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Sustainability Optimization Method of Built Environment with Integrated Physical Environment and Virtual Perception Simulation: A Case Study of Campus Open Space

Yizhou Wu, Yueer Wu * and Yaxin Pan

School of Design and Architecture, Zhejiang University of Technology, Hangzhou 310058, China; zjutwyz@zjut.edu.cn (Y.W.); 15990133139@163.com (Y.P.)
* Correspondence: 19550125712@163.com

Abstract: High-quality built environments significantly enhance residents' health, urban livability, and sustainability. However, the lack of precise pre-evaluation of designs and user perceptions during the design phase often results in suboptimal improvements. This study proposes a method for evaluating and optimizing design schemes based on multidimensional physical environment simulations and virtual perception, using a university campus as a case study. Initially, we establish simulation models for sound, wind, thermal, and light environments and analyze the current state of virtual perception in the campus environment. Subsequently, we integrate the evaluation results of the physical environment and virtual perception to identify three priority intervention areas and develop corresponding design strategies. Finally, we reapply the method for pre-evaluation of the design schemes and further optimize the designs. The results show that the optimized schemes receive positive feedback in virtual perception evaluations. This study leverages the combined use of multidimensional physical environment simulations and VR technology to create an immersive virtual environment with measurable physical perception experiences, providing a new approach for guiding the sustainability of built environments.

Keywords: built environment; physical environment; virtual reality; integrated evaluation; optimization method; sustainable design

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1. Introduction

In the latter half of the 20th century, the world witnessed a significant and irreversible trend toward urbanization, with a projected 68% of the global population expected to reside in urban areas by 2050 [1]. However, the rapid expansion of cities has given rise to numerous environmental issues, including the heat island effect, noise pollution, lack of wind movement, and smog, all of which directly impact the quality of urban living environments. The World Urbanization Prospects, released by the United Nations in 2018, provides important insights into the future development of cities, covering a wide range of areas such as urban design, resource use, environmental protection, and social equity, with a clear focus on sustainable, inclusive, and resilient environmental strategies to address future challenges [2].

At this stage, in-depth research on optimizing the built environment has been carried out in a wide range of disciplines and fields, from the optimization of land use and transportation systems [3,4], to the design of green spaces and the improvement of energy efficiency [5,6], to the concern for social equity and public interaction [7]. Through constantly innovative theoretical approaches and technological tools, future cities will be smarter, more ecological, and better able to cope with environmental conflicts and social challenges towards a sustainable future development model. From a micro perspective, to ensure sustainable development, it becomes crucial to prioritize space renewal and spatial reconstruction to create livable and sustainable spaces. Designers are constantly

striving to find optimal spatial forms that can deliver such environments [8]. However, there are persistent technical challenges, particularly concerning the precise control of spatial design schemes. Therefore, it is necessary at this stage to model and evaluate the specific built environment.

The physical environment is the fundamental condition provided by nature, and the built environment depends on the resources in the physical environment, such as land, vegetation, air, and energy [9]. The physical environment includes various elements, including acoustics, wind, thermal conditions, lighting, and landscape, among others [10]. These elements directly impact the well-being and health of urban residents and have a greater impact on sustainable urban development. Excessive noise, for instance, can cause hearing damage and urban noise pollution [11,12]. Unfavorable wind and thermal conditions can reduce comfort and increase energy consumption [13]. Inappropriate lighting conditions may cause eye strain and visual discomfort, while excessive or poorly designed lighting can lead to light pollution [14,15]. On the other hand, a well-designed physical environment has a positive influence on both human health and sustainable cities, with a visually appealing landscape helping to alleviate stress and minor ailments while also maintaining ecological balance [16]. The physical environment, which is shaped by the interaction of different factors, plays a crucial role in shaping how outdoor activities are perceived [17]. Through the simulation of a multidimensional physical environment and accurate analysis of sound, wind, heat, light, landscape, and other dimensions, we provide optimized solutions to reduce environmental impact and enhance sustainability.

Perception is the process of receiving external stimuli through the sense organs (e.g., sight, hearing, smell, touch, taste) and processing and interpreting them in the brain to form awareness and understanding of the external world [18]. Virtual perception refers to the simulation of the perceptual experience in the real environment through digital technology, sensors, and other technical means, so that the user in the virtual environment can "perceive" similarly to the real world [19]. Through the simulation and analysis of complex environmental and resource management problems, virtual perception provides strong support for urban planning, energy management, ecological protection, and other areas of sustainable development [20].

This study aims to investigate an optimization technique for built environments through the use of integrated physical environments and virtual perception simulations. This research uses the Zhejiang University of Technology campus as the research site. The specific objectives of this study are as follows: (1) to assess the quality of the campus' built environment in terms of wind, thermal, acoustic, light, and landscape environments; (2) to propose and implement an integrated evaluation framework that combines objective physical environment assessments with subjective perceptions, in order to identify priority areas for intervention; and (3) to design intervention schemes for these priority areas, using physical environment simulations and VR technologies. The overall goal is to achieve a comprehensive evaluation and optimization of the built environment by following a logical process of "current situation analysis—parameter simulation—design optimization—scheme evaluation—decision making".

2. Literature Review

Traditional sustainability optimization studies of the built environment have been conducted mainly in a monolithic manner, aiming at achieving a built environment that is low-energy, high-efficiency, environmentally friendly, and livable. These methods include objective assessments that utilize open space and environmental data [21,22], as well as subjective approaches like field surveys, imagery, and virtual scenarios [23,24].

The research can be traced back to Luke Howard's *Climate of London* in the early 19th century, which began a systematic study of the physical environment by observing and discovering the urban heat island phenomenon and related environmental problems while organizing the climate of London during the decade from 1807 to 1816 [25]. Le Corbusier pioneered the incorporation of urban climate into the design of urban planning and used

ventilation and shading as basic strategies for building design [26]. Subsequently, Olgyay systematically combined urban design, locality, urban climate, and human comfort [27].

From an objective perspective, according to the reading and organizing of the related literature, it was found that scholars at home and abroad have different focuses on the research of the physical environment, which is specifically reflected in the scale, indicators, and intervention stage of the research.

In terms of research methodology and indicators, the initial research relied mainly on field measurement methods and on-site monitoring using instruments in order to explore the actual pattern of change in physical environment data. Subsequently, the research gradually evolved into laboratory simulation and eventually shifted to computer-based physical environment simulation techniques, realizing a stage-by-stage change in physical environment research methods. However, the impact of factors such as regional climate change on the physical environment makes it difficult for existing techniques and instruments to conduct large-scale, global field monitoring. Currently, these methods are mainly used to provide basic data on the current state of the environment to support simulation analysis and calibration. Specifically, some scholars selected equivalent continuous A sound level (LAeq), peak traffic noise (L_{10}), and other evaluation indexes for noise prediction [28]. They predicted hot and cold sensory indexes (PMV) [29], human comfort index (SSD), mean radiant temperature (MRT), standard effective temperature (SET) [30], and other thermal comfort indexes and models for evaluating the thermal environment. These were combined with the wind environment's wind speed, wind direction, and other evaluation quantities to construct the evaluation indexes of the wind and thermal environment [31]. The indexes of the light environment are mainly based on the requirements of the daylight standard in the National Green Building Evaluation Standard (GB/T50378-2019) [32]. At this stage, physical environment simulation is facing challenges, such as model complexity and computational resources, cross-disciplinary data integration and standardization, etc. Future research directions may also require larger-scale multi-scale simulations, more efficient parallel algorithm development, and a deeper integration of AI and physical simulation.

In terms of the research scale, it has gradually expanded from the building scale to the regional planning scope [33]. Some scholars have studied the layout of building groups, the simulation of the surrounding flow field [28], and the analysis of the physical environment and its environmental quality measurement [34] based on the building group scale. Other scholars have extended the research scale to the neighborhood level, and some countries have included indicators, such as air circulation, noise and dust prevention and reduction, and human comfort into the consideration of neighborhood renewal design [31]. Shen et al. have further extended the research scale to the urban area, exploring the relationship between the physical environment and the urban form, and the application of physical environment regulation tools in urban planning [35]. However, the studies tend to focus on the historical changes in the physical environment, the characteristic laws, and the construction of the theoretical system, with less relevance to the optimization of the built environment, planning and design, and spatial morphology [36]. According to the stage of intervention, research on the physical environment often includes "design-in evaluations" and "post-occupancy evaluations" [37]. "Design-in evaluations" quantify and predict physical environment performance based on design simulations. Additionally, "post-occupancy evaluations" assess the effectiveness of built environments. However, these studies lack guidance and feedback for optimizing built environment designs [38].

From a subjective perspective, the research focuses on exploring how people understand, evaluate, and experience the landscape and other elements in built environments through their senses, cognition, and emotions. In terms of research methodology, it not only combines qualitative methods such as questionnaires and interviews but also includes quantitative analysis tools such as behavioral observation and psychological testing. The perception of the built environment is a complex and multidimensional process, which is influenced by a combination of factors, such as the landscape structure, the combination of natural and artificial elements [39], the cultural and social context [40], and the environ-

mental atmosphere and experience. In addition, the introduction of modern technologies, such as virtual reality (VR) simulations, enables designers and the public to perceive spatial layout, visual effects, etc., through virtual models, thus providing support for perception assessment and design optimization in urban planning and environmental design [41]. Specifically, the mechanism of virtual perception technology includes visual perception, tactile perception [42], spatial perception and navigation [43]. It is widely used in the fields of spatial layout of cities, environmental protection [44], smart city construction [45], and public safety management [46]. It can be seen that the current application of virtual reality (VR) technology in spatial studies mainly focuses on updating external environmental attributes [47]. Conversely, research on VR applications in built environment simulations is still relatively underdeveloped.

In summary, the existing studies generally overlook the objective reality that the built environment has a complex and comprehensive effect on people due to the lack of integrated evaluation research and interactive feedback optimization from designers and users. However, with the advancement of digital and virtual reality technologies in the fields of urban and rural planning, architecture, and landscape design—including spatial experience [48], built environment evaluation [49], and placemaking [50]—these technologies can address the limitations of traditional singular evaluation methods for built environment spaces.

3. Materials and Methods

3.1. Technical Route

The research team of this article has conducted a preliminary exploration of the multidimensional simulation of the built environment from four dimensions: wind, heat, sound, and landscape, in past studies to examine and simulate health-related physical environments and to provide new tools for pre-evaluation and optimization in planning and design [10]. However, there are still some shortcomings. On the one hand, the built environment, oriented in a broad sense, still suffers from an insufficient number of parameters and incomplete coverage of integrated evaluation dimensions, and on the other hand, there is a lack of guidance and feedback on the prior evaluation of the design solutions to determine the potential improvements of the recommendations. Building on the original theory and methodology, this study employs a stepwise optimization process that includes a multidimensional evaluation of the overall environment, local morphological zoning, and human-scale spaces. Both subjective and objective methods are integrated to explore optimization techniques for built environments. At the same time, the optimization scheme is simulated and evaluated with the help of virtual reality technology. This study consists of three steps, as shown in Figure 1.

Step 1: Conduct a field survey of the case area to collect real-time data on wind, thermal, acoustic, and light environments. Compare the field measurements with the simulation results to validate the accuracy of the simulations.

Step 2: Conduct an objective evaluation of the simulated wind, thermal, acoustic, and light environments. Then, conduct a subjective assessment of the visual landscape environment of the campus space using the Semantic Differential method questionnaire. Based on the integrated evaluation results, identify areas with poor environmental quality that require focused optimization. Determine specific indicators that need improvement according to the evaluation results, physical environment simulation maps, and the semantic differential scale.

Step 3: Propose targeted renovation strategies and schemes. Due to the constraints of modifying real-world scenarios, VR virtual technology is employed using the MARS (Bright City) platform. Evaluators utilize VR glasses to evaluate the optimized virtual scenes (Figure 2). Multiple rounds of simulation and comparison aid in determining the optimal design scheme.

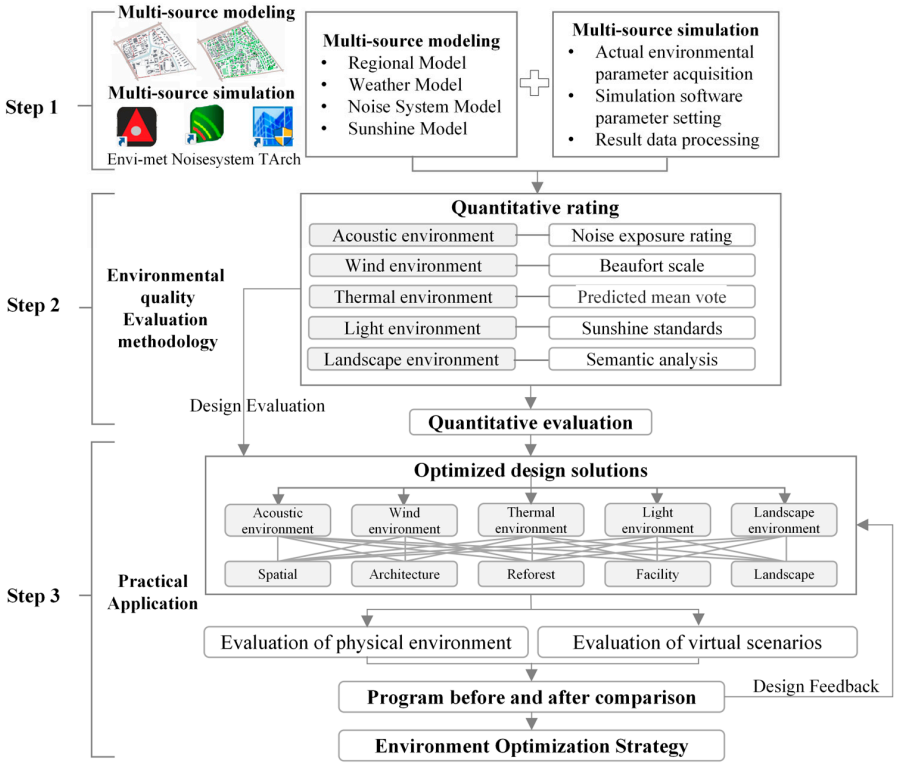


Figure 1. Technical route.

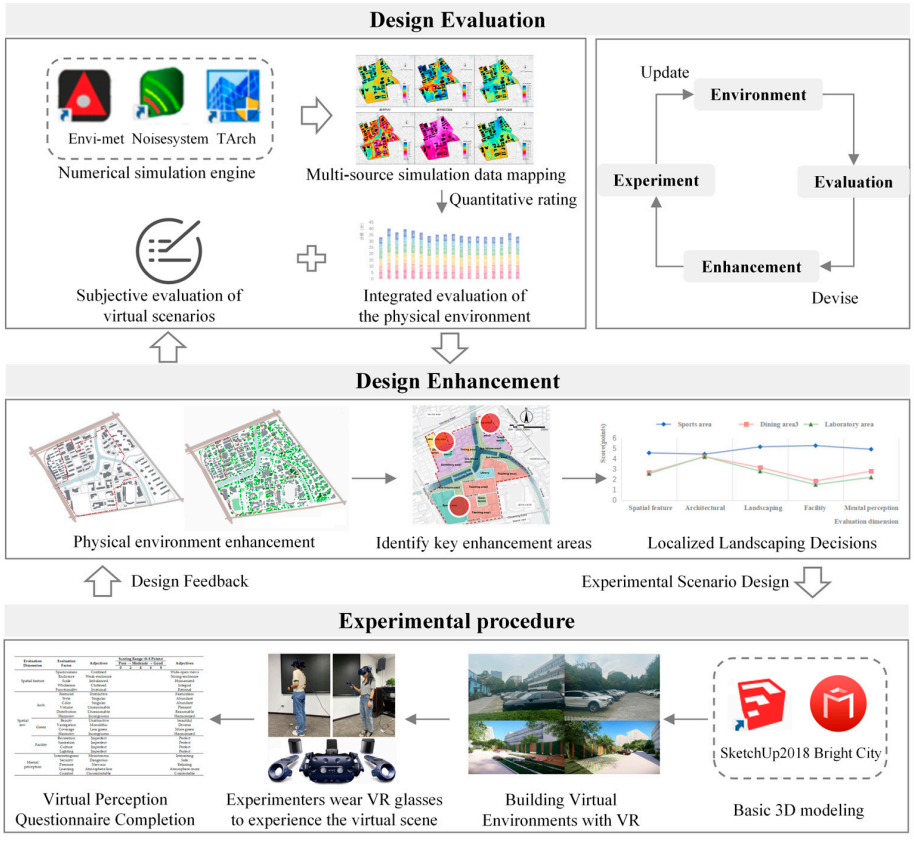


Figure 2. Flow of virtual perception experiment.

3.2. Multidimensional Physical Environment Simulation

Considering the multifunctional and complex nature of university campuses, this study specifically examines the built environment of Zhejiang University of Technology's Zhaohui Campus, located in Hangzhou, Zhejiang Province, China (118°21′–120°30′ E, 29°11′–30°33′ N). The campus is situated in a subtropical monsoon climate zone, characterized by distinct seasons and ample rainfall. Covering an area of approximately 59.7 hectares, the campus is influenced by various factors, including urban main roads, green vegetation, rivers, and buildings. The campus consists of 18 main functional areas, including administrative and teaching areas, sports zones, ecological leisure areas, libraries, student living quarters, teaching laboratories, and dining halls. Based on the terrain characteristics and balanced distribution principles, 133 sampling points were set (Figure 3). Using the current topographical data of the area, simulation models were created for the acoustic, wind, thermal, and light environments (Figure 4). After completing the preliminary preparation of geographic information acquisition and model area simplification, the main operation steps include grid delineation, drawing the buildings and the ground surface, adding vegetation, and setting the ground surface material. The model grid's calculation height was set at 1.5 m. The wind and thermal environment simulations were performed on 15 July 2021, and 21 December 2021, respectively, starting at 9:00 a.m. and lasting 12 h. As an example, the physical environment values at the pedestrian level of 1.5 m were studied at 2:00 p.m., with specific parameters listed in Table A1 [10,51]. The selection and setting of the simulation parameters summarize the existing relevant research results and the experimental experience of the team, while the generic evaluation formulas defined in this paper are based on the cited published papers. In this study, the light environment simulation is included in the evaluation system, so the parameter set is increased by about 20%. In addition, the winter dimension is added to the evaluation of the wind and thermal environments, making the assessment of the physical environment more scientific and comprehensive.

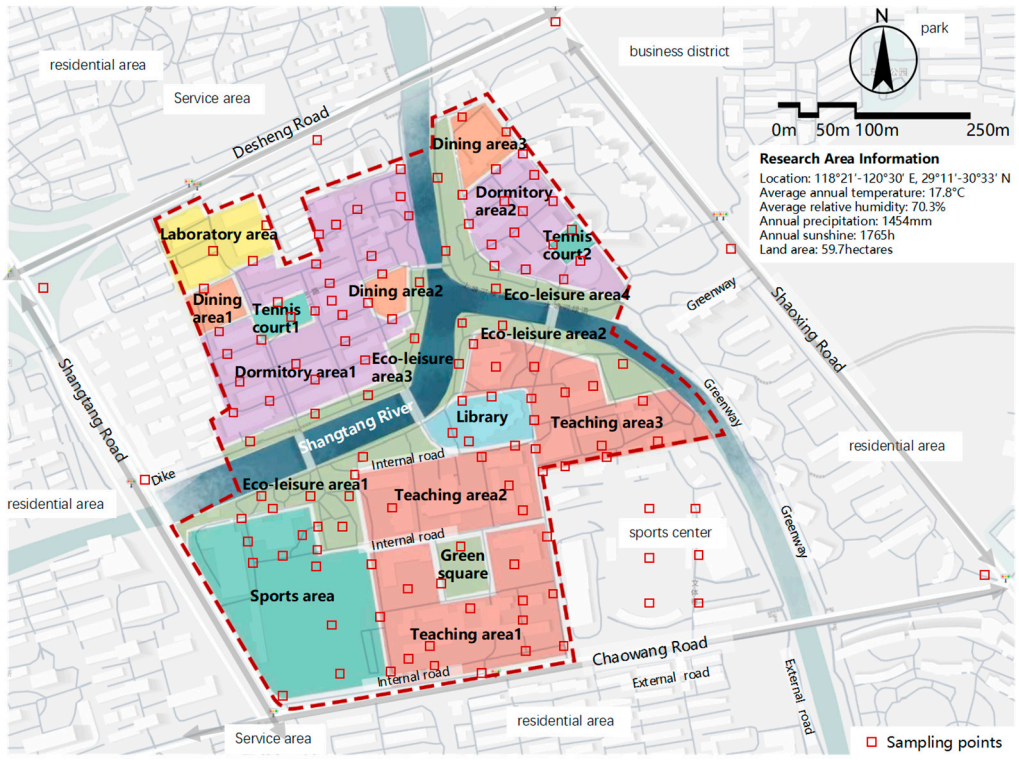


Figure 3. Campus Functional Zoning and Sampling Site Distribution.

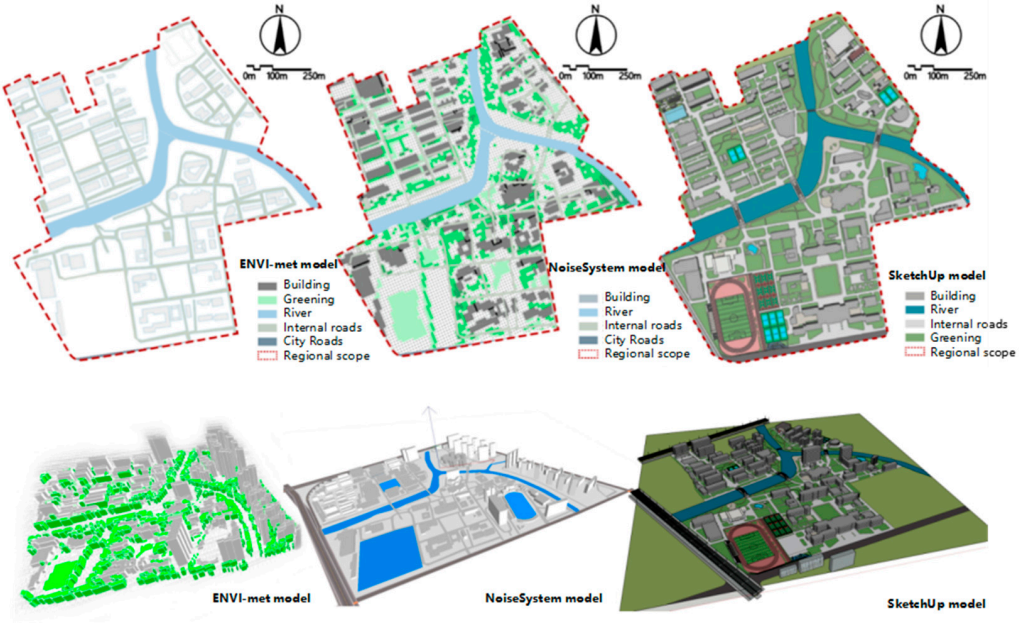


Figure 4. Plan view of the study site and simulated 3D model.

For acoustic environment simulation, the NoiseSystem three-dimensional noise impact assessment system was utilized. This system constructs models based on the "Technical Guidelines for Environmental Impact Assessment—Acoustic Environment" (HJ2.4-2009) [52]. It considers the combined effects of all sound sources, attenuating objects, and meteorological elements within the prediction area. The acoustic environment was evaluated by examining the output data of equivalent A-weighted sound level (LA) and octave band sound pressure level (LP). The specific model calculation method is introduced in the study of Wu et al. [53], and this study will not go into further details.

For wind and thermal environment simulations, the ENVI-met 4.0 system was utilized, which incorporates various models such as urban meteorology and thermodynamics. This system allows for the simulation and analysis of microscale wind and thermal environments, as well as human comfort levels [54]. By calculating and outputting meteorological data, such as air temperature, humidity, wind speed, and mean radiant temperature, combined with the BioMet module to compute PMV, a comprehensive evaluation of the wind-thermal environment was conducted. Likewise, the specific model calculation method was introduced in the study of Wu et al. [10].

Light environment analysis was conducted using the Tianzheng Architecture software 8.0, with the winter solstice serving as the evaluation standard based on the "Residential Building Sunshine Standard". The sunlight analysis tool was used to perform time- and location-based sunlight simulation calculations to evaluate the building's sunlight duration, sunlight area, shadow range, and other related factors.

3.3. Landscape Environment Perception Evaluation

3.3.1. Pre-Optimization Area Assessment

For the evaluation scene, nodes with high foot traffic and abundant environmental elements, including buildings, greenery, and facilities, were selected within each functional zone (Figure 5). The Semantic Differential method questionnaire was employed, along with relevant studies on built environments [55,56], to select adjective pairs that are related to spatial characteristics of built environments. These pairs formed 23 evaluation factors distributed across three dimensions: spatial characteristics, spatial environment, and psychological perception (see Table A2). The sampling unit comprised individuals over 18 years of age, covering a wide range of groups such as local students, international students, teachers, logisticians, and off-campus visitors. Of these, 32% were faculty and

staff, 36% were students, and 32% were off-campus visitors or other special people, with 52% of respondents being male. Respondents' visual-spatial perception and preference ratings of landscape elements were obtained by completing a questionnaire. A total of 186 questionnaires were collected, resulting in a survey efficiency rate of 96.8%. Additionally, 10 individuals from each of the 18 zones were randomly chosen to participate in the survey. Based on their perceptions of the landscape environment in the area, taking into account the characteristics of the campus landscape and the actual situation of the evaluation zone, the landscape environment quality was scored on a scale from 0 to 8 in order to achieve quantifiability and feasibility.

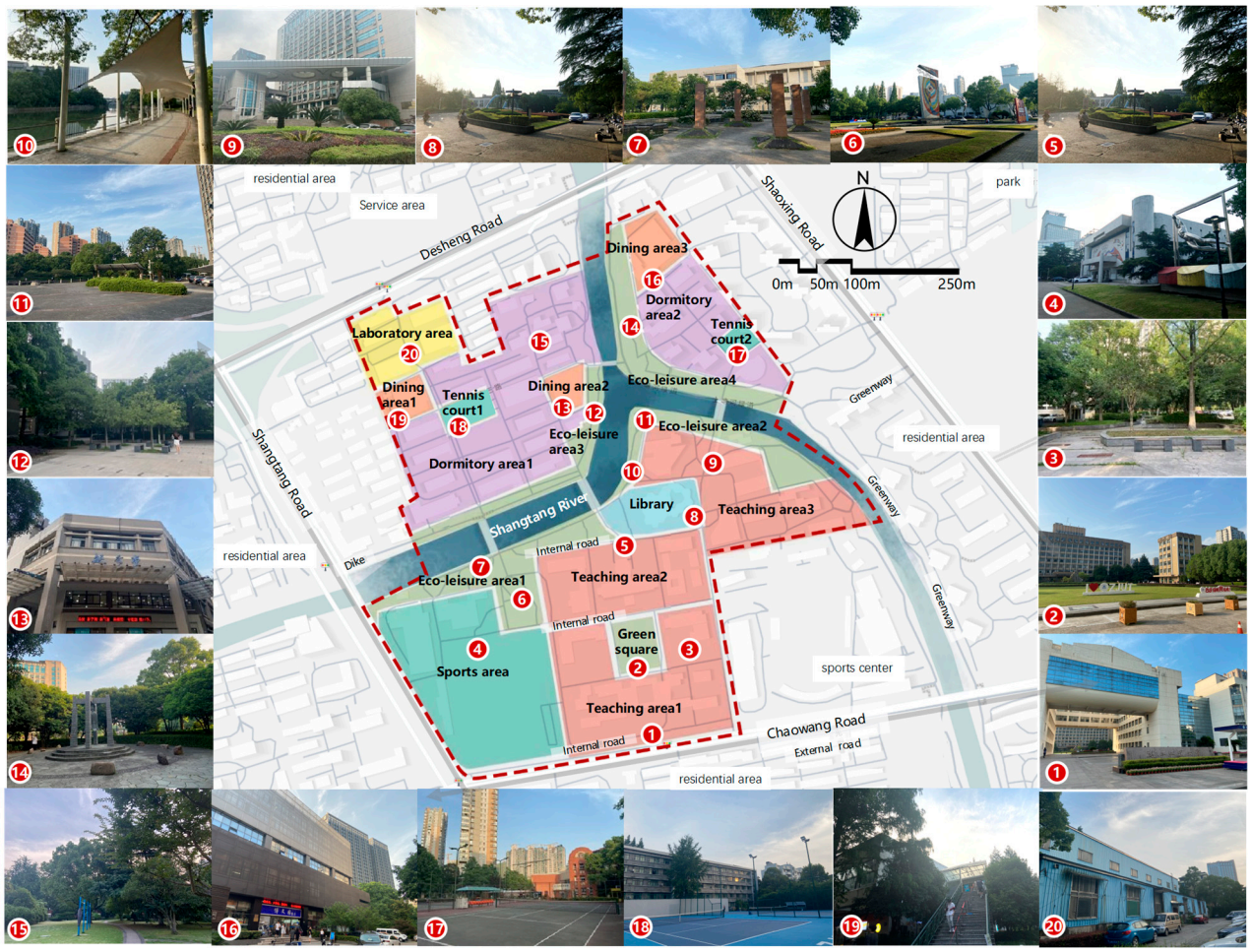


Figure 5. Distribution of points in landscape environment perception scene.

3.3.2. Post-Optimization Virtual Reality Perception Evaluation

Due to the limitations of modifying real-world scenarios, VR technology was employed on the MARS platform to create optimized virtual scenes in priority intervention areas. After the informed consent statement, fifty participants from the initial real-world scenario survey were selected for subjective perception evaluation, utilizing VR and other related equipment to assess the optimized virtual scenes. The experimental test lasted 30–45 min, and in addition to being asked to make score evaluations and preference comparisons of different virtual scenarios, the researchers recorded the behavioral data (movement paths, reaction times, etc.) and physiological data (heart rate, etc.) of the experimenters throughout the entire process in the virtual environment, in order to validate the perception performance.

3.4. Multidimensional Physical Environment Evaluation Standards and Integrated Assessment

A relationship model between the spatial morphology of the built environment and the physical environments (acoustic, wind, thermal, and light) was established to simulate physical environment data at sampling points. This includes wind speed, temperature, equivalent A-weighted sound level, and sunshine duration. The evaluation standards for each category of the physical environment were determined based on national standards or existing research. The simulated values for sound, wind, thermal, light, and landscape environments were normalized and dimensionless on a scale of 0 to 8 (see Table A3).

The quantification of the acoustic environment is based on the "Environmental Quality Standard for Noise" (GB3096-2008) [57], which categorizes the annoyance levels of sound pressure into five levels and assigns scores to the simulation results accordingly.

For the wind environment, the quantification standard primarily considers wind speed at pedestrian height [58,59]. Using the Beaufort scale definition and pedestrian wind comfort criteria [60], wind speeds below 5 m/s are considered comfortable, while wind speeds over 10 m/s are deemed uncomfortable. The impact of wind speed on humans is categorized into six levels for scoring.

For the thermal environment, this study used the PMV index, which considers climate factors like air temperature and relative humidity based on the human energy balance mechanism [61]. The PMV is preferred due to its detailed consideration of human parameters and clothing thermal resistance [29]. The comfort levels for thermal environment simulations in winter and summer are scored within the PMV range of −1.5 to 1.5, based on the ASHRAE 9-point scale for −1, 0, and 1.

The evaluation of the light environment focuses on building sunlight and refers to the "Urban Residential Area Planning and Design Standards GB50180-2018" (2018 edition) [62]. The standard requires a minimum of 1 h of sunlight on the winter solstice, and the effective sunshine duration is used as the basis for scoring the simulation results.

The integrated assessment system comprised five dimensions: wind, thermal, acoustic, light, and landscape environments. Each dimension was evaluated and scored based on predefined standards. The scores were then given equal weights of 20% each and combined using the following formula:

$$\mathrm{OSA} = \sum(\mathrm{P_i} * \mathrm{W_i}) \quad (1)$$

In Equation (1), OSA is the overall score for the area, $\mathrm{P_i}$ is the score for each category, and $\mathrm{W_i}$ is the weight of each category.

4. Results

4.1. Model Performance Evaluation

We compared the simulated data with the observed in situ data and evaluated the differences between the simulated and measured values of the average radiant temperature, wind speed, and equivalent A sound level at each sampling point across the campus to validate the performance of the model. The results are shown in Figure 6, and the slopes of the linear regressions are all close to 0.9, indicating a strong linear relationship between the simulated and observed values. In addition, the R^2 values of the fitted equations are all over 0.96, which further demonstrates that the model has a high degree of fit between the observed and simulated values, and can be used to simulate physical environments related to sustainability.

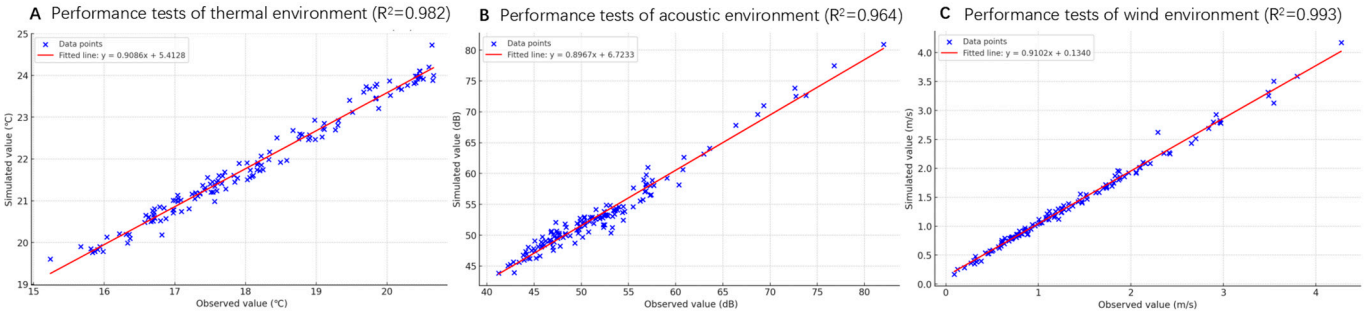


Figure 6. Curves of simulated value and observed value.

4.2. Output Results Analysis

4.2.1. Acoustic Environment Evaluation Results

Based on the simulation and evaluation results for the acoustic environment (Figure 7, Table 1), the overall acoustic conditions of the campus are satisfactory, with an average score of 7.58, variance (Var) = 1.64, and standard deviation (SD) = 1.28 (max = 8, min = 5.33). However, there are noticeable variations between different areas: regions near buildings and green spaces exhibit higher acoustic scores, while areas near the campus perimeter and certain sections along the river experience elevated sound pressure levels due to proximity to busy roads and other sources of traffic noise, exceeding 70 dB. Areas within the campus with lower scores include the teaching and experimental zones, dining area 3, and sports zones, primarily influenced by the nature of activities and nearby road traffic. These areas are exposed to noise without sufficient shielding from buildings and green spaces.

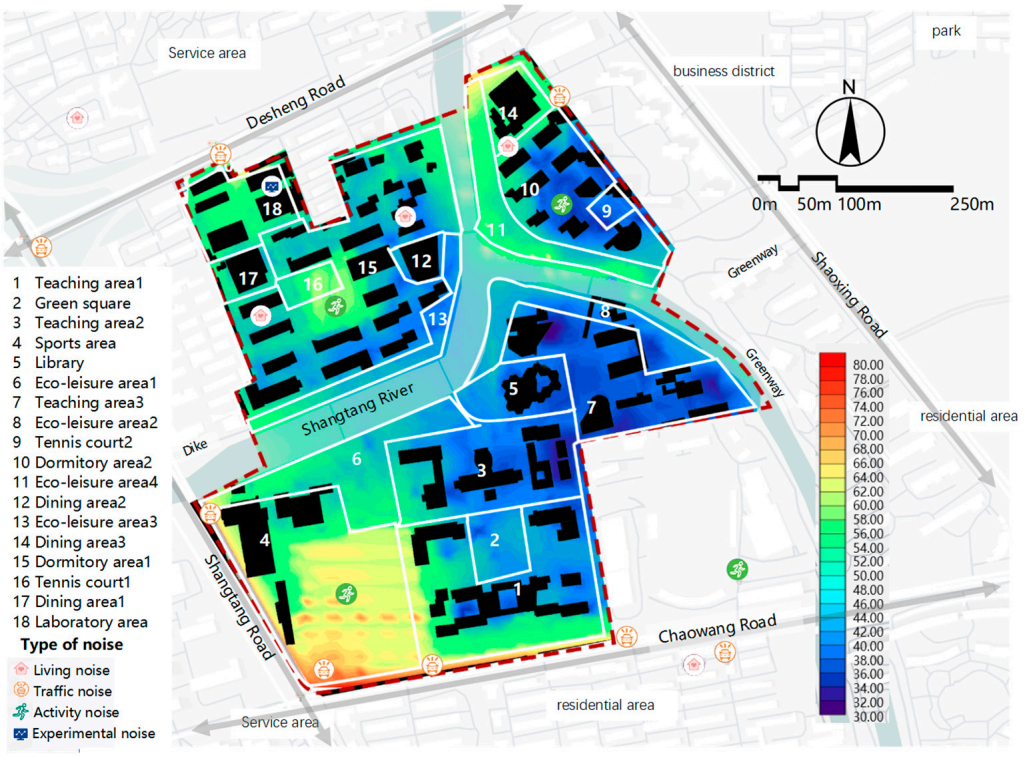


Figure 7. Sound environment simulation results and sound source distribution.

Table 1. Acoustic environment simulation evaluation results.

Zone	Score	Zone	Score	Zone	Score
Sports area	5.33	Teaching area1	7	Dining area1	8
Eco-leisure area1	8	Teaching area2	8	Dining area2	8
Eco-leisure area2	8	Teaching area3	8	Dining area3	6.8
Eco-leisure area3	8	Green square	8	Laboratory area	6.67
Eco-leisure area4	8	Tennis court1	7	Dormitory area1	7.64
Library	8	Tennis court2	8	Dormitory area2	8

4.2.2. Wind Environment Evaluation Results

According to the simulation and evaluation findings on the wind environment (Figure 8, Table 2), the average score for the wind conditions on campus is 6.17, with a Var = 0.64 and SD = 0.80 (max = 7.6, min = 4.53). The overall wind environment falls within the comfortable range, with wind speeds below 5 m/s. Areas characterized by light breeze, gentle breeze, and calm winds are observed around buildings, enclosed structures, and densely built regions. Conversely, higher wind speeds are recorded in more open areas, like sports zones and central areas of the river, creating ventilation corridors. The areas with high wind environment scores are primarily concentrated in the ecological leisure zone and sports zones, while lower scores are found in the administrative teaching zone, library, and student living areas. Although the tennis court is open, the surrounding buildings obstruct air circulation, resulting in a local heat island effect caused by thermal circulation.

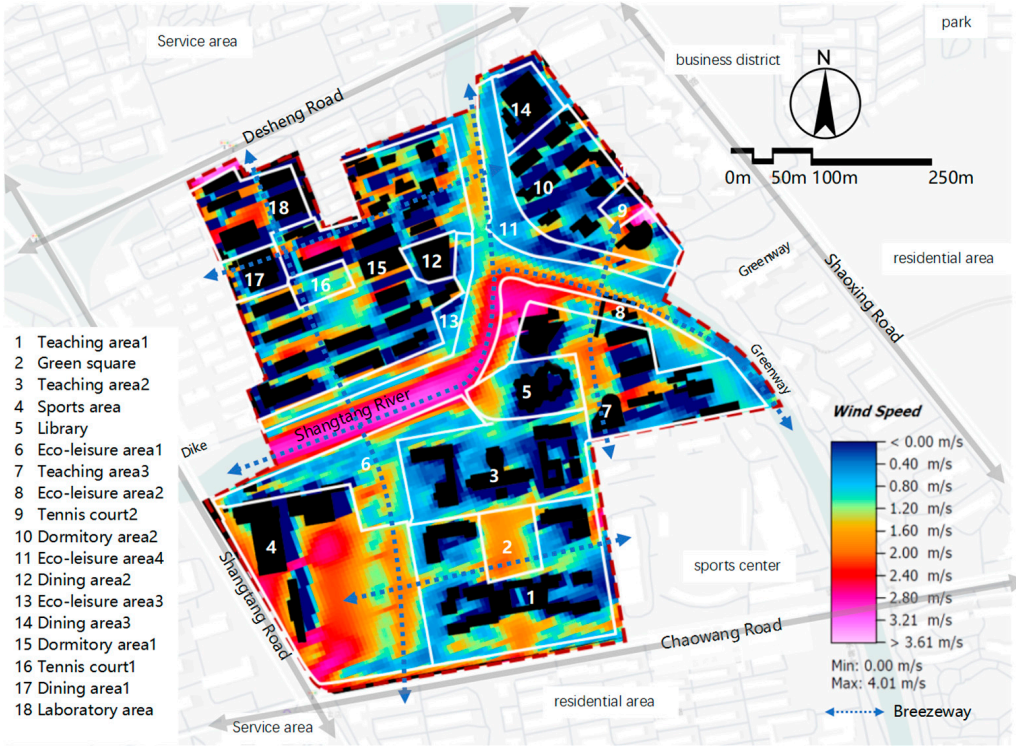


Figure 8. Wind environment simulation results and breezeway schematic.

Table 2. Wind environment simulation evaluation results.

Zone	Score	Zone	Score	Zone	Score
Sports area	5.67	Teaching area1	6.14	Dining area1	5.33
Eco-leisure area1	7.6	Teaching area2	6	Dining area2	5.33
Eco-leisure area2	6.8	Teaching area3	6	Dining area3	6.4
Eco-leisure area3	7.6	Green square	6	Laboratory area	6.53
Eco-leisure area4	7.14	Tennis court1	4.53	Dormitory area1	6.55
Library	6.14	Tennis court2	5.33	Dormitory area2	6

4.2.3. Thermal Environment Evaluation Results

According to the thermal environment simulation and evaluation results (Figure 9, Table 3), the average score for the campus thermal environment is 5.13, with a Var of 0.08 and SD of 0.29 (max = 5.5, min = 4.65), indicating minimal differences. The summer PMV values show relatively uniform and comfortable thermal environments around buildings and highly greened areas, whereas the winter PMV values vary significantly, with less comfortable areas primarily in the sports zones and central areas of the river.

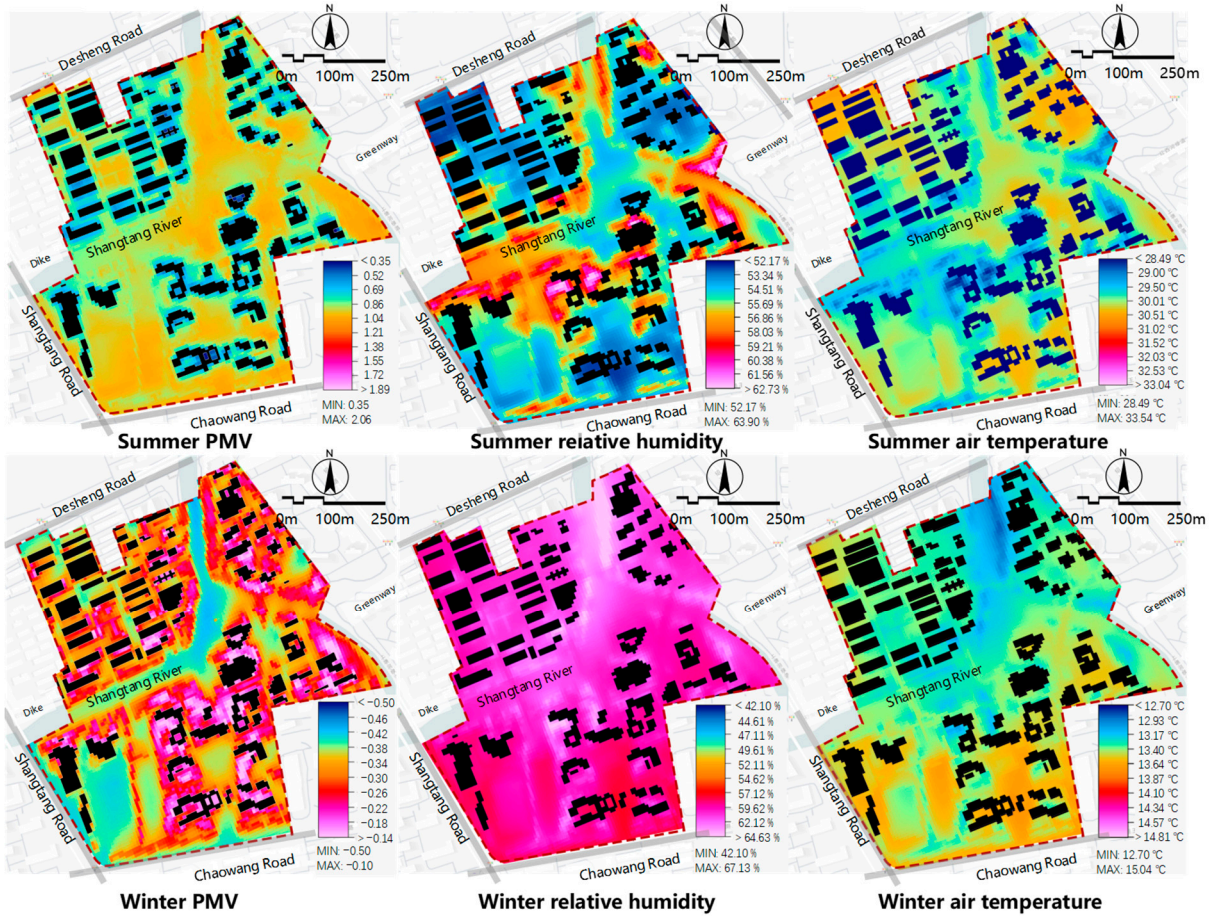


Figure 9. Thermal environment simulation results.

The optimal ambient temperature range for humans is 22–28 °C [63], and the preferable relative humidity range is 30–70% [64]. The results indicate that summer temperatures within the study area generally exceed 28 °C, with localized high-temperature areas in the sports zone, administrative teaching zone, student living area, and teaching and experimental zones. The ecological leisure zone, which is close to the river and has extensive greenery, has higher humidity and lower temperatures, providing a cooler sensation. In winter, temperatures generally fall below 22 °C, and relative humidity is more uniform.

The river areas have higher humidity and lower temperatures, creating a sensation of damp coldness.

Table 3. Thermal environment simulation evaluation results.

Zone	Score	Zone	Score	Zone	Score
Sports area	4.92	Teaching area1	4.95	Dining area1	5.5
Eco-leisure area1	5.08	Teaching area2	5.25	Dining area2	5.25
Eco-leisure area2	4.65	Teaching area3	5.42	Dining area3	5
Eco-leisure area3	5.1	Green square	5	Laboratory area	5
Eco-leisure area4	5.05	Tennis court1	5.08	Dormitory area1	5.31
Library	5.4	Tennis court2	5.33	Dormitory area2	5.1

4.2.4. Light Environment Evaluation Results

Based on the light environment simulation and evaluation results (Figure 10, Table 4), the average score for the campus light environment is 6.46, with a Var of 0.56 and (SD of 0.75 (max = 7.71, min = 5.33). Areas with ample sunlight are mainly concentrated in the sports zone, ecological leisure zone, and Tennis Court 1. These areas have fewer buildings, and the buildings are not tall, especially in the sports zone and Tennis Court 1, which are sufficiently distant from surrounding buildings, allowing ample sunlight exposure and resulting in higher scores. Conversely, densely built areas such as the student living area and administrative teaching zone, with higher building heights and shorter distances between buildings, have lower scores due to insufficient sunlight in the spaces between buildings.



Figure 10. Light environment simulation results.

Table 4. Light environment simulation evaluation results.

Zone	Score	Zone	Score	Zone	Score
Sports area	7.14	Teaching area1	6.14	Dining area1	6
Eco-leisure area1	7.71	Teaching area2	6	Dining area2	5.53
Eco-leisure area2	6.8	Teaching area3	6	Dining area3	6
Eco-leisure area3	7.6	Green square	6	Laboratory area	6.67
Eco-leisure area4	7.14	Tennis court1	7.33	Dormitory area1	6.36
Library	7.14	Tennis court2	5.33	Dormitory area2	5.4

4.2.5. Landscape Environment Perception Evaluation Results

Based on the results of the landscape environment perception evaluation (Table 5), the campus landscape environment has an average score of 4.26, with a Var = 0.29 and SD = 0.54 (max = 5.05, min = 2.90). The highest-scoring areas are mainly in the ecological leisure zone near the river and in large green areas such as plazas, where there is diverse plant arrangement and a unique landscape. On the other hand, the lowest-scoring areas are primarily in the teaching and experimental zone, student living area, and dining area. These areas have a high building density, which creates a sense of enclosure and oppression. The plant landscaping in these areas is also disorganized. Overall, the perception of the landscape is higher in the leisure zones and plazas compared to other areas.

Table 5. Landscape environment simulation evaluation results.

Zone	Score	Zone	Score	Zone	Score
Sports area	4.65	Teaching area1	4.32	Dining area1	3.87
Eco-leisure area1	5.05	Teaching area2	4.16	Dining area2	3.86
Eco-leisure area2	4.65	Teaching area3	4.19	Dining area3	3.61
Eco-leisure area3	4.68	Green square	4.89	Laboratory area	2.90
Eco-leisure area4	4.70	Tennis court1	4.65	Dormitory area1	4.50
Library	4.16	Tennis court2	4.16	Dormitory area2	3.66

4.3. Integrated Evaluation and Identification of Priority Intervention Areas

Our comprehensive evaluation of the multidimensional physical environment indicates an overall score of 5.92. The thermal environment and landscape environment perform poorly, with average scores of 5.13 and 4.26, respectively. Conversely, the acoustic environment and light environment perform well, with average scores of 7.58 and 6.46, respectively. The wind environment has an average score of 6.15, similar to the overall average score. Therefore, it is necessary to optimize the thermal, landscape and wind environments as a whole.

In terms of major functional zones, there are certain differences between the areas. The sports zone has the lowest overall average score (5.54), followed by the teaching and experimental zone (5.56), and dining area 3 (5.56). The ecological leisure zone and the library, located on both sides of the river, have higher overall average scores. Conversely, areas near the west and north sides of the sports zone and the surrounding teaching and experimental zones have lower scores (Figure 11).

Based on the evaluation results, designers can prioritize intervention areas by targeting the lowest-scoring zones and their clusters. For example, in terms of landscape environment performance, optimization strategies should focus on the teaching and experimental zone and dining area 3. Specific landscape optimization strategies can be proposed based on the scores of different landscape evaluation factors. Furthermore, the poorly performing zones can be considered comprehensively to identify the environmental categories that need improvement and to develop corresponding optimization strategies. For instance, in the sports zone, efforts should be made not only to optimize the landscape environment but also to enhance the quality of the thermal and acoustic environments. Similarly, the teaching

and experimental zone, which has poor overall performance, requires a multidimensional approach to optimization strategies that address priority intervention areas.

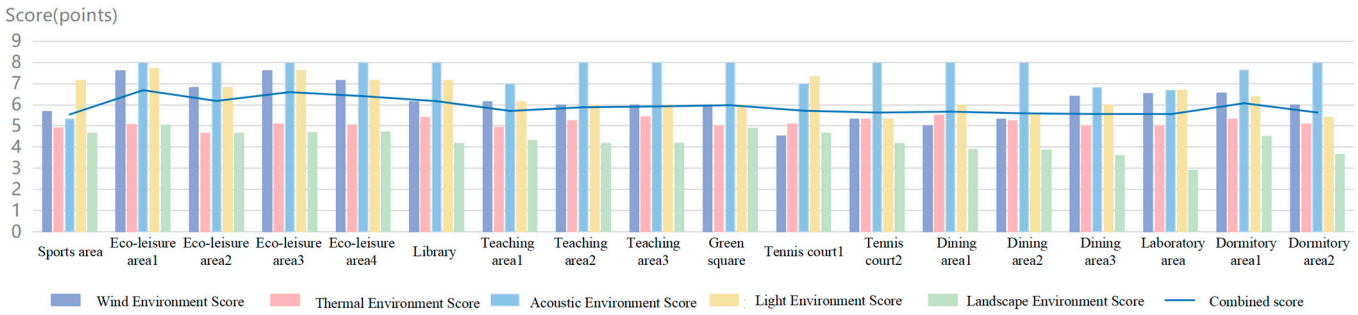


Figure 11. Statistics on quantitative environmental scores by dimension.

5. Simulation and Discussion of Optimization Plans

5.1. Overall Environment Optimization and Evaluation Results

Based on a comprehensive evaluation of the built environment and the identification of priority intervention areas, an overall optimization design for the campus built environment was conducted. Due to the challenging nature of significantly altering the existing building layout and forms, this study focuses on optimizing through greening and constructing noise barriers (Figure 12).

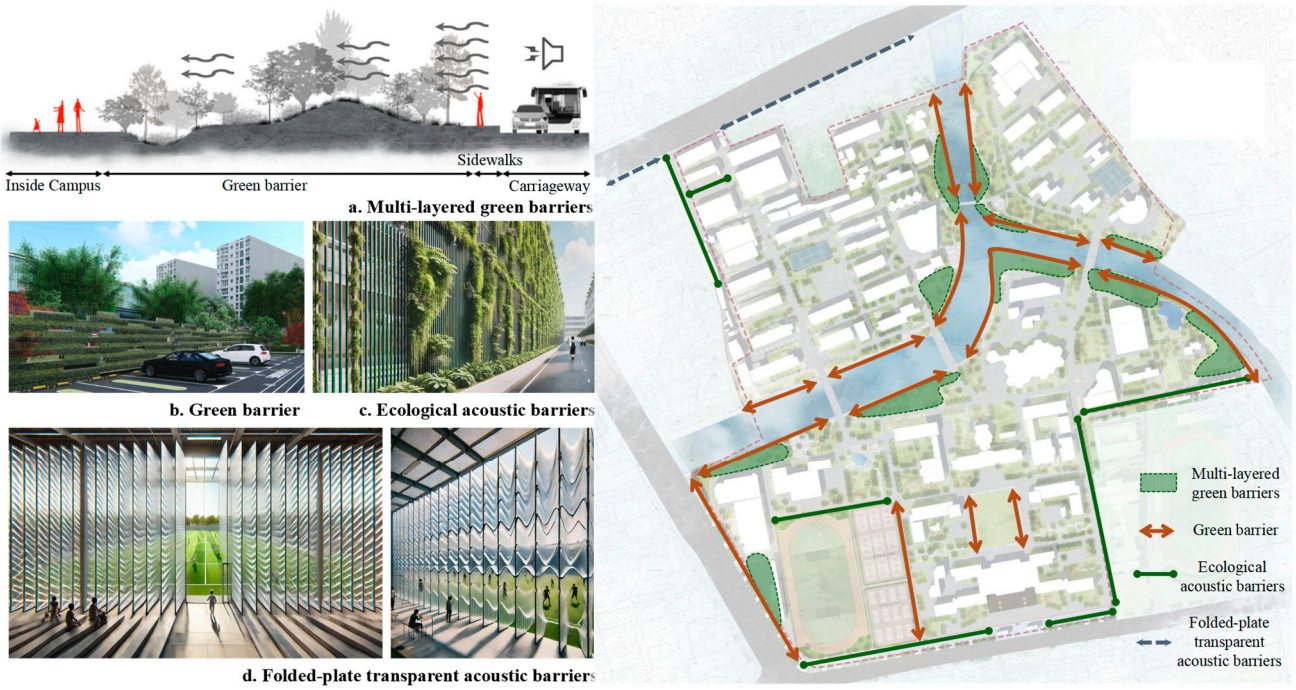


Figure 12. Green barrier and sound barrier setup.

Greening serves the purpose of reducing noise around the campus, while also blocking dust and exhaust from nearby traffic and construction environments [65]. Furthermore, greenery affects the wind and thermal environment, providing cooling, humidifying, and shading effects in the summer, thereby enhancing overall comfort. Tall trees are found to improve the thermal environment more effectively than low shrubs and lawns. The specific optimization directions are as follows:

(1) Install multi-layer green barriers to isolate noise: Based on the current greening status and the evaluation of the physical environment in each area, multi-level greening

barriers are primarily set at the boundaries between campus spaces and urban roads. These barriers are arranged in multiple layers (high, medium, and low) with regard to height, width, and location to isolate traffic noise from the surroundings and activity noise from various functional zones within the campus (Figure 12a).

(2) Combined measures to mitigate temperature extremes: According to the simulation results of summer air temperatures, greening belts mainly consisting of arbor trees are added to the sports zone and administrative teaching zone to mitigate local high temperatures. Considering the low temperatures in winter and the high wind speeds in the central river area, it is deemed necessary to implement greening barriers or windbreak measures in the form of landscape walls on both sides of the river [66].

(3) Increase green coverage to reduce gaseous intrusion: Widen the original green belts on both sides of the river, optimize the structure of the green belts, and appropriately lay out windbreaks to achieve the purpose of blocking the wind and reducing the infiltration of cold air in winter [67]. In addition, this approach can help block dust and exhaust from the surrounding traffic and construction environment.

(4) Optimize landscape facilities to enhance ecological benefits: The existing campus green spaces are further optimized in terms of greening forms and functional landscape facilities, such as scenic walls, the selection of local or adaptable plants, and rational planning of planting layouts, to create diversified ecological barriers for all seasons.

Noise barriers, which are structures that obstruct the line of sight between the noise source and the receiving point, create a sound shadow area where sound waves are significantly attenuated, thus reducing environmental noise [68]. The specific optimization directions are as follows:

(1) Acoustic optimization through the use of natural terrain: In conjunction with the previously mentioned strategy of greening as a noise barrier—especially in ecological recreation areas with terrain height differences and natural obstacles—areas with high green coverage can fully utilize the noise reduction effect of large areas of vegetation. This approach not only helps to realize the natural transition of space but also further develops the social benefits of the activity area (Figure 12b).

(2) Satisfy functionality and aesthetics with ecological sound barriers: To achieve effective noise isolation through greening, it may not always be feasible to allocate a significant planting area, especially in limited campus spaces. In such cases, eco-friendly noise barriers that combine vegetation and physical barriers can be employed within the campus. For example, a sound barrier could be installed on the south side of the sports area, with a height of 3 m. These barriers are designed to blend with the surrounding landscape elements by utilizing materials, colors, and shapes that seamlessly integrate with the environment. This approach enhances the visibility and aesthetic appeal of the campus landscape (Figure 12c).

(3) Increase visual transparency and environmental harmonization with folded panel sound barriers: In areas near major noise sources, such as elevated roads on the north and west sides, as well as sports centers on the east side, folded plate noise barriers are recommended, as they are more effective than upright barriers. Transparent or partially transparent materials are utilized to create a sense of spatial openness and reduce the feeling of enclosure for pedestrians (Figure 12d).

Based on a comparison of the overall environment before and after optimization (Figure 13), it is evident that the quality of the acoustic environment has significantly improved. This improvement is most notable in the sports zone, Tennis Court 1, and the teaching and experimental zone, where the scores have witnessed a notable increase. The scores in the administrative teaching zone 1 and student living area 1 have experienced a marginal increase with minimal changes, while the acoustic environment score in dining area 3 remained unchanged. The analysis found that all such zones are crowded and, therefore, need further enhancement of their internal acoustic environment, such as the

use of sound-absorbing materials, the introduction of white noise systems, and other measures [69].

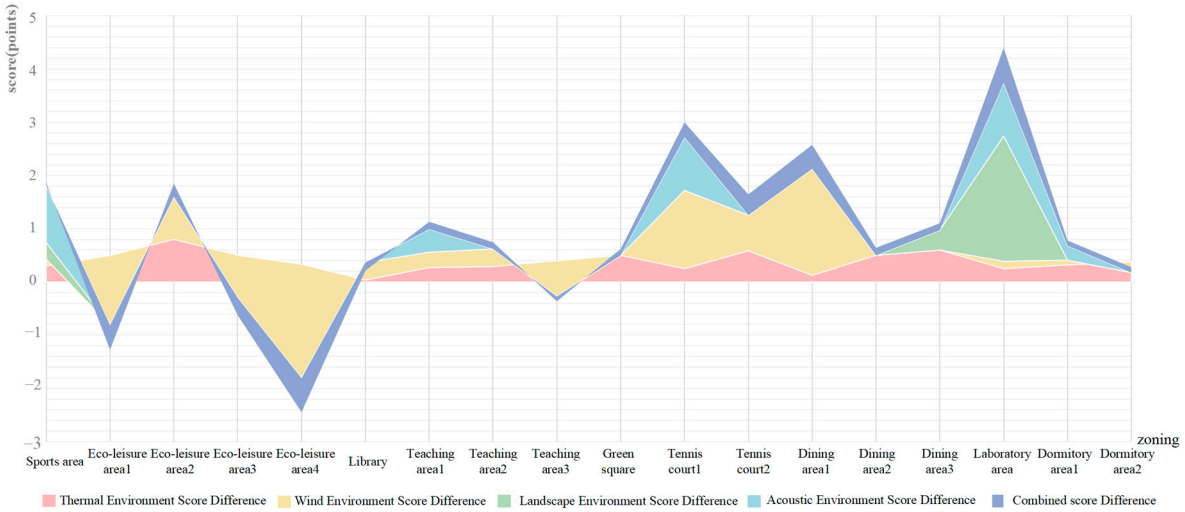


Figure 13. Comparison statistics before and after optimization of the overall environment.

The comparison of thermal environments pre- and post-optimization reveals a slight improvement in all areas, except for the library zone, where no significant changes were observed. Analyzing the possible causes, the large area of glass and the hard square paving in the library area are the main factors. Therefore, improving this area by replacing the materials and installing shading devices will be the most direct and efficient solution [27].

The wind environment scores, on the other hand, fluctuated significantly after optimization. There was a noticeable decline in wind environment quality in certain areas, such as ecological leisure zones 1, 3, and 4, while the wind environment quality in Tennis Court 1 and dining area 1 notably improved. The analysis found that the addition of continuous barriers impeded the flow of natural wind and created vortexes or negative pressure zones, which in turn reduced the quality of the wind environment. Therefore, it is necessary to further optimize the height, shape, and material design of the barriers and rationally lay out the ventilation corridors [37].

5.2. Key Area Optimization and Evaluation Results

Based on the results of the subjective perception evaluation of the campus landscape, it is evident that the sports zone, dining area 3, and teaching and experimental zone received the lowest overall scores. Consequently, the landscape improvements should primarily focus on these three areas. Upon reviewing the SD curve diagrams of these areas (refer to Figure 14), it becomes apparent that the landscape perception in the sports zone is relatively well-balanced. However, the facilities in dining area 3 and laboratory area are deemed inadequate, and the laboratory area is relatively poor in terms of spatial sense, overall sense, and insufficient fun and learning atmosphere. The specific optimization directions are outlined as follows:

Sports area: There are opportunities to enhance the learning atmosphere and tree species diversity. Given that this area primarily serves sports functions, landscape walls can be utilized to enhance the atmosphere. These walls will combine noise barriers with greenery to enrich the landscape effect. Additionally, they will prevent excessive noise from sports activities from impacting the surrounding area (Figure 15a).

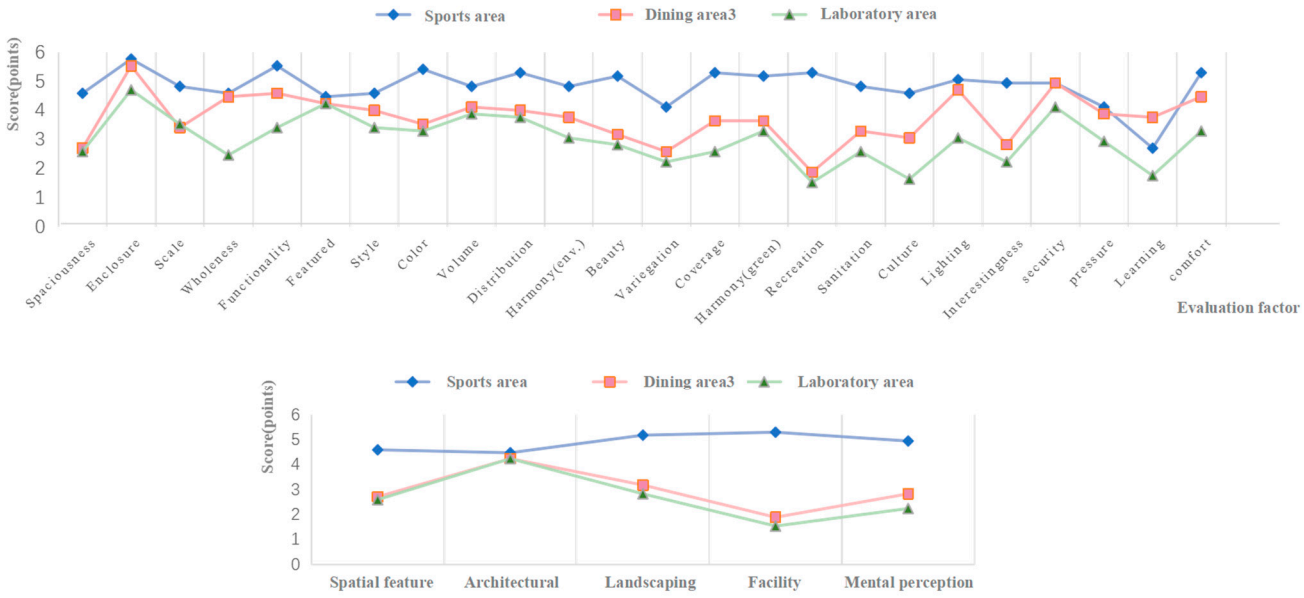


Figure 14. Statistics of landscape perception results for the three regions.



Figure 15. Comparison of virtual and real effects of landscape node optimization.

Dining area 3: In addition to upgrading the corresponding facilities, the current greening is relatively disorganized and lacks a variety of flowers. Furthermore, there is a lack of seasonal continuity. To optimize the greening in this area, trees, shrubs, and grass

can be combined around the buildings. Additionally, seasonal flowering shrubs should be added to ensure year-round visual interest (Figure 15b).

Laboratory area: The site consists of old buildings and large internal parking lots, which contribute to significant air pollution and noise. The noise originates from the experimental buildings, adversely affecting the campus environment. To address these issues, small rest gardens can be designed within the parking area, and the space can be separated by sound barriers. At the same time, the corner space is utilized to increase the space for teachers and students to rest and socialize. Consequently, the landscape visual effect will improve, the function of space will be enriched, and traffic and experimental noise will also be significantly reduced (Figure 15c).

After optimization, the evaluation results of the priority intervention areas (Figure 16) demonstrate a general improvement in the environmental quality of the experimental areas. Notably, the laboratory area experienced the most significant enhancement in landscape environment quality. The landscape quality in the sports zone and dining area 3 also improved, albeit to a lesser extent. These results indicate the effectiveness of the overall landscape improvement strategies.

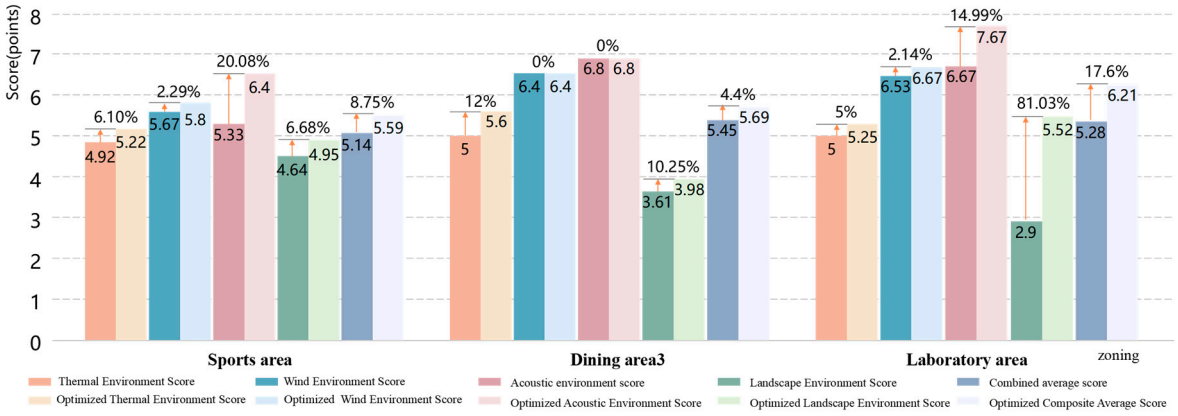


Figure 16. Comparison of experimental area environment before and after optimization.

The sports zone witnessed significant improvements in the acoustic and landscape environments. However, there is potential for further enhancements in the wind and thermal environments. On this basis, unused spaces can be transformed into functional sports grounds, where local microclimates are created through optimized design, thus regulating the wind–heat effect (Figure 17a).



Figure 17. Design Optimization Before and After Comparison.

The acoustic and wind environment in dining area 3 remained unchanged. As a result, restrictions were put in place at area intersections to prohibit motorized vehicles. At the same time, the outward swing space was extended with a resting platform, and additional ventilation and noise barriers were installed to create a friendly pedestrian-only plaza (Figure 17b).

The laboratory area can further enhance the score of the physical environment by setting up a cultural and recreational corner at the entrance of the site while optimizing the

traffic flow. This can be achieved by creating a flow form adapted to the site through the organization of landscape vignettes, structures, and greenery and weakening the closure effect caused by the enclosure of buildings (Figure 17c).

These findings validate the effectiveness of the proposed design strategies. Through multiple simulations and adjustments, the optimal solution can be identified. The utilization of targeted optimization design and multiple simulation feedback, taking into consideration the attributes of different areas, will aid in achieving optimal decisions.

6. Conclusions

This study has developed an integrated optimization method for the built environment based on multidimensional physical environment simulations and virtual reality perception. The design process followed a logical sequence of "current situation analysis—parameter simulation—design optimization—result evaluation—decision-making", emphasizing comprehensive feedback between humans and the environment. The wind, thermal, acoustic, light, and landscape environments of the Zhaohui campus of Zhejiang University of Technology were evaluated and analyzed using research methods such as physical environment simulation, on-site measurements, and questionnaire surveys. ENVI-met, NoiseSystem, and other simulation software were used for the simulation and prediction of the physical environment in the study area. Based on the evaluation results, strategies for overall environmental optimization were proposed, with detailed designs for the three areas identified as needing the most improvement. The physical environment simulation models were optimized and refined according to the design strategies, and simulations were conducted again. In addition to obtaining the optimized simulation data, VR technology was used to conduct questionnaire surveys on the visual effects of virtual scenes. By combining subjective and objective data, a comparative analysis of the pre- and post-scheme was performed to verify the effectiveness of the design strategies. This process achieved a step-by-step optimization from a multidimensional overall environment and local area morphology to human-scale spaces, representing a beneficial attempt to diversify theoretical research perspectives on built environment optimization. It provides a basis and technical support for the optimization and adjustment of the built environment. Through empirical exploration of the entire process, this study examined the application of this optimization method in built environment design practice, verifying that the integrated subjective and objective evaluation model can enhance the comfort and sustainability of the built environment.

However, this study has certain limitations. The research involved a process-oriented exploration that combined objective multidimensional physical environments, subjective semantic analysis, virtual perception interaction feedback, and step-by-step built environment optimization. However, these methods are prone to limitations related to data forms and software errors. Specifically, the 3D space construction details in the physical environment simulation software are insufficient, resulting in a lack of vegetation variety compared to the real built environment. Additionally, the representation of building forms and road traffic primarily relies on geometric analysis, limiting the ability to optimize at a human-scale spatial morphology level. Furthermore, the study lacks comprehensive research on the intrinsic relationship between spatial morphological elements and the physical environment, which is crucial for clarifying the planning direction of each dimension of the physical environment.

In future research, it is recommended to conduct a more in-depth and comprehensive quantitative evaluation of spatial morphology and the physical environment. This evaluation should aim to automatically calculate the optimal design scheme based on the results of the built environment evaluation and apply it to planning decision-making implementation. Such an investigation would require subsequent research with a more thorough approach.

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Appendix A

Table A1. Model simulation parameter settings.

ENVI-Met Simulation Parameter Setting		
Category [10]	**15 July 2021**	**21 December 2021**
Wind speed at 10 m height (m/s)	3	6
Wind direction (0 = N; 90 = E; 180 = S; 270 = W)	60	190
2 m relative humidity (%)	50	40
Atmospheric initial temperature (K)	309.15	295
Roughness length of measurement site	0.01	0.01
Soil layer		
Soil moisture in different layers	45–60%	35–50%
Initial temperature of different layers	311 K–317 K	293 K–299 K
BioMet (Bio-Meteorological Auxiliary Sensor System)		
Walking speed (km/h)	3.6	3.6
Clothing insulation factor (clo)	0.5	2
Noise System simulation parameter setting		
Barometric pressure (Pa)	100,400	1,001,800
Air temperature (°C)	34	16
Relative humidity (%)	50	40
Ground effect	Guided algorithm	Guided algorithm

Note: Organized on the basis of existing relevant research results and the team's experimental experience (2022).

Table A2. Landscape evaluation scale of SD method.

Evaluation Dimension	Evaluation Factor	Adjectives	Scoring Range (0–8 Points)					Adjectives
			Poor → Moderate → Good					
			0	2	4	6	8	
Spatial feature	Spaciousness	Confined						Wide-open views
	Enclosure	Weak-enclosure						Strong-enclosure
	Scale	Imbalanced						Humanized
	Wholeness	Cluttered						Integral
	Functionality	Irrational						Rational

Table A2. *Cont.*

Evaluation Dimension		Evaluation Factor	Adjectives	Scoring Range (0–8 Points)					Adjectives
				Poor → Moderate → Good					
				0	2	4	6	8	
Spatial env.	Arch.	Featured	Distinctive						Featureless
		Style	Singular						Abundant
		Color	Singular						Abundant
		Volume	Unreasonable						Pleasant
		Distribution	Unreasonable						Reasonable
		Harmony	Incongruous						Harmonized
	Green	Beauty	Unattractive						beautiful
		Variegation	Monolithic						Diverse
		Coverage	Less green						More green
		Harmony	Incongruous						Harmonized
	Facility	Recreation	Imperfect						Perfect
		Sanitation	Imperfect						Perfect
		Culture	Imperfect						Perfect
		Lighting	Imperfect						Perfect
Mental perception		Interestingness	Monotonous						Interesting
		Security	Dangerous						Safe
		Pressure	Nervous						Relaxing
		Learning	Atmosphere-less						Atmosphere-more
		Comfort	Uncomfortable						Comfortable

Table A3. Multidimensional physical environment evaluation assignment.

Noise Standards	A Sound Level (dB)	Classification	Score (Points)
Category 1	<55	Quieter	8
Category 2	55~60	Quiet	6
Category 3	60~65	Average	4
Category 4 (4a)	65~70	Noisy	2
Category 4 (4b)	>70	Noisier	0
Beaufort scale [60]	**Wind speed (m/s)**	**Degree of impact**	**Score (points)**
0	0~0.2	senseless	0
1	0.3~1.5	Unnoticeable	6
2	1.6~3.3	Feeling of wind	8
3	3.4~5.4	Hair blowing away	4
4	5.5~7.9	Dust flying	2
5	>8.0	Trees swaying, hard to walk	0
ASHRAE standard [29]	**PMV value**	**Thermal Feelings Voting**	**Score (points)**
−1	−1.5~−1	cool	0~2
	−1~−0.5		2~4
0	−0.5~−0.1	Comfortable	4~6
	−0.1~0.1		6~8
	0.1~0.5		4~6
1	0.5~1	Warm	2~4
	1~1.5		0~2
Hours of sunshine (h)			**Score (points)**
<1			0
1–2			2
2–4			4
4–6			6
>6			8

Note: Organized on the basis of existing relevant research results and the team's experimental experience (2022), while adapting the classification according to the actual simulated values.

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