Engineering Advances, 2024, 4(4), 179-187
https://www.hillpublisher.com/journals/ea/
ISSN Online: 2768-7961

Research on the Optimization Design of Rural Spaces Based on Wind Environment and Thermal Comfort

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How to cite this paper: Kun Yang, Jixin Zhao, Yixin Wang, Chunming Zhang. (2024) Research on the Optimization Design of Rural Spaces Based on Wind Environment and Thermal Comfort. *Engineering Advances*, 4(4), 179-187.
DOI: 10.26855/ea.2024.10.005

Received: September 30, 2024
Accepted: October 28, 2024
Published: November 25, 2024

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Abstract

In this study, based on the simulation and analysis technology of wind and thermal environments, digital and performance-based research methods are employed. The Rhinoceros & Grasshopper platform, along with digital environmental performance simulation tools such as Ladybug, Butterfly, and OpenFoam, is used to analyze performance simulation. The connection between the wind and thermal environment and architectural spaces is established. Design decisions are made through data feedback, model adjustment, and strategy verification. Based on the UTCI index, four categories of thermal comfort spaces are scientifically classified. The characteristics of classified thermal comfort spaces and their impacts on the human body are summarized and analyzed. Based on the elements of thermal comfort spaces, reasonable optimization concepts are proposed. Taking into consideration factors such as the current spatial conditions and transformation potential, a simulation analysis of the wind and thermal environment in rural spaces in southwestern Yunnan is conducted. Optimization strategies are formulated based on the optimization concepts as design objectives. The reliability of the quantitative analysis technology and optimization strategies for microclimate environments is validated through the evaluation of optimized data. This technology is applied to the research of optimizing rural space design, providing a scientific basis for the planning and design of green rural spaces.

Keywords

Wind and thermal environment; Thermal comfort; Quantitative analysis; Performance simulation

1. Introduction

The rapid advancement of urbanization in our country has brought increasing significance to the improvement of the village environment [1]. A favorable thermal environment can enhance people's quality of life, and positively contribute to the sustainable development of rural areas [2]. Utilizing quantitative analysis techniques for the thermal environment can yield a more precise understanding of its characteristics, and offer a scientific basis for design decisions [3]. The thermal environment in rural spaces is influenced by various factors, including controllable elements such as green coverage, land use, building layout, and surface materials [4]. The city of Jinghong is situated in the Xishuangbanna Dai Autonomous Prefecture in the southwest of Yunnan Province. The village grapples with several comfort and ecological challenges due to the extended summer and absence of winter in the region, resulting in a hot and humid climate. Research is underway to study the thermal environment during the summer in this area.

2. Optimization design of rural space from the perspective of improving wind environment and thermal comfort

2.1 Thermal comfort evaluation indicators

Drawing from current research on the assessment of the thermal environment, this paper opts to utilize the Universal Thermal Climate Index (UTCI) as the evaluation metric for outdoor thermal conditions. The UTCI is a comprehensive index utilized to evaluate the effect of outdoor thermal conditions on the human body [5]. It takes into account several environmental factors including air temperature, humidity, wind, and solar radiation, and integrates the physiological responses of the human body to quantify the perceived temperature and the level of heat stress in specific environmental conditions.

Table 1. Classification of Universal Thermal Climate Index (UTCI) levels

The UTCI (Universal Thermal Climate Index) ranges in degrees Celsius (°C)	Physiological stress response
＞+46	Extreme heat stress
+38–+46	Severe heat stress
+32–+38	Moderate heat stress
+26–+32	Mild heat stress
+9–+26	No heat stress
+9–0	Mild cold stress
0–-13	Moderate cold stress
-13–-27	Severe cold stress
-27–-40	Extremely severe cold stress
＜-40	Extreme cold stress

2.2 Wind-heat environment simulation

The simulation and analysis of the wind-heat environment involves studying various aspects [6], Digital environmental performance simulation tools such as Ladybug, Butterfly, OpenFoam, etc., which operate on the parametric design platform (Rhinoceros & Grasshopper), are utilized to integrate the wind-heat environment with architectural space. This process facilitates the development of design decisions by incorporating data feedback, making model adjustments, and verifying strategies [7]. This interaction is no longer one-way but has truly achieved mutual influence and responses between the environment and architecture [8], Comparative analysis of on-site observations and simulation results demonstrates the high accuracy of this wind-heat environment simulation route [9].

2.2.1 The simulation route for thermal comfort

To calculate thermal comfort, the computation of UTCI values at multiple sampling points is essential. The Outdoor Comfort Calculator component necessitates inputs such as dry bulb temperature, relative humidity, mean radiant temperature, and wind speed to conduct the required calculations. Meteorological data files can supply data for dry bulb temperature and relative humidity. However, the mean radiant temperature (MRT) must be computed using the Solar Adjust Temperature component, and the Butterfly plugin is employed to calculate the wind speed (Figure 1). Subsequently, by establishing the base parameters (Table 2), the simulation generates the thermal comfort results through the computation of these four key parameters.

Table 2. Basic parameters for thermal comfort simulation

Parameter	Value
Simulation time period	June 1st to August 31st
The average human height	1.72 m
The spacing between individuals	5 m
Reflectance (based on color)	0.08

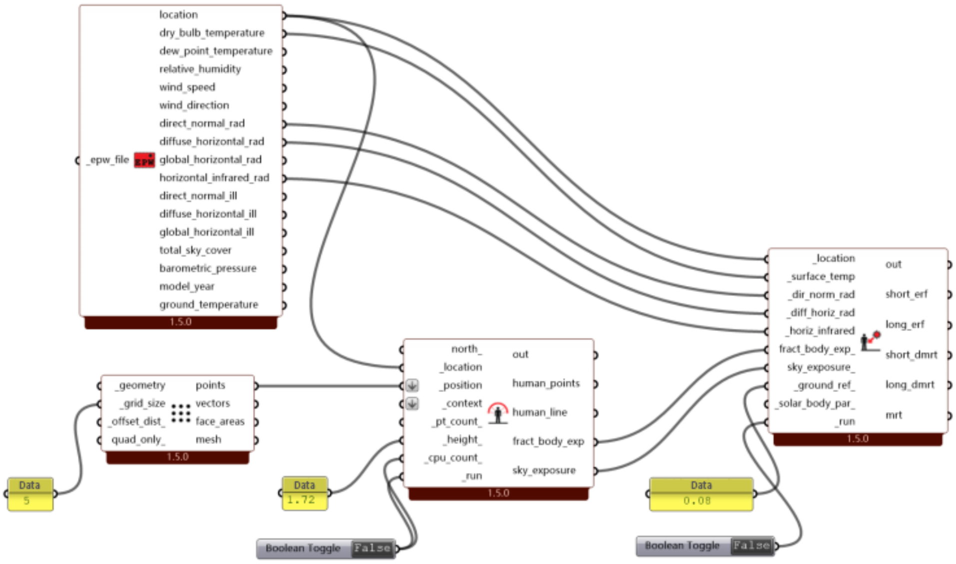

Figure 1. Module for Calculating Mean Radiant Temperature (MRT).

2.2.2 The wind environment simulation route

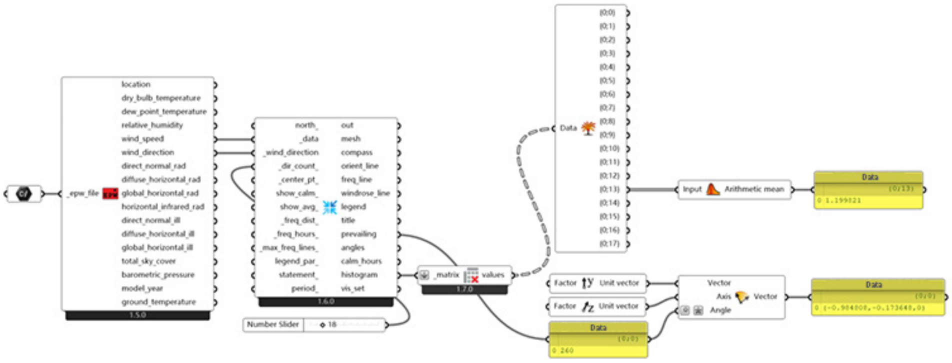

Figure 2. Module for Calculation of Prevailing Wind Direction and Average Wind Speed.

Table 3. Basic Parameters for Wind Environment Simulation

Parameter	Value
Average Wind Speed	1.2 m/s (1.199821 m/s)
Wind Direction (Incoming Wind)	South-West 14 degrees (-0.984808, -0.173648, 0)
Wind Height	1.5 m
Iteration Count	20 times

The calculation of the wind environment requires re-simulation of the neighborhood environment using the Butterfly plugin. The prevailing wind direction angle is extracted through the prevailing wind direction port. However, this prevailing wind direction angle cannot be directly used as wind direction data. Before it can be used as the prevailing wind direction, it needs to be flipped and converted into vector data in three-dimensional space. The wind speed dataset corresponding to the prevailing wind direction is extracted using the Explode Tree component. Subsequently, it is input into the Average component to calculate the average wind speed for the prevailing wind direction (Figure 2). Once the boundary conditions and grids are set, a turbulence model is constructed, and the wind environment is simulated by inputting all the basic parameters (Table 3).

3 Wind-heat environment simulation analysis

3.1 Test environment analysis

Jinghong City is situated in a hot and humid area, with an average annual temperature of around 21.9 °C and an average annual relative humidity ranging from 80% to 86%. The prevailing wind direction is predominantly northeast, and the average annual wind speed ranges from 0.5 m/s to 1.5 m/s (Figure 3). Additionally, the village exhibits a significant prevalence of unauthorized construction, characterized by high building density and an extremely chaotic layout [10].

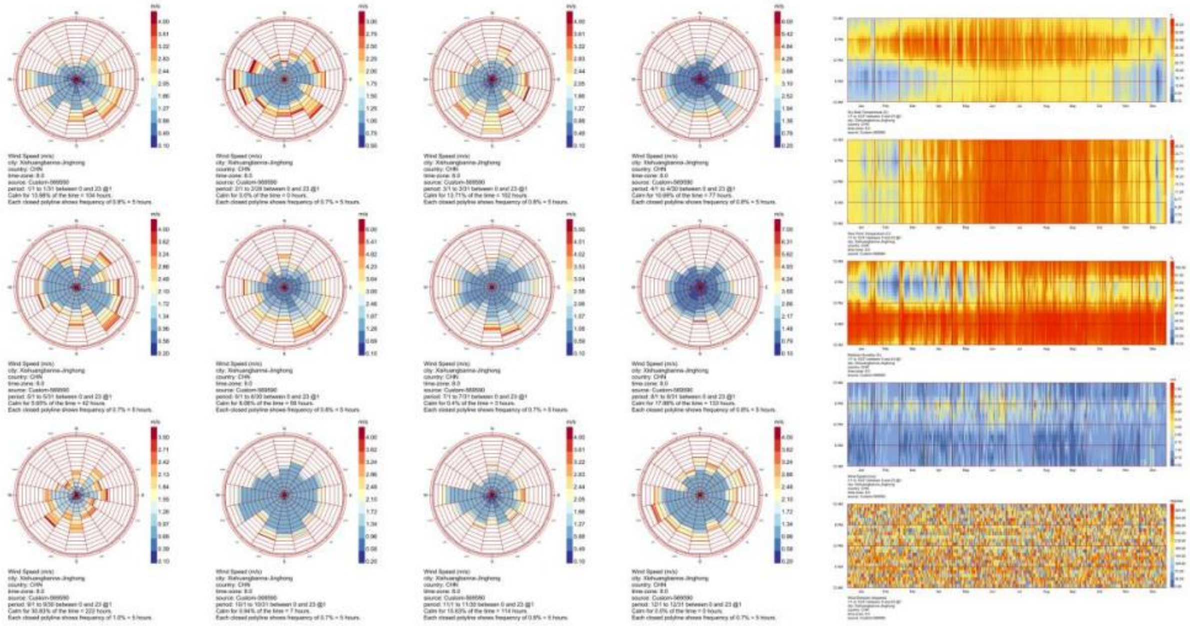

Figure 3. Meteorological Data Analysis of Jinghong City.

3.2 The overall ambience is relatively poor

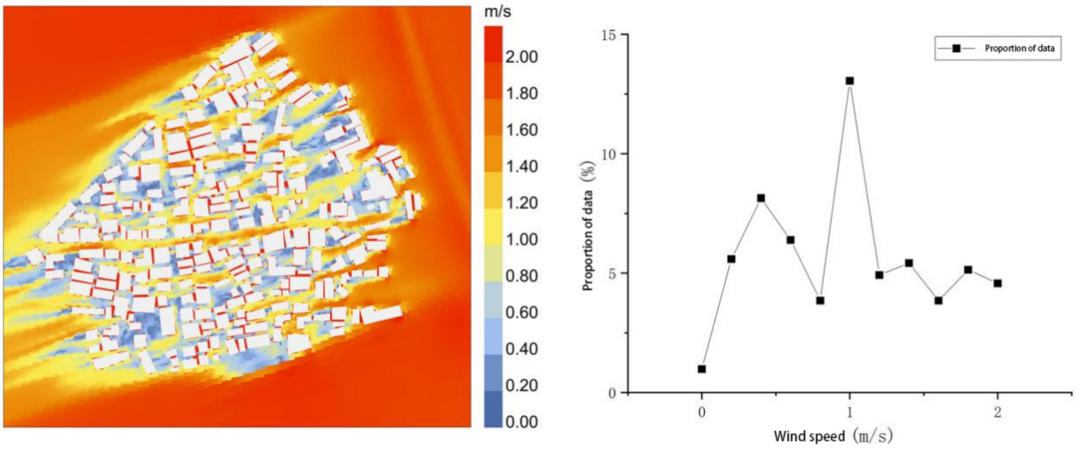

Figure 4. Wind Environment Data Analysis Chart for Mangge Village.

The overall building layout in Mangge Village is disorderly with a high building density. The majority of building clusters are enclosed, and these unfavorable conditions have influenced the overall ambient environment of the village. The wind environment analysis diagram of Mangge Village (Figure 4) illustrates that the proportion of the windless area (wind speed 0-0.2 m/s) is approximately 6.57%. The highest wind speed in the village is found between the buildings and the main road, whereas the lowest wind speed occurs within the enclosed building clusters. Wind speed at the windward opening is relatively high (exceeding 1 m/s), while the wind environment in some open spaces is intermediate (ranging from 0.8 to 1.4 m/s). The wind environment is unfavorable in the enclosed building clusters and certain open spaces (with wind speeds ranging from 0 to 0.6 m/s). The prevailing wind comes from the northeast. The building clusters oriented in the northeast exhibit slightly more favorable conditions compared to those oriented in the southwest. Additionally, certain individual buildings and building clusters disrupt the wind field, leading to changes in wind direction within the field and adversely affecting the overall wind environment [11].

3.3 The thermal comfort data is relatively low

According to the Universal Thermal Climate Index (UTCI) indicator and the thermal comfort analysis chart for Mangge Village (Figure 5), it can be inferred that there are numerous areas within the village with subpar human thermal comfort. The prevalent characteristic of these areas is the high enclosure of building clusters, which leads to reduced air circulation due to the high building density and enclosure. This obstructs the effective guidance of airflow, particularly between the southwest-facing streets and the prevailing northeasterly winds, resulting in a significant mismatch and exacerbating ventilation conditions. Consequently, this adversely affects human thermal comfort in the region [12]. In the more open areas within the village, the absence of shading facilities exposes the area to direct sunlight, causing excessively high temperatures that impact human comfort and contribute to the overall poor thermal comfort conditions [13].

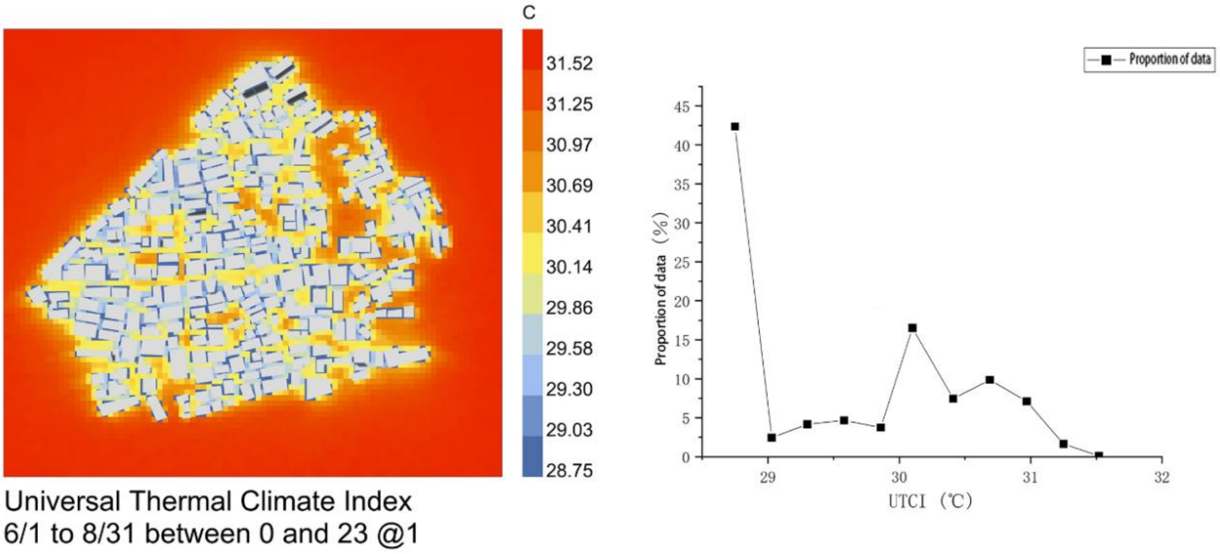

Figure 5. Thermal Comfort Data Analysis Chart for Mangge Village.

3.4 Scientific planning of thermal comfort space

By analyzing the diverse characteristics of the UTCI index, a scientific classification of thermal comfort zones is formulated (Table 4). However, it is essential to make adjustments to the optimization design strategy during the design process, considering the region's policies and actual circumstances.

4. Optimization design strategy based on improved wind environment and thermal comfort

4.1 Optimizing thermal comfort space and the wind-thermal environment with a parallel implementation of multiple measures

Based on the classification table of thermal comfort spaces, the second category of thermal comfort spaces is selected as the benchmark for optimizing design, and research on optimization design strategies is commenced [14].

The measure involves the partial demolition or alteration of building form and position to create favorable conditions for adapting to the prevailing wind direction and improving air circulation within specific locations (A1-A15 in Figure 6)

[15]. The plan includes widening the space between buildings to facilitate the entry of more wind resources into the streets (locations B1-B8 in Figure 6). Additionally, it involves optimizing the arrangement of buildings in specific areas to enhance the permeability of village spaces. This includes opening up enclosed building clusters to create U-shaped spaces that align with the prevailing wind direction, ultimately reducing the enclosed building clusters within the village space to improve the overall wind environment in the area (regions C1-C4 in Figure 6). Based on the optimized building form, organize the building facades to ensure smoothness within the space and minimize obstructions to air circulation caused by irregular building facades. These measures aim to introduce high-quality wind resources into the village space, improving ventilation and creating a high-quality wind environment for the residents [16].

Table 4. Classification of Thermal Comfort Spaces

Space Category	Space Characteristics	Thermal Comfort Range (°C)	Optimization Concept	Optimization Strategy
First Category	The first category of thermal comfort spaces is marked by high temps, high humidity, and poor ventilation.	38–46	Enhance street-level airflow through architectural optimization, expanding street areas, and creating public spaces.	Boost airflow by resizing streets, reconfiguring building clusters for openness, and adding vertical and rooftop greenery.
Second Category	The second category of thermal comfort spaces includes environments with temperatures slightly above the comfort level.	26–38	enhance permeability between buildings to improve overall ventilation in the area.	Enhance area ventilation by adjusting street widths for corridors, aligning streets with wind direction, and optimizing building clusters for better airflow.
Third Category	The third thermal comfort category relates to colder environments.	9–-27	Harness solar energy for heating and optimize street design for natural light, minimizing wind to boost thermal comfort in cold climates.	Improve thermal comfort in cold areas by installing solar panels on buildings, adjusting building layouts, aligning streets to reduce wind impact, and using dark, waterproof pavements.
Fourth Category	The fourth category of thermal comfort spaces includes extremely cold environments, typically below the comfortable temperature threshold for humans.	-27–-40	Improve thermal comfort in frigid environments by strategically arranging buildings and designing forms to maximize natural light.	Enhance thermal comfort in extremely cold settings by reducing building exposure, optimizing cluster layouts, and diversifying building shapes.

Figure 6. Illustration of wind environment transformation.

Based on the analysis of the UTCI, it is recommended to implement optimization measures such as planting tall trees in areas with poor thermal comfort to provide shade, thereby enhancing human comfort (A1-A3 areas in Figure 7). Additionally, arranging tree ponds on the main road and in open areas (B1-B6 areas in Figure 7) can further improve the thermal environment. In designated areas (C1-C7 in Figure 7), consider designing simple and transparent landscape ornaments that create viewing spaces while allowing wind to pass through. This approach can not only enhance spatial visual effects but also improve human comfort. Furthermore, altering the architectural form or adding shading facilities to reduce direct sunlight in specified locations (D1-D14 in Figure 7) can effectively lower the temperature in the spatial area, thus enhancing the comfort of individuals [17].

Figure 7. Schematic diagram of thermal comfort modification.

4.2 Quantitative analysis of wind thermal environment optimization data

4.2.1 Excellent wind environment optimization effect

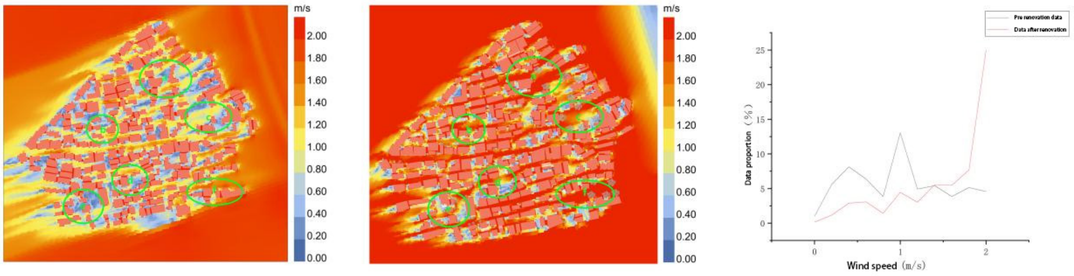

Figure 8. Analysis of Wind Environment Status (Left) After Renovation (Middle) Data Comparison (Right).

Following the optimization analysis based on the implemented strategies, a substantial improvement in the wind environment was observed. Through the analysis chart before and after the renovation of the wind environment (Figure 8), it is evident that alterations in the shape and positioning of the buildings resulted in the creation of specific areas that align with the prevailing wind direction, significantly reducing the presence of windless areas (areas a, b, c, and d in Figure 8). The wind environment has been significantly enhanced through the optimization design strategy. Widening the spacing between buildings and opening air ducts to introduce wind resources has led to a notable increase in wind speeds (areas b and d in Figure 8). Additionally, by re-optimizing the combination of certain building clusters to open up interior spaces of streets and alleys and reducing the number of enclosed buildings, U-shaped spaces have been created to align with the prevailing wind direction (areas a, e, and f in Figure 9). The data indicates a notable decrease in the proportion of the no wind zone (wind speed 0–0.2 m/s) from 6.57% to 1.31%, alongside a decrease in the soft wind zone (wind speed 0.3–1.5 m/s) from 45.62% to 25.85%. Additionally, the proportion of area data with a wind speed of 2m/s has increased substantially, from 4.57% to 24.97% (Figure 8).

4.2.2 Significant improvement in thermal comfort

Following the optimization analysis based on the implemented strategies, a notable improvement in thermal comfort has been achieved. The analysis of the thermal comfort situation before and after transformation (Figure 9) indicates that planting tall trees to provide shade has led to a reduction in temperature in certain areas, thereby enhancing human comfort in the area (areas b and f in Figure 9). The strategic arrangement of tree ponds on the main road and in open areas has significantly enhanced human comfort in the designated areas (areas a and d in Figure 9). Additionally, optimizing human comfort in the area has been achieved by introducing simple and transparent landscape ornaments (areas c, e, and f in Figure 9), as well as by modifying the architectural form or incorporating shading facilities to lower the temperature and improve human comfort (areas a and c in Figure9). The proportion of UTCI area values above 30 ℃ decreased from 42.63% to 36.71%, while the proportion of UTCI area values below 30 ℃ increased from 57.38% to 62.99% (Figure 9).

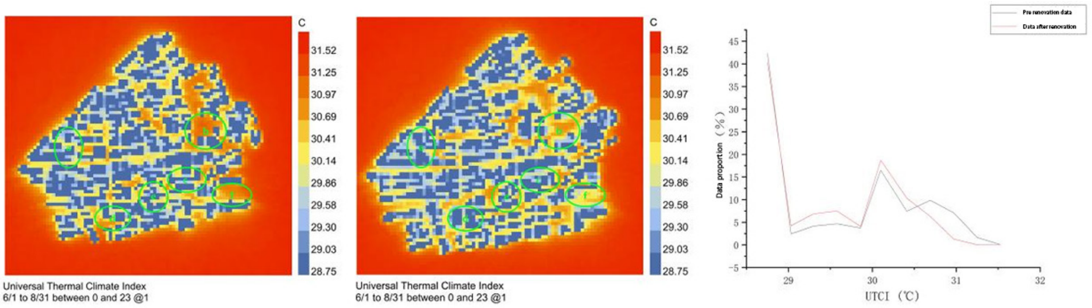

Figure 9. Current situation of thermal comfort (left) Data comparison after renovation (center) (right).

5. Conclusion

Applying wind thermal environment simulation methods allows for a rational and objective analysis of the wind thermal environment within the region. Formulating optimization design strategies that involve quantitative analysis of optimization effects can help reduce the impact of uncertain factors in design results. By employing these methods, the design process can be more robust and effective.

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