process

This study used the automatic optimization method with the aid of simulation performance to model and evaluate urban design at the city-block scale. Automatic optimization based on simulation performance generally includes the design process of the following four procedural steps: model generation, model setting, computer-aided optimization, and performance outputs. The schematic shown in Fig. 4 provides an overview of the research framework in this study.

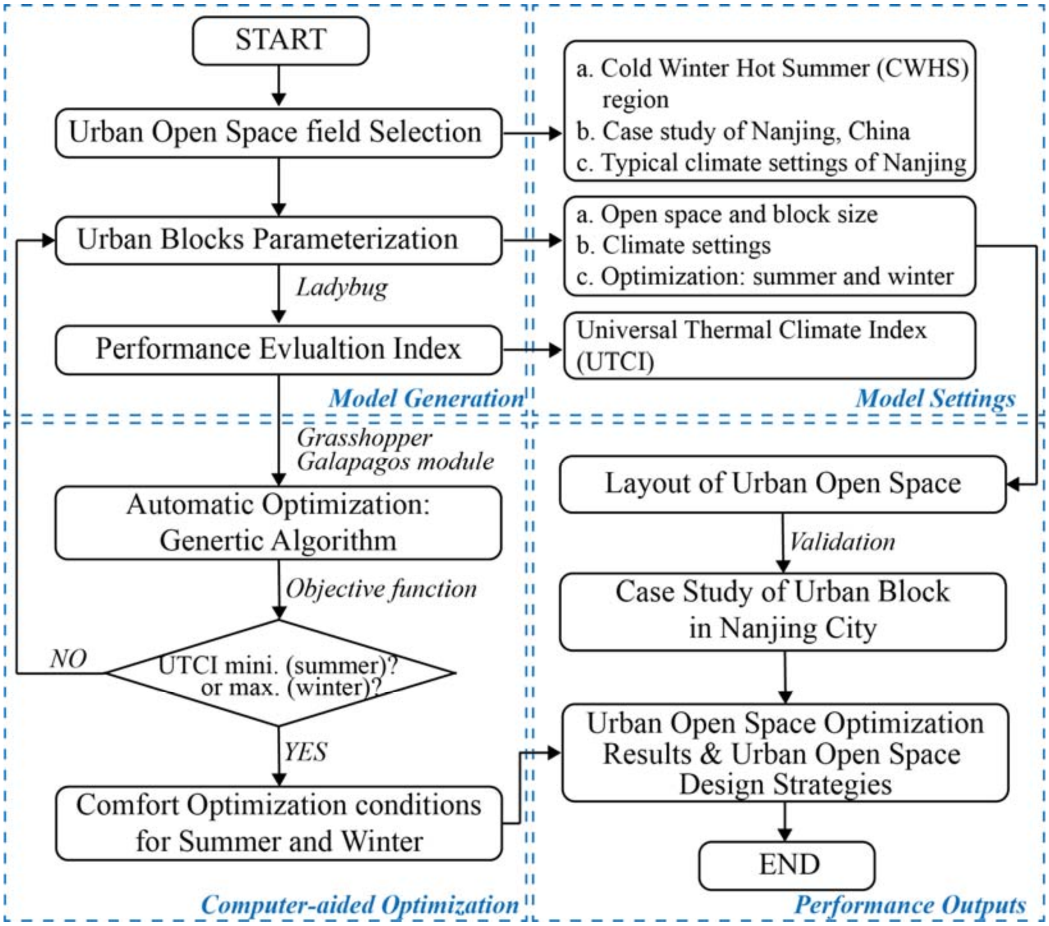


Fig.4. The research framework for performance simulation optimization.

This study selected two case studies; one is the ideal testbed, and the other is a real city block for validation. The former was used to test the impact of different layouts of open space and building heights on comfort (UTCI results) and the latter was used to validate the optimization process in the real urban block. Both selected cases are in the HSCW region and used the typical climate settings of Nanjing. The optimization algorithm utilized the genetic algorithm in the Grasshopper Galapagos module. Automatic optimization used the outdoor mean UTCI as the dependable variable and connected it to the fitness end of the Galapagos module and the building stock variable parameters. The buildings located on the block were adjusted automatically by the algorithm so that the goal-oriented optimization could realize the optimum outdoor environment. Namely, the goal was to minimize the value of mean outdoor UTCI in summer and maximize the UTCI value in winter. The optimal solution was obtained with the generation and evaluation of a number of possible options/scenarios. The optimized parameters are the location of open space and building heights. This study validates the proposed optimization process in the real urban block case study by comparing the UTCI results of the original and the optimized layouts. Finally, based on the simulation and optimization results, this study provides some strategies for the layout design of urban open space to improve urban thermal environment.

3. Results

3.1 Result of open space layout in summer

According to the model setup and summer climate parameters, a genetic algorithm was used to optimize the building height and the square location. The results provide an understanding of the open space layout while minimizing the outdoor average UTCI in summer. Fig. 5 shows an overall decline with the process of optimization smoothly until UTCI result converges to be steady. Throughout the entire optimization process, the maximum and minimum outdoor average UTCI was 37.3°C and 36.5°C, respectively. These temperatures were reached at Generation 42 and Generation 600, respectively. The difference is about 0.8°C. Therefore, the layout of the open space can positively affect the building and outdoor environment by almost a degree Centigrade.

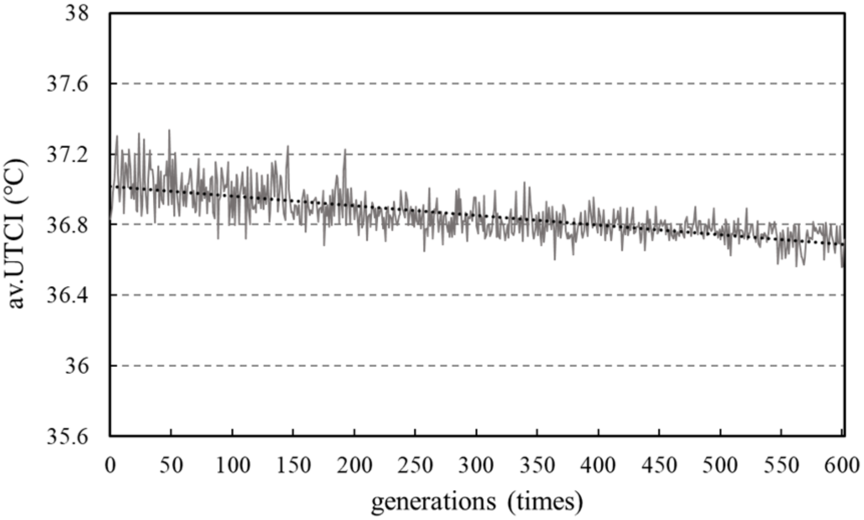


Fig.5. The mean UTCI results of the generations for OLS.

Fig. 6 presents the distribution evolution of building heights in the optimization process case of OLS and includes 20 selected cases, including the maximum and minimum value of the UTCI, and the change from high and low in the process of optimization. OLS-1 has the worst performance while OLS-20 has the best performance. The layout changes of the buildings within the open space are displayed in the form of diagrams for easy visual representation.

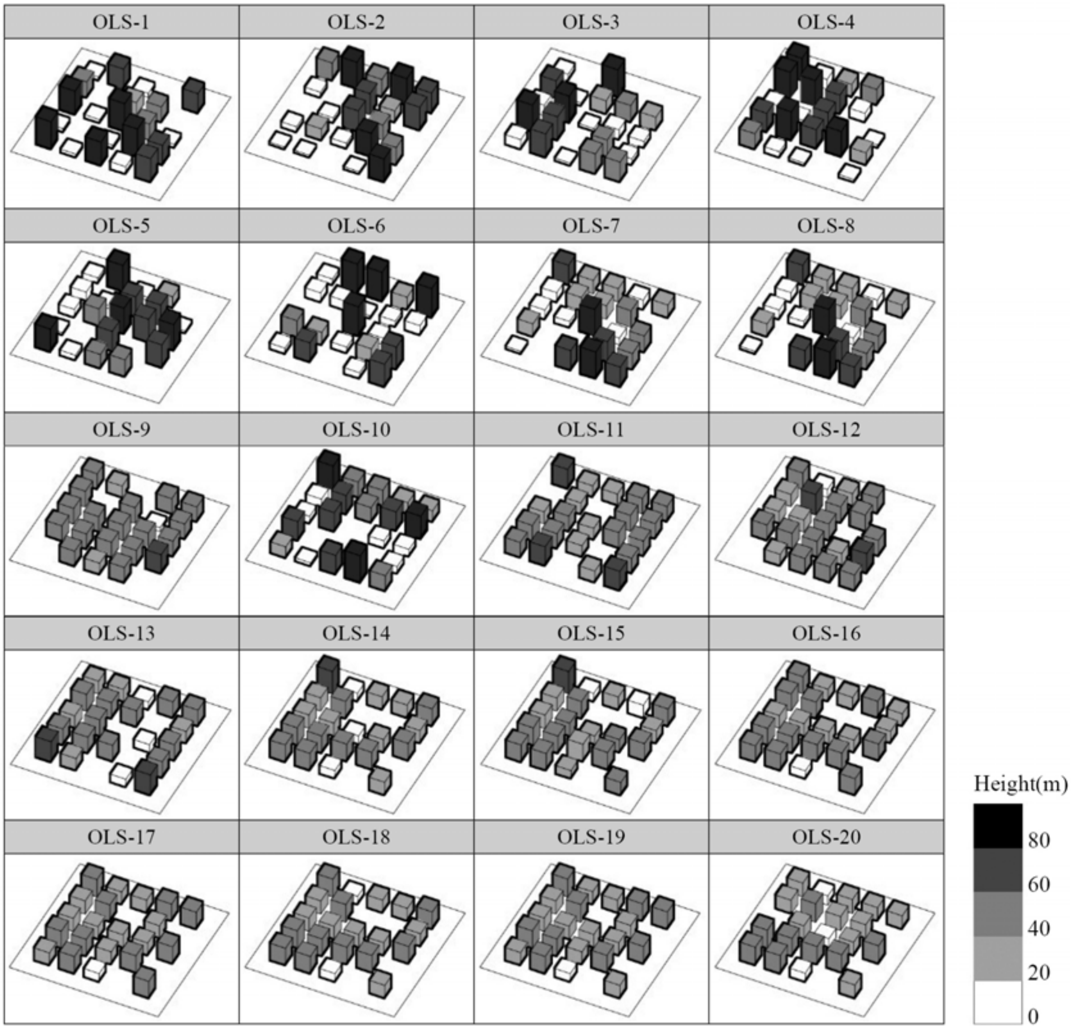


Fig.6. The evolution of building heights during the optimization process for OLS.

3.1.1 Optimization of vertical layout

At the beginning of the optimization process, the frequencies at which different building heights occur were equivalent, and the discrete height value was large. The height ranged from less than 10 m to 90 m. To provide perspective, the average height of a single story is about 3m (10 ft). The biggest difference between the maximum and minimum heights reached was about 80 m. During optimization, the maximum height declined gradually to about 60 m, and the minimum height rose gradually to about 20 m. The distribution of building heights gradually converged.

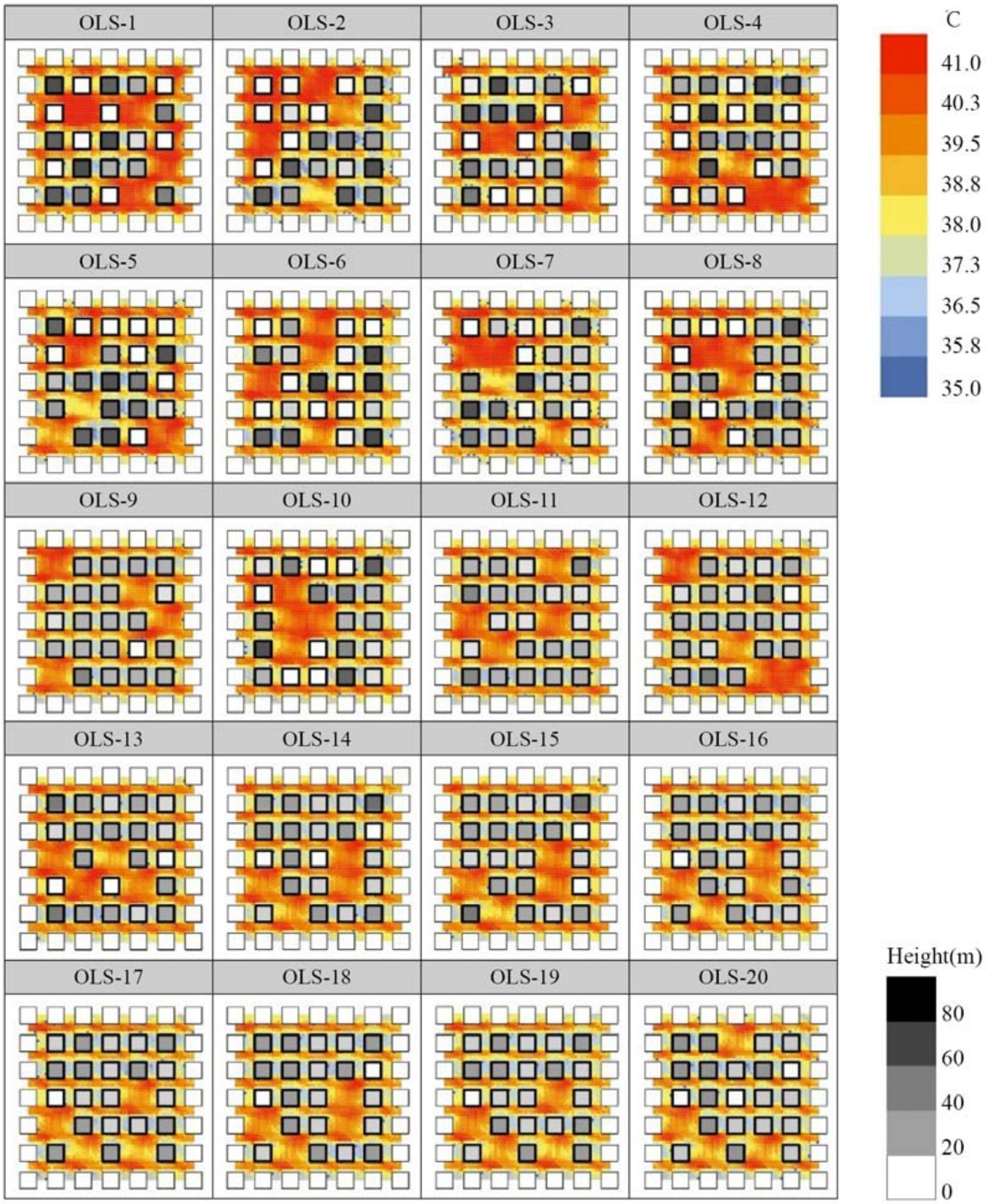


Fig. 7. The UTCI results and the building height distribution based on the performance simulation for OLS.

Fig. 7 shows the UTCI and building height distribution results for OLS. The height distribution of the buildings can be observed from the plane from 0 to 90m. The optimization results show that in the first 10 generations, the high-rise buildings distribute evenly and interspersed throughout the entire urban block (Fig. 7). From Generation 13 onward, the extremely tall buildings in the model ceased to exist. Taller buildings tended to conglomerate toward the upper left corner, i.e., the northwest corner of the model. The optimal results appeared in Generation 20. The model assumed an overall layout from northwest to southeast and from tall to short buildings (Fig. 7).

The results show that the comfort between buildings was influenced by the vertical layout of the open space and by the solar and wind environment. Considering the premise of an unchanged plot ratio, the different building heights enabled the model to assume a situation of a small number of tall buildings and a lot of low buildings. This left space that cannot be hidden by building shade and was directly exposed to blazing sunlight. According to the model, reasonably distributed building heights provide considerable shading and can promote the comfort of the outdoor micro-climate in summer.

The guidance of the southeastern wind in summer, typical of Nanjing, China, is another important factor that affected the comfort of the micro-climate. The overall layout of the buildings from high to low and from northwest to southeast helped bring in the wind from the southeast corner. This allowed a breeze to cross the site as much as possible, bringing fresh air and cooling to the entire environment. This also helped to reduce the outdoor humidity and temperature, thus improving the outdoor comfort. The distribution of the OLS-20 buildings embodies this point. In contrast, completely equal heights, e.g., the distribution shown in OLS-9, failed to make full use of the guiding effect of the wind-building height interaction. In contrast, in OLS-2, the southeastern wind failed to bring a cooling effect to the northwestern corner of the model because the wind was blocked by tall buildings located in the southeastern corner (Fig. 8).

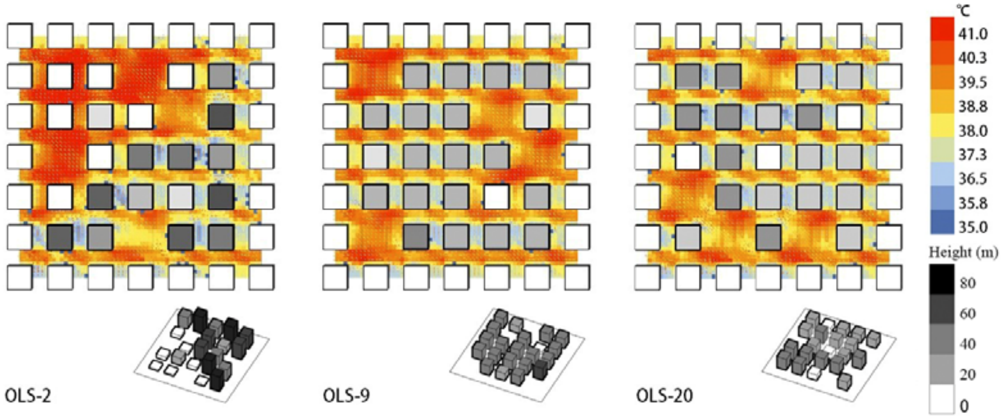


Fig.8. Vertical layout and UTCI results of OLS-2, OLS-9, and OLS-20.

3.1.2 Optimization of horizontal layout

When squares are open and barrier-free, instead of having a narrow or small-space schematic, wind can flow without resistance, which results in an increased wind speed. In addition, the wind can remove vapor and heat, making the outdoor micro-climate cooler. However, the space would suffer from solarization due to the lack of shading. Since the square area remained unchanged in the results, the square location is the key to acquiring the best comfort in the summer, by balancing the allocation of the two points. The results indicate that OLS-20, the square most conforming to the wind direction, can help bring the benefits of the wind to each corner of the model (Fig. 9). In addition, the even distribution mode enabled the open space in the model to enjoy shade brought by surrounding high buildings and promoted overall environmental comfort. On the contrary, the optimized square allocated against the wind direction in OLS-1 did not enjoy the benefits brought by ventilation and cooling. Moreover, the square was encircled by low buildings and is exposed to the sunlight. Thus, its UTCI was obviously higher than that of other spaces. Furthermore, as derived from OLS-10, the concentration of the square can reinforce the ventilation but fully exposes the open space in the middle to sunlight. Although the square was surrounded by high buildings, the increased benefit from ventilation did not offset the negative impact of the solar radiation. This made the comfort of the entire environment lower than that of the plane layout of even distribution.

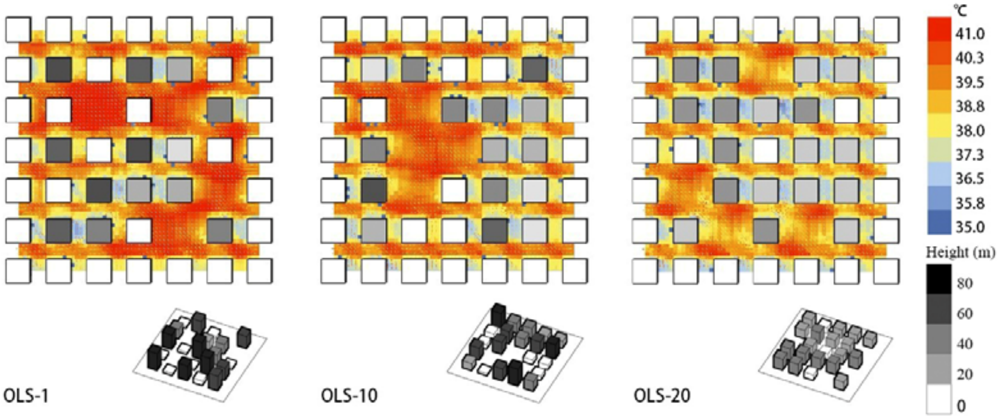


Fig.9. Horizontal layout and UTCI results of OLS-1, OLS-10, and OLS-20.

3.2 Results of open space layout in winter

Fig. 10 shows the continuous optimization of the genetic algorithm and the inherent fluctuation during the algorithm's search to seek feature. Notably, the fluctuation from Generation 330 to Generation 660 was particularly extreme. During this interval, the optimization direction was continuously searched for and sometimes overshot. The optimization trend became steadier after Generation 660. During the entire optimization process, the highest and lowest outdoor average UTCI was -1.9°C (at Generation 667) and -4.9°C (at Generation 151), respectively. This resulted in a difference of about 3°C. The results indicate that the layout of the open space has a more obvious impact on the improvement of outdoor comfort in the winter than in the summer (Fig. 10).

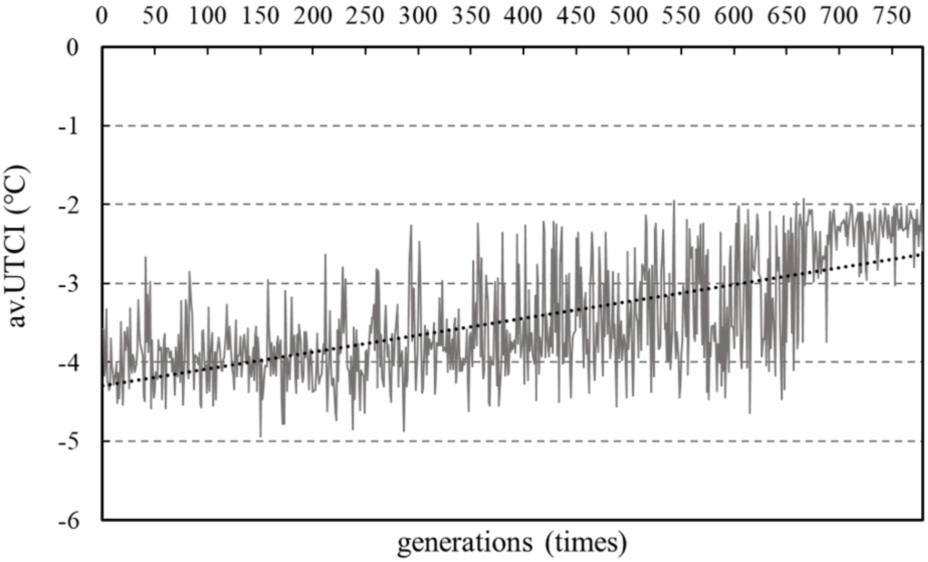


Fig.10. The mean UTCI results under the algorithm generations for OLW.

The results depicted in Fig. 11 present 20 different optimization cases. This includes the layout change of open space and the maximum and minimum values of the UTCI, where OLW-1 shows the minimum value and OLW-20 the maximum value.

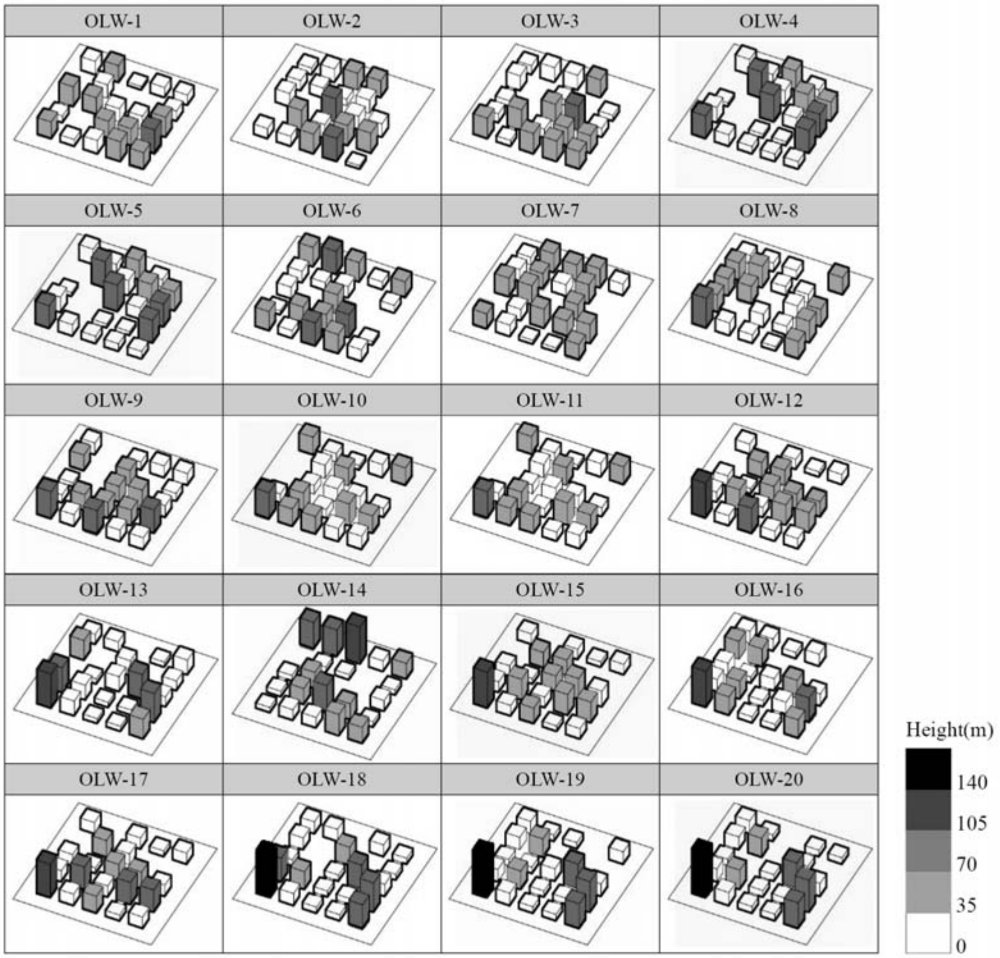


Fig.11. The evolution of building heights during the optimization process for OLW.

3.2.1 Optimization of vertical layout

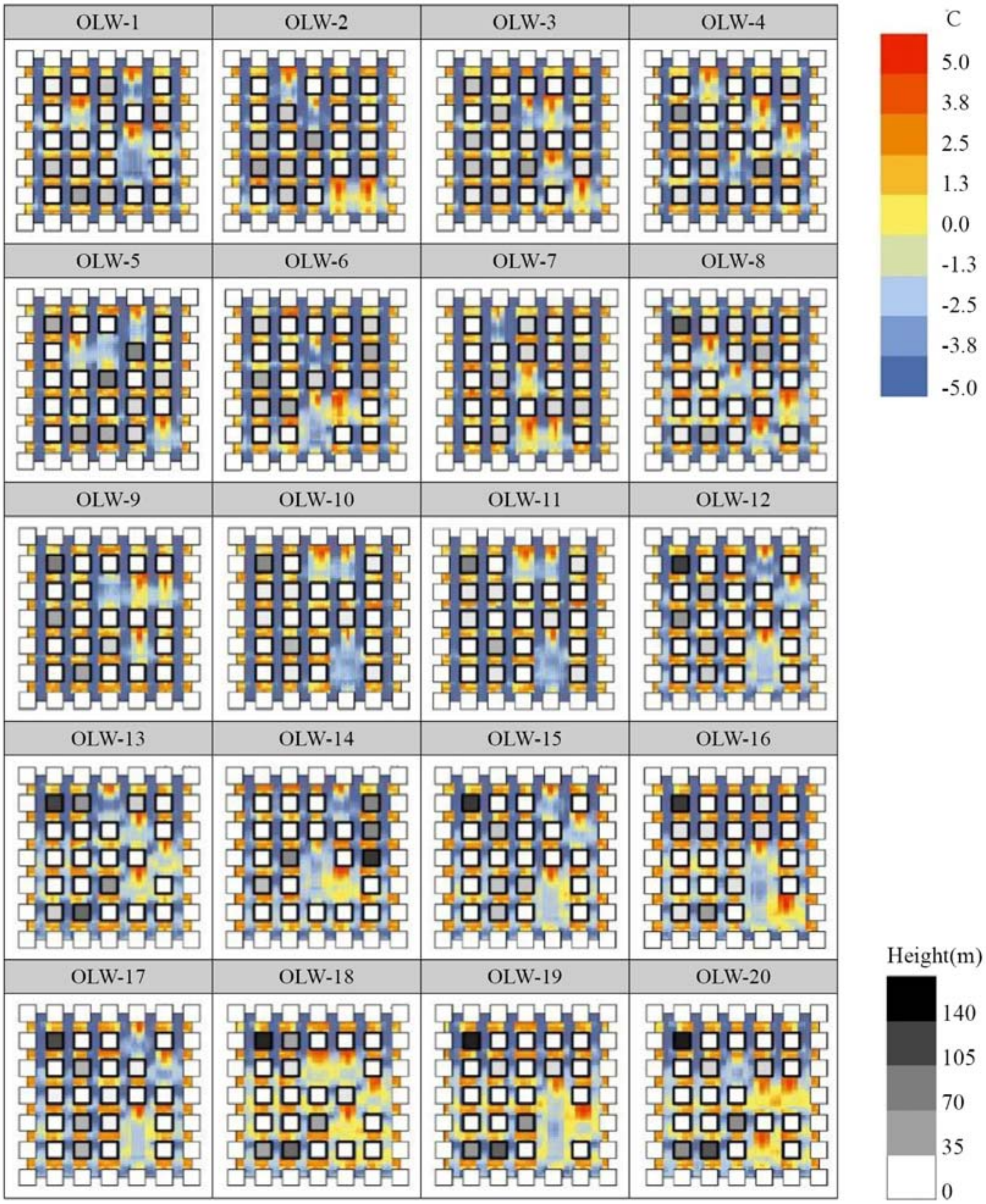


Fig.12. The UTCI results and building height distribution based on performance simulation for OLW.

The color depth in Fig. 12 represents the interval of building heights from 0 to 140m, with the darker color indicating a taller building. The height distribution of the buildings can be observed from the plane. Initially, buildings of different heights were distributed evenly within the prescribed city-block. From Generation 8, the highest buildings in the model started to be distributed predominately in the upper left corner, namely the northwestern corner. This trend lasted until the optimal result of Generation 20. The results indicate that most of the buildings in the urban block were low-rise buildings (less than 40 m), while the high-rise buildings distributed at the edge of the base.

During winter months, the maximized promotion of the reception of solar radiation is an important means in raising the outdoor temperature. In the optimization of the first seven generations, on the premise of having an unchanged plot ratio, the height of a lot of buildings in the model was between 30m to 60m. In turn, a lot of outdoor space was covered by shade. From Generation 8 onward, low buildings preserved sunny areas for the neighboring street and square, while the shade of the tallest buildings, located on the northwestern corner or other edges, had a smaller overall effect. Fig. 13 contrasts OLW-6, OLW-14, and OLW-20. The figure shows that the medium high-rise buildings, located in the center of urban block case OLW-6, reduced the UTCI of the open space by around 5°C due to shading. Conversely, the UTCI of the open space in the center of the urban block case OLW-20 was around 0°C, suggesting there was minimal cooling due to building shading.

In the Nanjing region, the winter monsoon is an important, unfavorable factor that affects comfort. The monsoon creates a northern wind that affects the optimization process. From iteration OLW-18 onward, in order to block the northern wind, the optimization tool prescribed a wind screen wall with buildings in the northernmost location of the space. This practice is superior to the practice of allocating a square in the north to open a way for the northern wind. Therefore, the funnel draft effect brought by high buildings should be avoided. By comparing the urban block cases OLW-14 and OLW-20, allocating high buildings on the edges of the city-block can not only reduce the impact of shading but also can reduce the reinforcing effect of the local wind environment caused by the layout of the tall buildings.

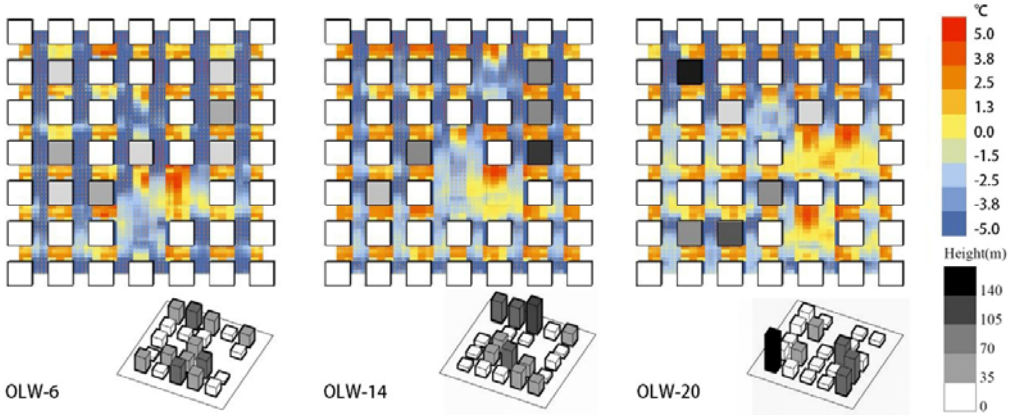


Fig.13. Vertical layout and UTCI results of the OLW-6, OLW-14, and OLW-20.

3.2.2 Optimization of horizontal layout

As can be detected from the square location diagram, square locations were gradually narrowed down from a disorderly distribution to 16–20 and 23–24 intervals. The highest frequency occurred at Location 17 of the square, occurring 13.85% of the time (432 times). The lowest frequency occurred at Location 1, occurring only 0.06% of the time (twice). Squares had the effect of increasing the wind speed and reducing the outdoor comfort in the winter. Simultaneously, the squares expanded the solar radiation, raising the outdoor temperature. Allocating the square by balancing these two points was key to achieving the best comfort in the winter. To further examine the optimal result, OLW-20, the square perpendicular to the prevailing wind direction can help weaken the wind effect. Moreover, since the open space was allocated farthest from the tallest buildings, the airflow vortex brought by high buildings was avoided and the shading due to the buildings was reduced. This provided an optimal outdoor thermal environment. In the OLW-15 of a similar layout, the square allocated according to the wind direction was greatly affected by the wind, with its UTCI being obviously lower than that of OLW-20. In addition, the square allocated near the northern side, since it can be derived from OLW-5, was subject to the invasion of the northern wind due to a lack of the obstruction from buildings. Moreover, the layout of having adjacent tall buildings, exposed the open space to a high-speed airflow vortex, increasing the wind speed and thus reducing the overall outdoor UTCI (Fig. 14).

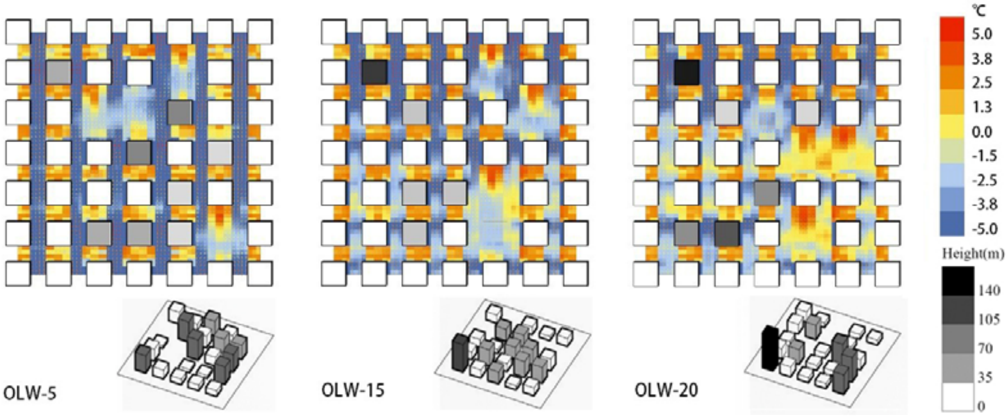
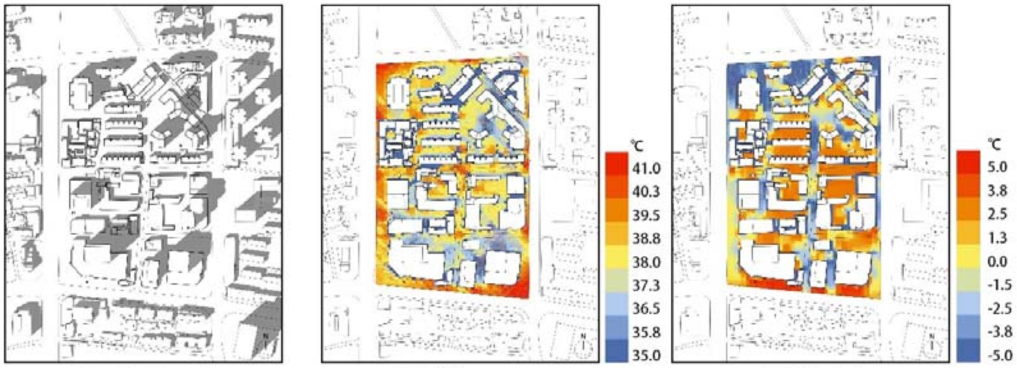


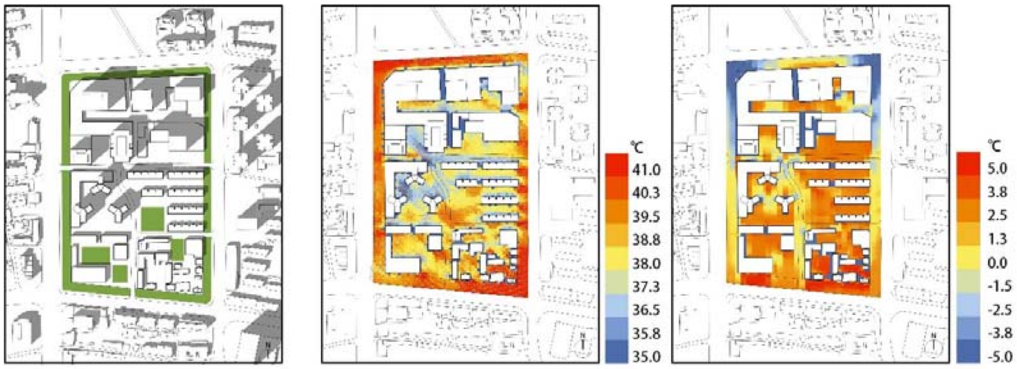
Fig.14. Horizontal layout and UTCI results of OLW-5, OLW-15, and OLW-20.

3.3 Validation results

The validation case consists of one urban block located in the main urban area of Nanjing city. The optimization process can be easily applied to the actual urban block. Fig. 15 shows the UTCI results for summer and winter, respectively, according to the original layout. Meanwhile, in the actual urban block, the average UTCI value is 37.4°C, the average radiation temperature is 39.6°C, and the average air velocity is 1.1 m/s for the summer season. For the winter season, the average UTCI value is -1.9°C, the average radiation temperature is 1.7°C, and the average air velocity is 0.9 m/s. The simulation results are consistent with the practical experience. In the simulation, the high-rise buildings created more shadow on the northern open space in the block, which reduced the available sunlight of the urban block, while the remaining inner space was exposed to the sunlight. Moreover, the turbulence caused by the high-rise buildings on the edge of the block would make people feel uncomfortable. In winter, the north wind is the dominant wind, while in summer, the inner space has low wind speeds and remains relatively hot. Due to the problem of functional ownership, the inner open space is isolated and fragmented, failing to offer any advantages.



(a) original layout (b) UTCI-summer (c) UTCI-winter



(d) optimized layout (e) UTCI-summer (f) UTCI-winter

Fig.15. Validation case study simulation results of UTCI for the original layout (above) and the optimized layout (below).

The block open space was redesigned using the optimization process applied for the testbed, and the optimization scheme was obtained based on ensuring the same volume rate, building density, and function type. Compared with the original layout plan, the simulated plan retained most of the original functional buildings, which ensured the original function of the block. Green belts were set aside for block extension to reduce the mutual influence between block buildings and the surrounding environment, as well as to isolate noise and pollution on the road. The average UTCI value was 38.0°C, the average radiation temperature was 41.7°C, and the average air velocity was 1.3m/s for the summer season. For the winter season, the average UTCI value was -0.2°C, the average radiation temperature was 2.3°C, and average air velocity was 0.7m/s.

In summer, the outdoor UTCI and radiation temperature increased as Shown in Fig. 15. The main reason for the increase was the open space corridor set aside for extension was exposed to sunlight - receiving more solar radiation energy. Since the simulation tool cannot simulate the benefits of green spaces (e.g., trees and grass obsorb solar energy) and the artificial heat source in the surrounding environment, the UTCI and radiation temperature will be a little higher than the actual results. Compared with the original scheme, the wind speed was improved, and the wind formed by the internal systematic open space had obvious effects. For instance, the wind was effectively guided to the interior of the entrance, which improved the overall ventilation effect. In winter, the outdoor average UTCI and radiation temperature were significantly increased, and the wind speed was reduced. Placing the high-rise buildings and the annex buildings at the north end of the site effectively blocked the north wind, which made the southern site and open space have a low wind speed and good sunshine. Overall, the optimization scheme improves the urban thermal comfort.

4. Discussion

4.1 Implication of this study

Some researchers, in the literature review, proposed to evaluate comfort conditions in urban open spaces using field surveys to investigate human physical and psychological factor [42]. However, it is time-consuming and limited by the variation of human thermal perception. Additionally, some studies recommended urban open spaces should consider bioclimatic [43] or micro-climate development [11]. Such studies provide good insights in considering human and green factors, such as human thermal perception, green space [44], pollutant detection [45]. However, such studies ignored the optimization of the building heights and location of open space for thermal comfort. Therefore, this study fills the gap by proposing an automatic optimization method and workflow to assess and optimize urban open space layout design. The Ladybug plug-in and the integrated genetic algorithm, based on the

Grasshopper platform, was used for the simulation of open space layout and the UTCI. Due to its simplicity, understandability, and ease of use of plug-ins, Grasshopper is prominently used in the field of green urban design. The optimization method using the tool fits nicely with the parameterized platform Grasshopper, which can be applied to future research.

This study selected a testbed and an actual case from real urban block site in Nanjing city, China, to validate the automatic optimization process. The results show that the urban block open space optimization method can increase the thermal performance. Furthermore, this study demonstrates that the layout of the open space affects the outdoor comfort of urban block. The study considered (1) the analysis of parameterized open space and (2) the impact of the open space layout considering the UCTI during the winter and summer seasons. On one hand, simulation consultants can work together with architects at the early design stage by helping to develop the conceptual and schematic design. On the other hand, simulation techniques may also validate building performance after designs are finished and make the designs green through technical alterations [46].

The computer-aided optimization process established in this study shows a certain novelty of facilitating medium-scale urban design according to simulations for different evaluations of open space layouts in different seasons. Contributions of this study focus on (a) providing a method of urban block design process along with simulation enabled design performance validation to improve urban design efficiency and effectiveness; (b) providing urban block design visualization and a combination of design and performance to improve accuracy and reasonability; and (c) providing insights into future integrated urban design with a combination of diverse computer-aided tools. Therefore, the following basic guidelines can be derived from this study based on computer-aided optimization to improve the micro-climate of urban open space, in regions with hot summer and cold winter.

4.1.1 Vertical layout of open space

The vertical attribute of open space can be influenced by building heights of the enclosed open space and different vertical attributes thoroughly impact the heat of solar radiation and the change of wind speed on the site. Table 3 summarizes vertical layout strategies for open spaces. The layout of building height requires attentions since it strongly impacts the ventilation and sunshine. In summer, close open space heights enable even shade between buildings, reduce heat from solar radiation, and increase wind speed. Additionally, open space with its height gradually declining from the northwest to the southeast can also more effectively bring in the southeastern wind. Moreover, the distribution of a dislocated open space can help adjust the air flow to cross the block, promote ventilation and take away heat. In winter, open space layout consists of mostly low-rise buildings and a small portion of high-rise buildings, which ensure a good sunshine condition. Having building heights in open space that decline from the northwest to the southeast can effectively prevent the northern wind with a drag-effect on the high-altitude wind and a protective wind shadow area by the high-rise buildings. It also avoids the shade of buildings located on the southern portion of the site. Allocating high-rise buildings on the edge of the site can reduce the unfavorable impact of the airflow vortex.

Table 3. Summary of vertical layout strategies for open space.

		Strategies	Reasons
Summer	Radiation environment	Open space maintains even or close heights	Enable even building shade, and reduce the radiation temperature
	Wind environment	Decrease building heights from the northwest to the southeast	Enhance southeastern wind, promote ventilation and reduce heat
Winter	Radiation environment	Place low-rise buildings near the southern open space and high-rise buildings near northern open space	Acquire sufficient sunshine and prevent the northern wind
	Wind environment	Decrease building heights from the northwest to the southeast and place high-rise buildings on the edge	Reduce wind shadow area wind speed on the southern side, and avoid building shade

4.1.2 Horizontal layout of open space

Horizontal layout of the open space directly impacts shade utilization and changes in wind speed. Placing evenly square open space in the urban block can help promote the ventilation. Combining open space with high-rise buildings can promote a shielding to direct solar irradiation and promote ventilation with local high-speed turbulence function of ground. Thus, architects and planners should try to optimize the layout of open space to lead wind direction in the summer and avoid the state of static wind. In addition, they should expand the width and area of the open space to raise the wind speed and enhance airflow into the urban block. In the winter, square open spaces should be distributed in the south with low-rise buildings to avoid shadow and the airflow influence brought by high-rise buildings. Additionally, open space should be distributed at an angle of 45°or less to lead wind direction. Table 4 concludes the strategies and reasons for the horizontal layout of open space.

Table 4. Summary of horizontal layout strategies for open space.

		Strategies	Reasons
Summer	Radiation environment	Distribute evenly square and other-type open spaces near southern site	Enable square space under shade of surrounding buildings
	Wind environment	Place open space south, and increase southern and southeast open space area	Lead southeastern wind, increase wind speed and bring more air into urban block
Winter	Radiation environment	Distribute square and other type open spaces near southern site	Avoid shading brought by buildings
	Wind environment	Reduce northern open space area and windward opening size, increase southern open space area, and avoid south-north linear layout	Reduce the northern wind with building wind shadow area, and form a static wind area

Additionally, architects and planners should also pay attention to the difference of climatic conditions to define the influence weights of their respective effects to the thermal environment, and eventually formulate a design strategy of open space that is adaptive to local conditions. With regards to the overall layout in both summer and winter, the layout of the open space more obviously impacts the improvement of outdoor comfort in the winter than in summer. However, considering the optimization performance of energy-saving and human comfort, optimization strategies should give priority to summer conditions when optimization strategies encounter conflicts between summer and winter.

4.2 Limitations of this study

This study also yields some limitations. Firstly, the simulation software used in this study was simplified without considerations of building materials, building and ground long-wave radiation, and the artificial radiation of the building. Therefore, the real heat-island intensity could not be simulated. Moreover, the role of wind in reducing humidity was not considered. Therefore, the improvement function of wind to the micro-climate of urban block, especially in summer, decreased during the simulation evaluation. Secondly, open space is a complicated part of the urban system. For instance, open space constitutes factors such as greening and materials. Due to limitations of the simulation software and hardware equipment, this study only analyzed the correlation between several open space layouts and micro-climates; more factors should be considered in future work. Thirdly, this study selected an outdoor mean UTCI as the evaluation index. Although the evaluation of UTCI to outdoor comfort is reliable, it fails to consider comprehensive comfort indices. For example, on a windy day (i.e., high-speed air flow), people tend to feel the discomfort due to the wind environment. Therefore, other methods could be included, such as mapping human bioclimatic map with human activities in open space [47], sun and wind desirability [48]. Moreover, future work should measure thermal comfort instead of only the mean value of UTCI for the entire environment as a judging standard [40], which is an indispensable premise for the intensive development of performance-driven optimization design. Lastly, this study applied the genetic algorithm for optimization of a single target based on a few independent variables. Future work should include more optimization parameters (e.g., location and benefits of green space) as well as multiple objective functions.

5. Conclusions

This study investigated the thermal comfort in the open space of urban blocks in Nanjing, China. A performance-driven urban design optimization process was conducted for urban open space with simulation tools to examine outdoor average

UTCI. In this study, two cases—one testbed and one real urban block—were used to validate the computer-aided simulation process. The optimization results in the testbed showed that UTCI values varied from 36.5 °C to 37.3 °C in summer and from -4.9 °C to -1.9 °C in winter, which demonstrates how a different layout can influence the comfort and micro-climate of urban open spaces. In the real case of the urban block, for the summer season, the average UTCI value is increased by 0.6°C since open space received more solar radiation and the simulation tool could not consider benefits of green open space, e.g., plants (trees, grass) can absorb solar energy. The average air velocity in summer is increased by 0.2 m/s. In the winter season, the average UTCI value is increased by 1.7°C, and the average air velocity is reduced by 0.2 m/s. Therefore, the proposed computer-aided optimization process can improve the open space thermal comfort conditions of urban blocks.

Based on the simulation of cases in Nanjing city in the cold-winter and hot-summer region, the findings suggest some strategies of layout design of urban open space to optimize thermal performance in summer and winter seasons. For open space optimization, architects and planners should (a) maintain even or close heights of open space, (b) distribute square or other types of open space near southern urban blocks, and (c) increase south and southeast open space areas and reduce the northern open space areas. As for building heights, architects and planners should (a) decrease building heights from the northwest to the southeast urban block, (b) place low-rise buildings near the southern open space and high-rise near the northern open space. Meanwhile, optimization should pay more attentions for urban open space design for summer condition by adding more strategies (e.g. adding green space). Given the computer-aided parameterized design platform, this study can provide significant insights for urban block open space design, facilitate traditional urban design methods, and improve outdoor comfort of urban blocks. The automatic process can be applied to not only other climate regions, but also other space types in the urban block, e.g., green spaces. Future works can focus on other urban block issues (e.g., sustainability, energy efficiency) once the outdoor climate has been optimized.

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