

Article

A Case Study on Energy-Saving Renovation Strategies for a Wind and Rain Sports Hall

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Abstract

Energy-efficient renovation of existing buildings is one of the important approaches to achieving sustainable development. This study takes a naturally ventilated sports hall (without heating or air conditioning systems) at a university in Weifang, Shandong Province, as the research object, where indoor thermal comfort levels remain low throughout most of the year. Adopting passive optimization as the core approach, the study aims to improve natural daylighting and winter thermal environment by adjusting window-to-wall ratio (WWR), window-to-floor ratio (WFR), skylight height, and glass thermal-optical parameters. The research methodology consists of two main stages: field measurement and multi-scenario simulation. On-site measurements were first conducted to ascertain the building's actual usage patterns, existing daylighting conditions, and temperature distribution characteristics. Subsequently, six scenarios—including the original design, the current condition, and four differentiated optimization schemes (Schemes A, B, C, and D)—were quantitatively evaluated for indoor daylighting and thermal performance using Ecotect Analysis 2011 and eQUEST 3.65. The simulation models were calibrated against field measurement data to ensure result reliability. Key findings are as follows. In terms of daylighting, daylight factor and indoor average illuminance increase significantly with higher WFR, with this growth trend noticeably plateauing around a WFR of 0.7. Illuminance uniformity should be comprehensively assessed using both of its calculation methods; skylights provide more balanced daylighting than side windows, and combined side-window and skylight schemes yield far superior illuminance uniformity compared to single-type window arrangements. Regarding thermal performance, in schemes incorporating skylights, indoor temperature rises with increasing glazing area when WFR is below 0.7; however, when WFR exceeds 0.7, building heat dissipation surpasses solar heat gain, causing indoor temperature to decrease. Considering annual thermal comfort performance, Scheme C achieves the longest cumulative comfort hours and the most balanced year-round thermal performance, making it suitable for renovation projects pursuing stable indoor environments. Scheme A demonstrates significant winter warming effects but suffers from overheating defects during summer and transition seasons, thus requiring enhanced ventilation measures. After implementing increased ventilation (5 air changes per hour), Schemes A and C achieve 36.7% and 37.2% more comfortable hours during the building's 10-month usage period, respectively, compared to the current condition. In conclusion, for large-space buildings such as sports halls, relying solely on increasing WFR and WWR for passive winter warming yields limited effects, and coordinated optimization of glass thermal-optical properties and ventilation strategies should be adopted.

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Keywords: wind and rain sports hall; passive measures; window-to-floor ratio (WFR); window-to-wall ratio (WWR); daylight quality; indoor temperature; comfortable hours

1. Introduction

The core value of sports activities lies in providing modern individuals with a crucial opportunity to temporarily detach from high-intensity work pressures and achieve a balance between body and mind. Sports activities play an irreplaceable role in maintaining and promoting both physical and mental health, a consensus that has been widely validated in the fields of sports medicine and public health [1,2]. However, an individual's willingness to participate in sports activities is not driven solely by health awareness; the physical environmental quality of sports venues plays a critical mediating role in this process. Research has shown that the comfort of the exercise space—particularly the quality of the light and thermal environments—directly affects the achievement of exercise experiences and outcomes [3–6]. As it is one of the types of human behavior with the most intense interaction between individuals and the external environment, the thermal exchange, visual perception, and spatial cognition between the human body and the environment during exercise impose more stringent requirements on the spatial environment.

The current state of sports facilities in China is far from ideal. A large number of sports facilities built many years ago are facing severe environmental performance challenges. Due to their early construction and the limitations of economic, technological conditions, and design standards at the time, these buildings generally suffer from problems such as insufficient daylighting, severe glare, and poor thermal comfort [7,8]. In some venues, light and thermal environment indicators even fail to meet the basic requirements of current national standards, which significantly diminishes the public's enthusiasm for participating in physical exercise and affects user comfort, creating a contradiction with the goals of China's national strategy for nationwide fitness. Of particular concern is the inherent characteristic of sports buildings—their large, high-ceiling spaces and massive volumes—which results in operating loads for HVAC systems, specialized lighting systems, and mechanical ventilation systems that far exceed those of conventional public buildings. This structural feature leads to significantly higher energy consumption per unit area for sports buildings compared to standard office and educational buildings. Existing research indicates that as a typical type of high-energy-consumption public building, sports venues commonly face multiple challenges, including high energy intensity, low waste heat recovery utilization rates, and inefficient operation of energy systems [9–11].

Due to the precise requirements of indoor sports activities and the need for energy efficiency in sports buildings, a substantial body of related research exists. Since this study focuses on the impact of changing the window-to-wall ratio of a wind and rain sports hall on indoor daylighting and indoor temperature variations, we have specifically reviewed existing research on parameters related to building side lighting, primarily including the sill height of side windows, the window-to-wall area ratio and the window-to-floor area ratio.

Regarding the sill height of side windows in uncovered sports halls, China's Code for Design of Primary and Secondary Schools GB 50099-2011 [12] stipulates that when an uncovered sports hall has enclosing walls and the exterior windows are not equipped with anti-glare facilities, the sill height from the indoor floor should preferably not be less than 2.10 m. The wall surface below the sill height should preferably be dark in color. Relevant scholars have also conducted some research. For instance, Rania Elghamry et al. [13] analyzed that under hot semi-arid climate conditions, when the window aspect ratio is 2:1 and the window is positioned in the middle of the wall, the total building energy con-

sumption is minimized; conversely, the scheme with an aspect ratio of 1:3 and the window located in the lower part of the wall exhibits the worst energy performance. Yang Di et al. [14], using Pearson correlation analysis, found a strong correlation between average illuminance and both space height and window-to-floor ratio, with correlation coefficients of -0.749 and 0.624 , respectively. This indicates that, under similar conditions, an increase in the indoor height of the gymnasium (which can be considered as the height of the lower edge of the lighting opening) helps improve the uniformity of indoor illuminance. Yang Zhao et al. [15] discovered through research on sports buildings that higher side window heights result in greater light penetration depth, higher illuminance at the center of the court, and better illuminance uniformity. Low-positioned side windows tend to cause excessive brightness at the edges of the court and insufficient illuminance in the center, resulting in the poorest uniformity. For small gymnasiums without stands, the effectiveness of side window daylighting ranks as follows: mid-height side windows > high side windows > double side windows > low side windows. The authors also derived a quantitative relationship indicating that skylight area increases approximately linearly with building height through linear regression, establishing height as a core influencing factor for skylight daylighting. In summary, for large-space buildings like sports venues, increasing the height of the lighting opening (e.g., using high side windows or skylights) is an effective design strategy to enhance indoor illuminance uniformity and reduce glare, while window openings located in the lower part of the wall lead to the worst energy performance.

Regarding research on the window-to-floor ratio and daylighting, China's engineering construction industry standard Technical Specification for Sports Facilities in Primary and Secondary Schools [16] stipulates that the minimum window-to-floor ratio for an uncovered sports hall should be 1:5.0 (0.2). Krarti et al. [17] demonstrated that for most public buildings, when the visible transmittance of the glazing is greater than 0.5 and the window-to-floor ratio exceeds 0.5, the energy savings for lighting achieved through natural daylighting are no longer significant with further increases in window area. Yang Zhao et al. [15] showed that the window-to-floor area ratio is a core parameter affecting the natural daylighting of gymnasiums and can serve as a benchmark indicator for evaluating other factors. The required window-to-floor area ratio for skylights is significantly lower than that for side windows, making skylights the optimal daylighting method for gymnasiums. The required window-to-floor area ratio increases with latitude, building height, and depth, and also increases as the transmittance of the glazing decreases. Maleki et al. [18] found that the ratio of window area to floor area in classrooms is particularly important in cold regions because it directly affects the amount of natural light and radiant heat entering the room, playing a key role in enhancing visual and thermal comfort. An appropriate ratio can reduce reliance on artificial lighting and heating systems. However, an excessively high window-to-floor ratio can lead to heat loss, energy waste, and discomfort due to glare. The study concluded that the optimal classroom window-to-floor ratio ranges from 0.125 to 0.2. Specifically, within this range, the lower end of the ratio yields the best glare control and adaptive thermal comfort, while the higher end of the ratio achieves the best daylight sufficiency.

In research on the window-to-wall ratio (WWR) of building side windows, a significant body of work has focused on the relationship between WWR and building energy efficiency. Introducing natural daylighting can effectively reduce a building's reliance on artificial lighting, thereby lowering lighting energy consumption and fully harnessing the beneficial effects of solar energy [19]. The WWR reflects the amount of natural light introduced. It is defined as the ratio of the total area of windows or glazed areas (including mullions and frames) to the total area of the exterior wall. Adjusting the WWR significantly impacts energy efficiency [20], often more so than changing the thickness of the exterior wall [21]. Of course, an excessively high WWR is also inappropriate, as it can

introduce new problems, such as glare [22,23]. Consequently, many scholars have investigated the optimal WWR value or optimal range. DING Yuxian et al. [24], through simulations of a teaching building in a severe cold region of China, demonstrated that since the thermal insulation performance of windows is generally much lower than that of walls, an excessively large WWR increases heat loss through the building envelope, leading to higher heating energy consumption. When the WWR ranged between 0.3 and 0.35, the total energy consumption for heating, air conditioning, and lighting reached a minimum. However, this study did not analyze the optimal WWR for different orientations of the building. Wen Zhang et al. [25] investigated a sports building in Qingdao, Shandong, and found that the WWR significantly affects the building's daylighting, ventilation, and overall energy consumption. Using tools such as genetic algorithms, the authors determined the optimal WWR configuration for the building: north: 0.37; east: 0.26; south: 0.53; and west: 0.41. Pathirana et al. [18] studied the impact of WWR on lighting energy demand and thermal comfort in naturally ventilated residential buildings under tropical climatic conditions. They found that the WWR's influence on thermal comfort ranges from 20% to 55%, while its impact on lighting electricity consumption is only between 1.5% and 9.5%. Therefore, when determining the WWR, greater emphasis should be placed on thermal comfort. Yanpeng Wu et al. [26], through a study of a university gymnasium in Beijing, showed that as the WWR increases, the total energy consumption of the gymnasium also increases, exhibiting a linear relationship. In this scenario, changes in the window area on the east and south facades had a minimal impact on total energy consumption. To enhance daylighting effectiveness, the windows on the east and south sides should be enlarged. Yuda Lyu et al. [20], in a case study of a gymnasium in Shanghai, found that the skylight area ratio is the most crucial factor affecting the energy consumption of large and medium-sized gymnasiums. They recommended a skylight area ratio range of 0.04 to 0.08 and a side window-to-wall ratio range of 0.1 to 0.3. The window-to-wall ratio of the side windows in this study differs somewhat from that reported by Wen Zhang et al. [25]. Yangbin et al. [27], in a study of a six-story residential building in Yinan, Shandong, concluded that for energy-saving goals, the recommended WWRs for the four orientations of the residential building are 0.25 for the east, 0.4 for the south, 0.3 for the west, and as small as possible for the north. Rania Elghamry et al. [13] found that window parameters generally have a minor impact on indoor relative humidity. Increasing the WWR leads to a simultaneous rise in cooling load, indoor temperature, total energy consumption, and operating costs, while the lighting load and heating load decrease correspondingly. Aida Maleki et al. [18], through a study of educational buildings in a cold region of Iran, discovered that the optimal WWR for classrooms ranges from 0.125 to 0.2. Specifically, within this range, lower WWRs provide the best performance regarding glare control and adaptive thermal comfort, while higher WWRs achieve the most desirable levels of daylight sufficiency. Bagheri et al. [28], using Rasht City, Iran, as a case study, systematically explored the impact of WWR on the annual energy consumption of low-rise residential buildings in a humid temperate climate. Employing DesignBuilder and parametric algorithms, the study simulated energy consumption variations for four orientations (North, South, East, West) with WWRs ranging from 10% to 100%. The results indicated significant differences in optimal WWRs across orientations: 21–25% for the south, 26–33% for the north, 54–57% for the east, and 58% for the west. Notably, the south-facing WWR exhibited a very strong positive correlation with energy consumption ($R^2 = 0.95$). Research shows that the specific optimal window-to-floor area ratio (or window-to-wall ratio, WWR) varies depending on research methods, climatic conditions, building types, and optimization objectives. Therefore, when determining the optimal WWR for a building, reference should be made to relevant findings from studies conducted on similar building types and within the same climatic region.

In terms of window glass performance indicators, Li et al. [29] pointed out that vacuum glazing and aerogel glazing possess excellent thermal insulation performance, with U-values below $1 \text{ W/m}^2\text{K}$, making them suitable for heating-dominated climate zones. Electrochromic smart windows, on the other hand, exhibit excellent performance in cooling-dominated climate zones due to their wide adjustable ranges of SHGC (0.09–0.47) and VT (0.02–0.62). Ming, Y. et al. [30] investigated passive technologies integrated into double-glazed windows, particularly transparent insulation material (TIM) and thermochromic (TT) materials. TIM can significantly enhance the thermal resistance of windows by forming micro-cavities within the interlayer. For example, a capillary TIM structure with a thickness exceeding 5 cm can achieve a thermal conductance below $2 \text{ W/(m}^2\text{K)}$. Compared to conventional Low-E insulating glass units, aerogel-filled insulating glass can reduce heat loss by more than 60%. However, both TIM and TT technologies have limitations: TIM possesses fixed optical properties, which may lead to increased heating and lighting energy consumption in winter; TT materials completely obstruct visibility after color transition. Mo et al. [31] took Fuzhou, China as a case study and found that summer cooling energy consumption accounts for approximately 75% of the building's total annual energy consumption in that region, making solar heat gain control (shading coefficient, Sc) the key to energy conservation. The above findings indicate that current window glass materials and technologies have become increasingly mature, capable of fully meeting the thermal performance requirements of transparent building envelopes in passive design.

This study takes a wind and rain sports hall at a university in Weifang City, Shandong Province, China, as the research object. The structure of the paper is arranged as follows: Section 2 details the research methodology; Section 3 evaluates the performance of the four optimization strategies through various simulation results; Section 4 analyzes the causes of these results and provides an evaluation of the study; and Section 5 summarizes the research findings.

2. Methodology

2.1. Climate Condition in Weifang

Weifang City is located in the western part of the Shandong Peninsula, occupying a central position within the peninsula city cluster. It spans longitude $118^{\circ}10'$ to $120^{\circ}01'$ east and latitude $35^{\circ}41'$ to $37^{\circ}26'$ north. Weifang is located in the north temperate monsoon zone, with land on one side and the sea on its back. Influenced by both the Eurasian continent and the Pacific Ocean, its continentality exceeds 50%, representing a warm temperate monsoon-type semi-humid continental climate. The climatic characteristics are cold winters and hot summers, with four distinct seasons. Spring is windy with little rain, with erratic temperatures in early spring and frequent late spring cold spells, while late spring sees rapid warming. Summer is hot and rainy, with high temperatures and humidity. Autumn is clear and crisp, with droughts common in late autumn. Winter is dry and cold, with frequent chilly winds. Due to the influence of the typical monsoon climate, temperatures vary distinctly across the four seasons, with an annual average temperature of 12.3°C . January is the coldest month of the year, with an average temperature of -3.3°C in Weifang, while July is the hottest month, with an average temperature of 26.0°C . Temperatures rise rapidly in spring and drop significantly in autumn [32,33].

2.2. Research Case Study and Current Status

The wind and rain sports hall is a type of campus sports building with Chinese characteristics, primarily referring to a venue on school grounds where students engage in indoor sports activities. The Code for Design of Primary and Secondary Schools [12] defines this type of building as a sports ground with a roof, including spaces with a roof but

no enclosing walls, as well as venues with both a roof and enclosing walls. These are typically small to medium-sized sports buildings with relatively simple functions [34,35]. Such buildings were often constructed under less favorable economic conditions. Consequently, the air conditioning and lighting equipment in these spaces are frequently inadequate, only capable of meeting basic teaching and sports activity needs. Unlike a standard gymnasium, a wind and rain sports hall generally does not have fixed spectator seating; higher-standard ones might have movable bleachers. This type of building is primarily located on school campuses, serving daily teaching, training, and the needs of both teachers and students.

This wind and rain sports hall was constructed in 2002 and has been in use for over 20 years. Although the construction standards of the hall were relatively low, its utilization rate is high, making it one of the main indoor venues for physical education courses and daily indoor exercise for faculty and students. The wind and rain sports hall is a single-story building with a floor area of 4770 square meters. It measures 45 m in length from east to west and 106 m in length from north to south, with a total of seven entrances and a building height of approximately 10 m. For most of the time, only the west entrance is open (Figure 1). The main structure of the building is steel-framed, with a span of 22.5 m per bay. The roof is a low-slope pitched roof, with approximately one-third of the roof area using translucent materials for skylights, which improves the daylighting quality during daytime use. The enclosure walls around the building consist of two parts. The lower 5 m high section is a 300 mm thick brick masonry wall, in which side windows are installed. These side windows have a sill height of 2.1 m, providing daylighting and ventilation for the interior. The remaining upper part of the walls is constructed using profiled metal steel sheets as the enclosure structure. Several small ventilation openings are provided on these profiled metal steel sheets.



Figure 1. Photograph of the wind and rain sports hall.

The lighting fixtures within the venue adopt two layout configurations based on functional differences of the courts. The two basketball courts on the south side employ a combined “overhead + side” lighting arrangement: three luminaires are installed along the central axis directly above each court, with two additional luminaires mounted on each of the two long sides. The two tennis courts on the north side and the two multi-purpose activity courts in the middle uniformly adopt a side-lighting configuration, with three luminaires installed on each of the two long sides per court. The mounting height of all luminaires is uniformly approximately 9.5 m.

The building has no air conditioning or heating equipment, and can only provide an indoor sports venue that offers shelter from wind and rain. During seasons with extremely high or low temperatures, such as summer and winter, it can easily cause discomfort for

indoor sports activities. Research has shown [36] that air temperature is the most significant factor affecting outdoor thermal comfort, with an influence greater than that of solar radiation and wind speed. In spaces without air temperature regulation facilities, the indoor temperature condition is an important indicator for measuring the quality of thermal comfort in the space.

In 2024, the sports hall underwent a renovation to accommodate the diversification of sports activities and meet the demands of social services. As part of this renovation, tennis courts were added to the facility. To meet the requirements of tennis, all side windows were sealed with gypsum boards to prevent tennis balls from entering the external security mesh outside the windows and breaking the glass. However, this significantly reduced the indoor daylighting quality. To improve the indoor lighting effect, the renovation also replaced the indoor lighting fixtures (Figure 2). At the same time, to address the issue of poor indoor air circulation caused by the sealing of windows, two spherical ventilators were installed above the roof of each court during the renovation. However, actual user feedback indicates that the renovation has caused numerous problems, the most prominent of which is a significant deterioration in indoor natural daylighting quality. Under overcast conditions, even during daytime hours, indoor illuminance fails to meet normal usage requirements, necessitating reliance on artificial lighting. This deficiency has directly triggered behavioral resistance from users—some sealed or obstructed windows were deliberately damaged after a period of use in order to restore natural daylighting. At present, the gypsum boards blocking the side windows of the four courts on the south side have been completely removed, while the gypsum boards blocking the side windows of the two tennis courts on the north side still remain. This is because the north-side courts are the main courts for tennis activities. On the south-side four courts, various activities such as basketball, volleyball, and tennis are frequently held, and the courts are adjusted at any time according to usage needs.

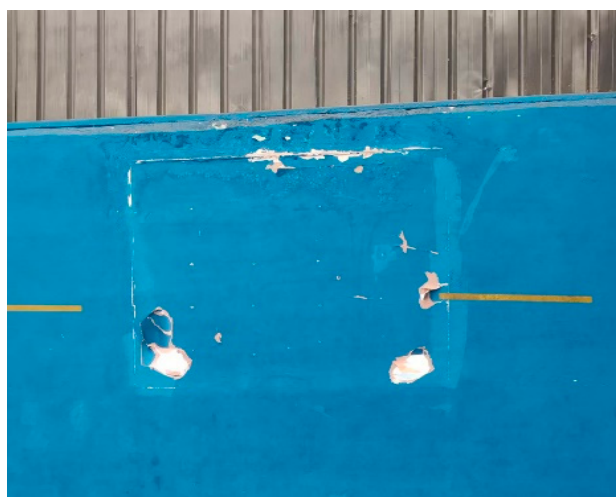


Figure 2. Window blocked with gypsum board from the interior.

The original primary functions of the sports hall include training and amateur competitions in basketball, badminton, and volleyball. The facility originally contained six standard basketball courts (Figure 3), with badminton and volleyball courts sharing space with some basketball courts on a time-sharing basis. After the 2024 renovation, four basketball courts were converted into tennis courts (Figure 4). The temporary functions of the sports hall also include large-scale indoor events such as campus job fairs.

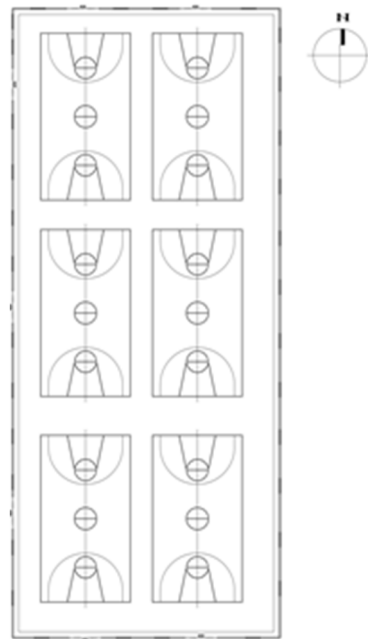


Figure 3. Indoor spatial distribution diagram of the original scheme.

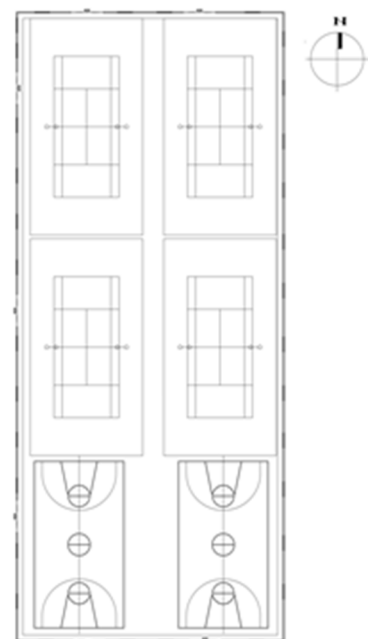


Figure 4. Indoor spatial distribution diagram of the current scheme.

2.3. Field Measurement

2.3.1. Field Measurement of Daylighting

The measurement was conducted under overcast sky conditions. The author performed on-site illuminance measurements on 24 May 2026, from 12:00 to 14:00. Two illuminance meters were used for simultaneous indoor and outdoor measurements. The dynamic range of the illuminance meters was 1–100,000 lx. A Leica Disto D5 laser distance meter was used for distance measurement. The daylighting test method was established according to the Method of Daylighting Measurements (GB/T 5699-2025) [37].

In the current scheme, the low side windows of the four courts on the south side have been damaged, effectively restoring the building to the state of the original scheme. On-site measurements were therefore conducted only on the two courts on the south side. There

were two reasons for this. First, the illuminance of the two south-side courts, being influenced by the south wall, is lower than that of the other four courts, representing the most disadvantageous scenario for daylighting performance. Second, to minimize the impact of the blocked low side windows of the two north-side courts on surrounding illuminance, measuring the two south-side courts could best reduce the influence of the blocked low side windows on the measured illuminance values. Consequently, it was decided to measure the illuminance of the two courts on the south side. A 4 m × 4 m measurement grid was adopted, with a total of 108 measurement points arranged (see Figure 5). The working plane for illuminance measurement was set at a height of 0.8 m above the floor, with measurement points located at a distance of 1 m from walls and columns [14].

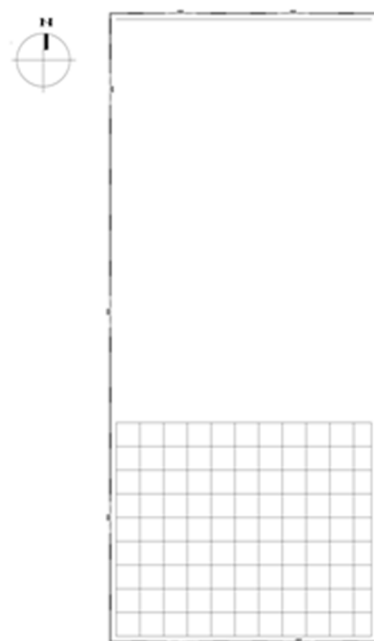


Figure 5. Layout of indoor illuminance measurement points.

After data processing and analysis, the results showed that the average outdoor illuminance during the measurement period was 16,820 lx. The average daylight factor of the building was 6.67%. Among all measurement points, the minimum illuminance value was 445 lx, and the maximum was 2030 lx. The average illuminance was 1122.02 lx. The illuminance uniformity (U1), calculated as the minimum illuminance among measurement points divided by the average illuminance, was 0.4. The illuminance uniformity (U2), calculated as the minimum illuminance divided by the maximum illuminance, was 0.22. The illuminance values at the measurement points exhibited a characteristic of decreasing with proximity to the walls.

2.3.2. Field Measurement of Temperature

To validate the effectiveness of the model, the author used a thermohygrometer to conduct real-time measurements of the indoor air temperature within the sports hall. During the summer use period, the two doors (5 m × 5 m) near the south and north sides of the hall remained open at all times; therefore, the measurement sites were selected as the two central courts, where the thermal environment was most unfavorable. The measurements were taken at a height of 1.1 m, with a total of 36 indoor measurement points, with 18 points arranged on each court. Indoor air temperature measurements were conducted at four specific times—10:00, 13:00, 16:00, and 18:00—over three consecutive days from 18 June to 20 June 2026. The 36 temperature readings obtained from different positions at the

same time were averaged arithmetically. Meanwhile, outdoor air temperatures were measured hourly from 6:00 to 22:00 over the same three days, with the outdoor measurement point placed in a shaded area around the sports hall. These measured outdoor temperature data were used to replace the relevant data in the eQUEST weather file for indoor temperature simulation, and the simulated indoor temperatures were compared with the measured results to verify the validity of the model.

2.4. Existing Problems

Based on the author's long-term on-site observations and usage experience, the wind and rain sports hall currently has the following four main problems: (1) There is poor indoor daylighting quality on overcast and rainy days, with low illuminance under natural conditions. Artificial lighting is required particularly in winter when evening approaches. (2) Indoor thermal comfort level is inadequate: The building is equipped with neither heating nor cooling systems. Indoor temperatures in winter are only slightly higher than outdoor temperatures, while in summer, indoor temperatures sometimes exceed outdoor temperatures. (3) The numerous low-side windows are detrimental to volleyball activities: When practicing against the wall, the ball's rebound effect is significantly weakened by impact with the wire mesh protective screens on the windows, thereby interfering with training. Moreover, compared to high-side windows, low-side windows are more prone to causing glare issues [38]. (4) The building's exterior façade presents a poor esthetic appearance, detracting from the campus streetscape: The sports hall is situated immediately adjacent to the city's main arterial road. Following the widening and reconstruction of this road, the original tall tree-lined greenbelt was replaced by low shrubs, leaving the building fully exposed to street-level view. The upper portion of the building envelope is clad in profiled color-coated steel sheets, which, after prolonged use, exhibit noticeable rusting and corrosion, compromising the overall image of both the campus and the urban streetscape.

2.5. Renovation Schemes

From the perspectives of poor indoor illuminance, insufficient thermal comfort, and streetscape appearance in the wind and rain sports hall, this study takes the pre-renovation state (original) and the current state (current) as two baseline scenarios. In addition, four additional retrofit schemes combining different configurations of side windows and skylights were developed based on existing research and design cases. These schemes were used to compare and analyze the natural daylighting performance and temperature variations of each scheme, in order to examine the effects of different retrofit strategies on indoor natural daylighting and temperature. The findings of this study can serve as a basis for the next renovation of the building.

The four retrofit schemes are as follows:

Scheme A: Replace the upper portions of the building's four exterior walls, which are originally enclosed with profiled metal steel sheets, with translucent acrylic panels to increase the window-to-wall ratio (WWR) in all four orientations (east, south, west, and north).

Scheme B: The difference from Scheme A is that the west exterior wall maintains its original low window-to-wall ratio and does not have high side windows added. This is because the west side is adjacent to the interior of the school campus and is not visible from outside the school, having a smaller impact on the urban streetscape. Furthermore, research has shown that excessively large west-facing windows can significantly increase the cooling load [18], i.e., significantly raise indoor temperatures in summer. To avoid this adverse condition, Scheme B implements the same retrofits as Scheme A on the east, south, and north facades, while leaving the west facade unchanged.

Scheme C: This is similar to Scheme A, but with the skylights removed.

Scheme D: This is based on the original scheme, and the skylights are removed. This scheme is designed to study the impact of changes in side windows and skylights on the natural daylighting of the building.

2.6. Window-to-Wall Ratio and Window-to-Floor Ratio

Based on the relevant architectural drawings, the author calculated the window-to-wall ratios for the four cardinal directions (east, west, south, and north) for the six schemes mentioned above. The statistical results are shown in Table 1.

Table 1. Statistical table of side window-to-wall ratios for the six schemes.

Scheme Name	East Window-to-Wall Ratio	West Window-to-Wall Ratio	South Window-to-Wall Ratio	North Window-to-Wall Ratio
Original	0.064	0.059	0.04	0.04
Current	0	0	0	0
Scheme A	0.45	0.36	0.34	0.34
Scheme B	0.45	0	0.34	0.34
Scheme C	0.45	0.36	0.34	0.34
Scheme D	0.064	0.059	0.04	0.04

Window-to-Floor Ratio. The window-to-floor ratio (WFR) is also an important indicator affecting daylighting quality. However, because the impacts of skylights and side windows on indoor daylighting differ significantly, their areas cannot be simply added together. Relevant regulations stipulate that the skylight area must be multiplied by a position correction coefficient, K_c , where the value of K_c is equal to the ratio of the WFR requirement for top lighting (skylights) to that for side lighting (side windows). The correction coefficient for Grade III daylighting level is determined to be 1.6 [39]. From the calculation principle of the daylight factor, it is evident that a skylight of a given area contributes more to daylighting than a side window of the same area.

After calculation, the WFRs of the six schemes are shown in Table 2. Among the six schemes, Scheme A has the highest WFR, with a maximum value of 0.78, while Scheme D has the lowest WFR, with a minimum value of 0.03. This scheme uses only low side windows for daylighting. The WFR for the current scheme, which uses only skylights for daylighting, is 0.53. The WFR for illumination using only high side windows is 0.24.

Table 2. Statistical table of window area and window-to-floor ratio for the six schemes.

Scheme Name	Side Window Area (m ²)	Skylight Area (m ²)	Floor Area (m ²)	WFR
Original	166.5	1590	4770	0.57
Current	0	1590	4770	0.53
Scheme A	1164	1590	4770	0.78
Scheme B	784	1590	4770	0.70
Scheme C	1164	0	4770	0.24
Scheme D	166.5	0	4770	0.03

2.7. Analysis Tools and Evaluation Indicators

This study employed Ecotect and eQUEST software to conduct building performance simulation analysis. Weather files for Weifang City, Shandong Province, China, downloaded from the U.S. Department of Energy website, were used as meteorological input data for the simulation and evaluation strategies in both software tools.

Ecotect is a sustainable building design and analysis tool developed by Autodesk. It was originally conceived and developed by Dr. Andrew Marsh during his doctoral research at the School of Architecture and Arts, University of Western Australia [40]. The

software aims to assist architects and engineers in conducting interactive analysis and optimization of building performance during the conceptual design phase.

This analysis used Ecotect Analysis 2011. The climate file used in the software was downloaded from the official EnergyPlus website (www.energyplus.net). The downloaded weather file in EPW format for Weifang, China, was then converted into a readable WEA weather file using Ecotect's built-in conversion tool for subsequent use.

EQUEST is jointly developed by the Lawrence Berkeley National Laboratory (LBNL) and J.J. Hirsch & Associates. Its primary development purpose is to enable hourly energy simulation to be accessible to a broader range of designers. Building energy evaluation involves the dynamic process of complex building heat transfer, where heat gain or loss varies with indoor and outdoor climatic conditions. The eQUEST energy calculation software uses a forward-thinking approach to calculate indoor temperature and indoor heat gain based on outdoor weather conditions and envelope characteristics, subsequently calculating loads. Its calculation process is a dynamic equilibrium process, where the indoor temperature, cooling and heating loads, and electricity consumption of HVAC equipment at a given moment are influenced by the previous moment. Based on input building parameters (building structure, envelope materials, HVAC system type and layout, indoor occupant activity patterns, lighting equipment conditions) and indoor design temperature values, the software calculates the annual dynamic energy consumption of the building [41].

This simulation analysis used eQUEST version 3.6.5. The weather file used by eQUEST was the EPW format weather file for Weifang, China, downloaded from the official EnergyPlus website (www.energyplus.net). Subsequently, the weather file format converter was downloaded from the official DOE2 website (DOE2.com) to convert the weather file into the BIN format usable by eQUEST. This BIN file was then imported into the eQUEST software for analysis.

3. Renovation Strategies and Simulation Analysis

3.1. Simulation Setup

3.1.1. Daylighting Simulation Setup

1. Simulation Settings for the Original Scheme Compared with Measured Data:

Since the default design sky illuminance in the software differs significantly from the outdoor illuminance measured on the actual day, directly applying the default parameters to the model would result in considerable deviations between the simulated and measured values. Therefore, to ensure the validity of the model, it is necessary to calibrate the relevant input parameters separately when validating the original scheme. The specific modification is as follows: the default design illuminance value in the software is replaced with the average outdoor illuminance recorded during the measurement period. Meanwhile, to ensure comparability between the simulated results and the field measurement data, the arrangement of measurement points (grids) in the simulation analysis is kept consistent with that of the field measurements.

2. Basic Settings for Daylighting Simulation of Schemes:

To investigate the impact of variations in the number and location of daylight openings on indoor daylighting performance, indoor light environment simulations were conducted for each design scheme. In the Ecotect calculation model, a working plane at a height of 0.80 m above the floor was established, with a calculation grid resolution of 0.5 m. The side windows and skylights of the building were modeled according to actual conditions (Figure 6). The analysis plane height was selected as 0.75 m. The design sky illuminance for the Weifang region was calculated as 7655 lx according to the Tregenza formula.

Considering the significant influence of different sky conditions on the light environment in Ecotect, the overcast sky, which represents the most scarce natural light condition, is se-

lected as the sky environment to simulate the most unfavorable daylighting scenario. The light climate zone of the Weifang area belongs to Zone IV, with a light climate coefficient K value of 1.10, and the outdoor design illuminance from natural light E_s is 13,500.0 lx. According to the “Standard for Daylighting Design of Buildings” GB 50033-2013 [39], the standard value of the daylight factor for side daylighting in sports buildings is 2.2%.

The parameter settings in Ecotect included the skylights, the low side windows in the original scheme, and the high side windows in the retrofit schemes, as well as the settings for materials such as walls and floors. The skylight material was set to Translucent Skylight. The visible light transmittance of this material was 0.658, and the glass refractive index was 1.74. The low side windows in the original scheme were set to Single-Glazed Alum Frame, with a visible light transmittance of 0.753 and a glass refractive index of 1.74. The high side windows in the retrofit schemes used the same material as the skylights, with a visible light transmittance of 0.658 and a glass refractive index of 1.74. The wall material was set to Brick Plaster.

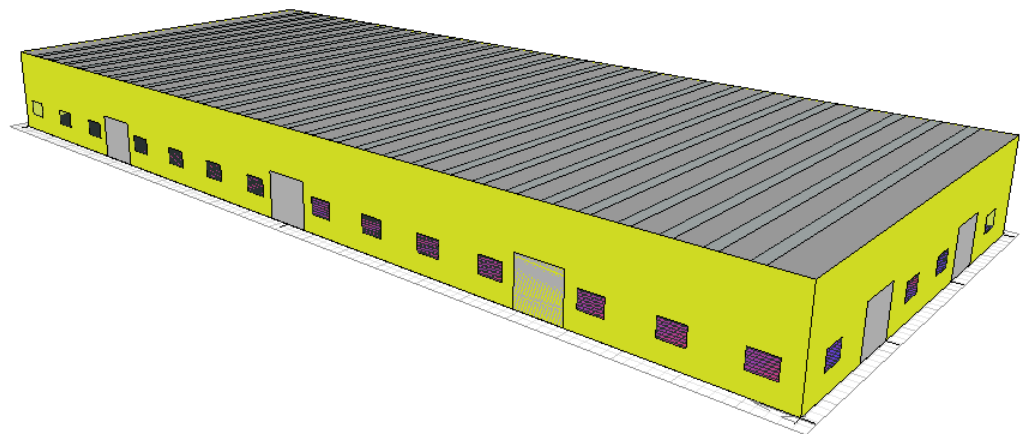


Figure 6. Model established using Ecotect.

3.1.2. Thermal Performance Simulation Setup

1. Parameter Settings of the Original Scheme for Comparison with Measured Results:

To eliminate the systematic deviation between the initial simulation conditions and the measured it was necessary to reset the key boundary conditions during the model calibration phase to validate the effectiveness of the model. The specific adjustments included: (1) replacing the default values in the eQUEST weather file with the hourly temperature and solar radiation data measured on the actual day; (2) setting the opening status of doors and windows during the measurement period to the fully open mode; (3) modifying the indoor heat gain intensity based on field survey conditions—since the survey period coincided with a statutory holiday, the observed number of indoor occupants did not exceed four people on any of the three days, and most sports participants were active outdoors, so the occupant-related load parameters were accordingly reduced. These three adjustments constituted the core content of the calibration process.

2. Basic Settings of Materials:

A model of the wind and rain sports hall was constructed in the eQUEST software (Figures 7 and 8). Using the software’s energy-saving renovation measures wizard, the sill height and the window-to-wall area ratios for each orientation were varied to simulate the energy consumption of the four different schemes, thereby evaluating the performance differences among the schemes.

The parameter settings in eQUEST were as follows. The roof was constructed using galvanized steel structure (steel, galvanized (weathered)) with no external insulation. Approximately 33% of the roof area was designated for skylights. The overall thermal transmittance (U-value) of the roof was approximately $4.46 \text{ W}/(\text{m}^2 \cdot ^\circ\text{C})$. The roof skylights were flat skylights with non-thermal-break aluminum frames. The glazing type was selected as Sgl Acrylic White (translucent). The lower part of the building's exterior walls consisted of 240 mm brick walls with 30 mm of cement mortar plaster on both sides. The thermal transmittance (U-value) of the wall was $2.42 \text{ W}/(\text{m}^2 \cdot ^\circ\text{C})$. The material for the upper part of the building's exterior walls (the translucent panels) was the same as the skylight material, using translucent acrylic panels. These daylighting panels were diffuse transmission type, with a thermal transmittance (U-value) of $11.64 \text{ W}/(\text{m}^2 \cdot ^\circ\text{C})$, a visible light transmittance of 0.5, and a solar heat gain coefficient (SHGC) of 0.435. The low side window glazing in the original scheme was single clear glass, 3 mm thick, with non-thermal-break aluminum frames. The windows were operable. The thermal transmittance (U-value) of the glass was $5.11 \text{ W}/(\text{m}^2 \cdot ^\circ\text{C})$, the visible light transmittance was 0.9, and the solar heat gain coefficient (SHGC) was 0.86. The exterior doors were modeled as Opaque. The door material and construction were steel doors with a polyurethane foam-filled core and no thermal break structure. The floor of the wind and rain sports hall was in direct contact with the soil and was modeled as a cement floor.

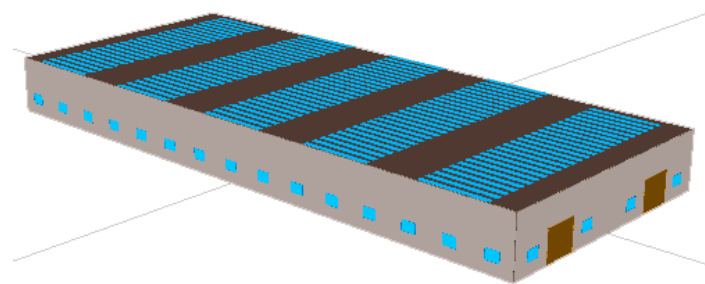


Figure 7. Model of Case1 established using EQUEST.

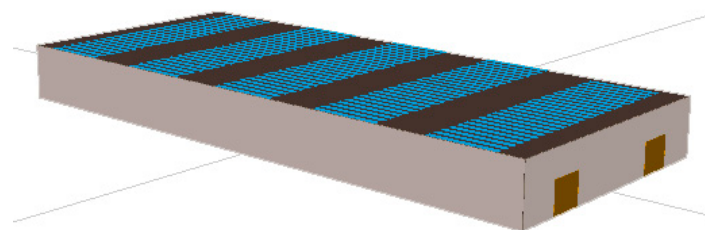


Figure 8. Model of Case2 established using EQUEST.

In terms of usage time scheduling, based on the university's historical academic calendars, it was found that throughout the year, the main usage period of the wind and rain sports hall is concentrated within two semesters: 1 March to 18 July and 1 September to 18 January of the following year, each semester lasting approximately 20 weeks. In terms of daily usage time, the main usage hours are concentrated from 10:00 AM to 6:00 PM on weekdays (Monday to Friday). During the winter and summer vacations, the utilization of the sports hall is relatively low.

3. Settings for Modifying Material Properties:

To further verify the changes in indoor temperature when altering window properties, the relevant parameters of the large-area glass were adjusted. The adjustment schemes mainly include Schemes A, B, C, and D. The original scheme and the current scheme were not adjusted due to their relatively small glass areas. The adjusted parameters primarily cover two parts: side windows and skylights.

For side windows, the glass conductance was reduced by adopting double-glazed Low-E glass, decreasing from $6.19 \text{ W}/(\text{m}^2\cdot\text{K})$ to $2.16 \text{ W}/(\text{m}^2\cdot\text{K})$. The shading coefficient was increased from 0.5 to 0.72. The visible transmittance was raised from 0.5 to 0.75 to enhance daylighting and indoor heat storage. The outside emissivity was reduced from 0.84 to 0.16.

For skylights, the glass conductance was reduced from $11.64 \text{ W}/(\text{m}^2\cdot\text{K})$ to $1.99 \text{ W}/(\text{m}^2\cdot\text{K})$. The shading coefficient was increased from 0.38 to 0.75. The visible transmittance was raised from 0.42 to 0.78 to enhance daylighting and indoor heat storage. The outside emissivity was reduced from 0.84 to 0.14.

The above optimization takes enhancing solar radiation heat gain of the building and improving the indoor thermal environment in winter as its core objectives. Therefore, in accordance with the actual operating condition in winter—where windows and doors are closed and only envelope gaps provide infiltration—the air change rate of the space is set at 0.5 ach.

3.2. Simulation Results

3.2.1. Daylighting Performance Simulation Results

1. Measured Results and Simulated Results of the Original Scheme

Based on the collation and analysis of the measured data, the average outdoor illuminance during the measurement period was 16,820 lx. The average daylight factor of the building was 6.67%. Among all measurement points, the minimum illuminance was 445 lx, and the maximum was 2030 lx. The average illuminance was 1122.02 lx. The illuminance uniformity (calculated as the ratio of the minimum illuminance to the average illuminance at the measurement points) was 0.40. The illuminance uniformity (calculated as the ratio of the minimum illuminance to the maximum illuminance) was 0.22. The illuminance values at the measurement points exhibited a characteristic pattern of decreasing values closer to the walls.

The simulated results of the original scheme compared with the measured results are shown in Figure 9. The simulation results indicate that the average daylight factor of the building was 6.63%. Among all measurement points, the minimum illuminance was 400 lx, and the maximum was 2100 lx. The average illuminance was 1114.49 lx. The results show that the simulated daylight factor was 0.04% lower than the measured value, and the simulated average illuminance was 7.53 lx lower than the measured value, with the differences accounting for 0.60% and 0.67% of the measured values, respectively. Regarding illuminance uniformity, the simulated U1 and U2 values were 0.36 and 0.19, which were 0.04 and 0.03 lower than the measured values, accounting for 10.3% and 13.4% of the measured values, respectively. The daylight factor and average illuminance from the measured and simulated results were in close agreement, with differences accounting for less than 1% of the measured values. The differences in illuminance uniformity were relatively larger, yet they did not exceed 15%.

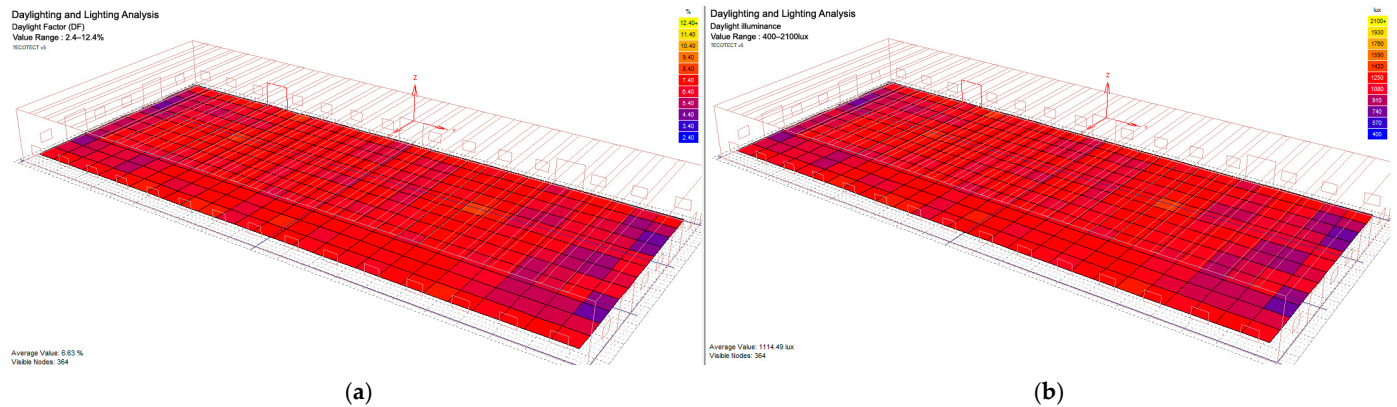


Figure 9. Simulated daylighting results of the original scheme compared with measured results. (a) Daylight factor distribution; (b) daylight illuminance distribution.

2. Simulation Results of Natural Daylighting for the Six Schemes

Figures 10–15 present the simulation results of natural daylighting for the six schemes under consideration.

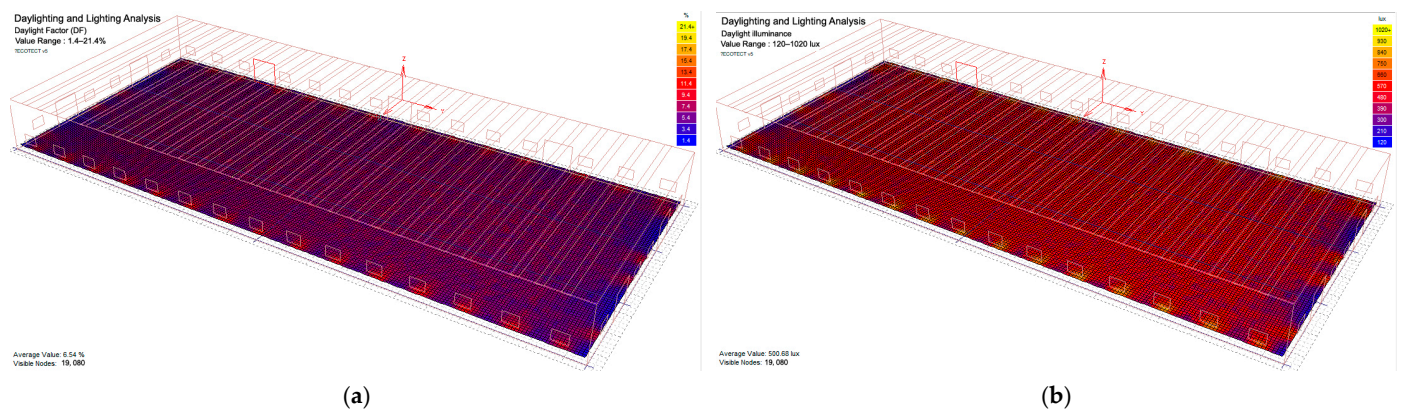


Figure 10. Simulation results of natural daylighting for the original scheme. (a) Distribution of daylight factor; (b) distribution of daylight illuminance.

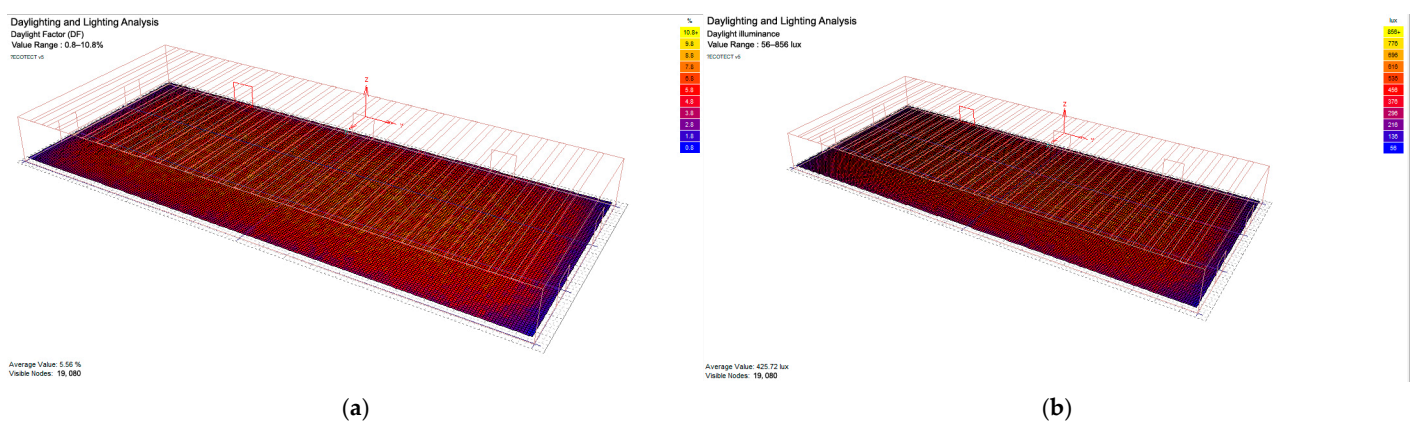


Figure 11. Simulation results of natural daylighting for the current scheme. (a) Daylight factor distribution; (b) daylight illuminance distribution.

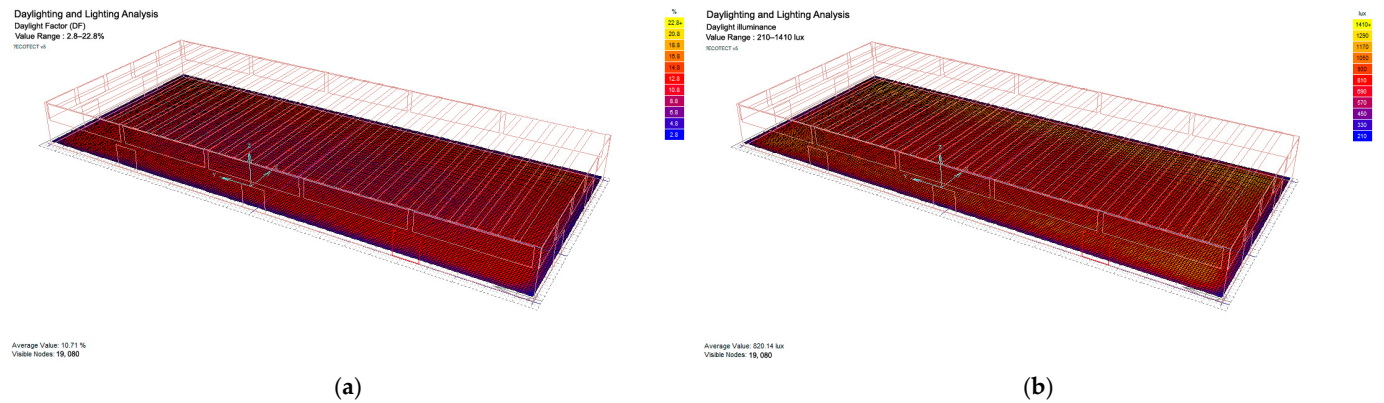


Figure 12. Simulation results of natural daylighting for Scheme A. (a) Distribution of daylight factor; (b) distribution of daylight illuminance.

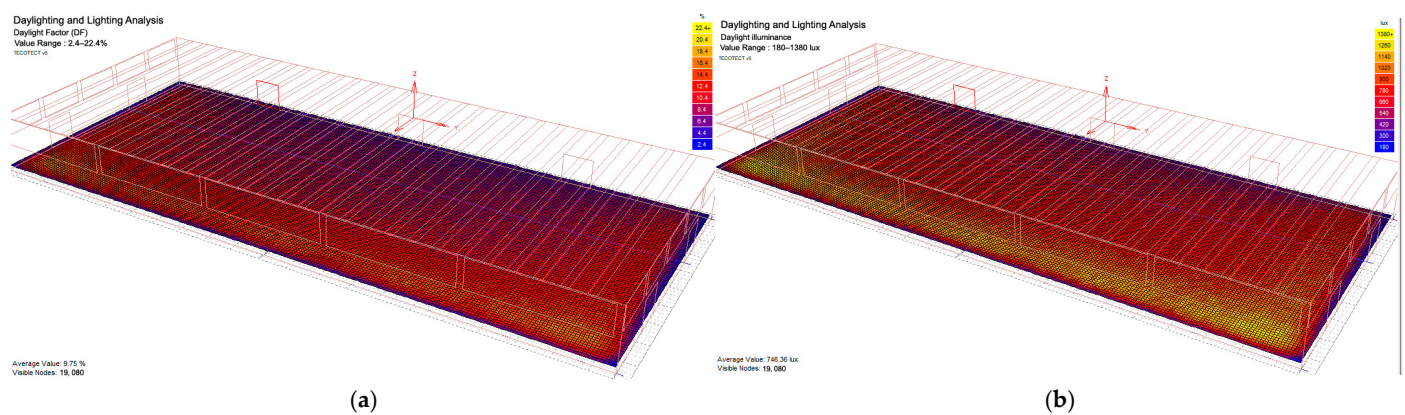


Figure 13. Simulation results of natural daylighting for Scheme B. (a) Daylight factor distribution; (b) daylight illuminance distribution.

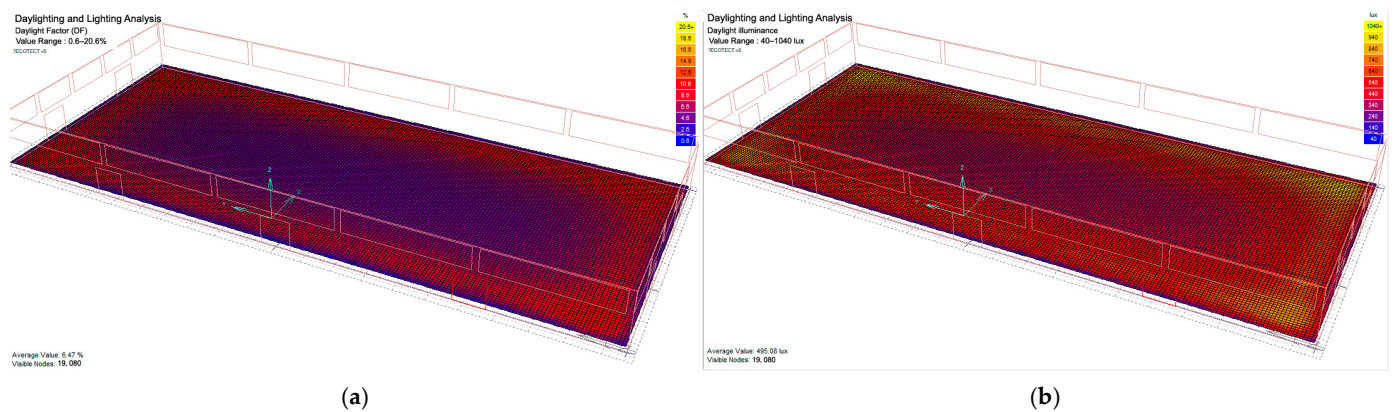


Figure 14. Simulation results of natural daylighting for Scheme C. (a) Daylight factor distribution; (b) daylight illuminance distribution.

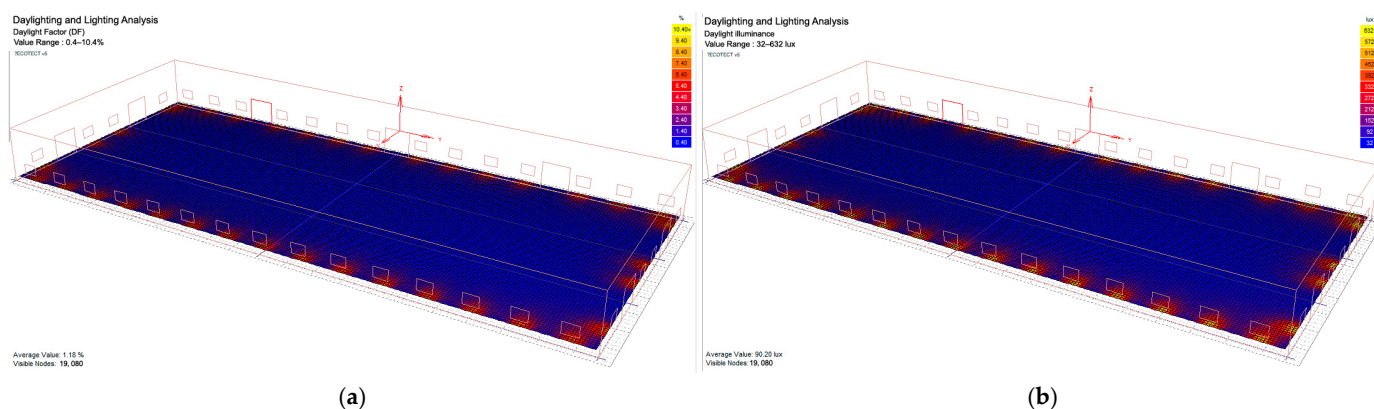


Figure 15. Simulation results of natural daylighting for Scheme D. (a) Daylight factor distribution; (b) daylight illuminance distribution.

Table 3 summarizes the side window area, skylight area, average daylight factor, average illuminance, and illuminance uniformity for the six schemes, based on the drawings and simulation results. Based on Table 3 and the measured natural daylighting data, the following characteristics can be observed.

Table 3. Natural daylighting simulation results for the six schemes.

Scheme Name	Side Window Area (m ²)	Skylight Area (m ²)	Average Daylight Factor	Average Illuminance (lux)	Illuminance Uniformity U1	Illuminance Uniformity U2
Original	166.5	1590	6.54%	500.68	0.24	0.12
Current	0	1590	5.56%	425.72	0.13	0.07
Scheme A	1164	1590	10.71%	820.14	0.26	0.15
Scheme B	784	1590	9.75%	746.36	0.24	0.13
Scheme C	1164	0	6.47%	495.08	0.08	0.04
Scheme D	166.5	0	1.18%	90.20	0.35	0.05

(1) The daylight factor of Scheme D falls below the standard requirement. According to the previous calculations, the window-to-floor ratio (WFR) of Scheme D is 0.03, which fails to meet the minimum WFR requirement of 1:5.0 stipulated in the Technical Specification for Sports Facilities in Primary and Secondary Schools (JGJ/T 280-2012) [16]. The simulation results for Scheme D also confirm that its average daylight factor of 1.18% is below the minimum requirement of 2% specified in the code.

(2) Schemes incorporating both side windows and skylights generally achieve higher daylighting performance. Scheme A, with the largest side window area, attains the highest daylighting performance among all schemes, with an average daylight factor of 10.71% and an average illuminance of 820.14 lx. Scheme B, with a slightly smaller side window area than Scheme A, exhibits a corresponding modest decrease in both daylighting metrics. The original scheme, which incorporates both side windows and skylights, achieves a daylight factor of 6.54% and an average illuminance of 500.68 lx. The current scheme, which has no side windows and relies solely on skylights, shows a marked attenuation in daylighting performance. Schemes without skylights generally exhibit lower daylighting performance overall. Scheme C, despite its large side window area, achieves only a 6.47% daylight factor and 495.08 lx average illuminance. Scheme D, with only a small number of side windows and no skylights, performs the poorest in daylighting, with a daylight factor of only 1.18% and an average illuminance of merely 90.20 lx.

(3) The trends of the two illuminance uniformity indices are not entirely consistent. Schemes A and B, the original scheme, and the current scheme—all of which feature skylights combined with side windows—exhibit generally higher U1 and U2 values than

schemes without skylights. Scheme C, which lacks skylights, exhibits extremely low values for both uniformity indices despite its large side window area, indicating prominent issues with uneven indoor light distribution. Scheme D, which has only a small side window area, achieves the highest U1 value among all groups (0.35), yet its U2 value is only 0.05. The substantial discrepancy between the two uniformity calculation results suggests that a single small side window tends to create excessively bright localized areas while resulting in an overall imbalanced daylight distribution.

3.2.2. Thermal Performance Simulation Results

1. Measured and Simulated Results of the Original Scheme

A total of 12 sets of outdoor measured temperature, indoor measured average temperature, and software-simulated indoor temperature data were collected from 18 June to 20 June at 10:00, 13:00, 16:00, and 18:00 each day. The temperature differences were calculated by subtracting the measured indoor temperature from the simulated indoor temperature for comparative analysis (Table 4). On 18 June, the outdoor temperature was generally high throughout the day, ranging from 29.1 °C to 31.4 °C. Only at 10:00 was the simulated value 2.4 °C lower than the measured value; from 13:00 to 18:00, the simulated results closely matched the measured values, with absolute temperature differences not exceeding 0.3 °C. On 19 June, the outdoor temperature was significantly lower, ranging only from 25.4 °C to 26.5 °C. Except for 10:00, when the simulated temperature was 0.9 °C lower than the measured value, the simulated values were all higher than the measured values at other times, with a positive deviation of 1.0 °C at 16:00, representing the largest overestimation error of the day. On 20 June, the outdoor temperature was in the moderate range of 27.8 °C to 30.1 °C, following a pattern similar to that of 18 June. At 10:00, the simulated value was 2.6 °C lower than the measured value; in the afternoon and evening, the simulated temperatures were generally consistent with the measured values, with absolute temperature differences not exceeding 0.9 °C. At 16:00, the temperature difference was 0 °C, indicating the best match. Overall, under the three outdoor temperature conditions, the simulation accuracy during the afternoon and evening hours was generally good; however, an underestimation of simulated temperatures (i.e., simulated values lower than measured values) was observed at 10:00 across all three days.

Table 4. Simulation results of natural daylighting for the six schemes.

Time	Measured Outdoor Temperature (°C)	Measured Indoor Average Temperature (°C)	Simulated Indoor Temperature (°C)	Temperature Difference Between Simulation and Measurement (°C)
18 June 10:00	29.1	29.3	26.9	−2.4
18 June 13:00	30.9	31.6	31.5	−0.1
18 June 16:00	31.4	31.8	31.9	0.1
18 June 18:00	30.8	30.7	31	0.3
19 June 10:00	25.6	26.2	25.3	−0.9
19 June 13:00	25.4	26.6	26.7	0.1
19 June 16:00	26.3	27	28	1
19 June 18:00	26.5	27.2	27.7	0.5
20 June 10:00	27.9	28.4	25.8	−2.6
20 June 13:00	30.1	30.9	30	−0.9
20 June 16:00	28.5	29.1	29.1	0
20 June 18:00	27.8	28.2	28.1	−0.1

2. Statistical Results of Monthly Average Temperature for Each Scheme after Changing Window-to-Floor Ratio

(1) Average Temperature of Each Month

The building is equipped with neither heating nor air conditioning systems; therefore, this study focuses on the effects of each optimization scheme on indoor natural room temperature. Utilizing eQUEST with heating and cooling systems disabled, the study conducted year-round hourly temperature simulations. Hourly temperature data were extracted for the period from 10:00 to 18:00 daily during the 10-month campus occupancy period, and monthly average indoor temperatures were calculated. The results are presented in Tables 5 and 6.

Table 5. Average monthly indoor temperatures during the spring semester usage period for the six schemes.

Scheme Name	Average Monthly Indoor Temperature During the Spring Semester (°C)				
	March	April	May	June	July
Original	14.32	23.1	28.99	33.64	34.5
Current	13.96	22.72	28.65	33.28	34.15
Scheme A	14.32	22.99	28.63	33.45	34.29
Scheme B	15.77	24.54	30.16	34.96	35.71
Scheme C	15.41	23.74	29.14	34.08	35.16
Scheme D	14.57	22.79	28.37	33.2	34.43

During the spring semester, indoor temperatures rise continuously with increasing outdoor temperatures, with the annual peak occurring in July. The temperature differences among schemes are relatively small; the highest July mean temperature among all schemes is 35.71 °C (Scheme B), while the lowest is 34.15 °C (current scheme), with a difference of only 1.56 °C between the two.

As shown in Figure 16, among schemes without skylights, the high-window-to-wall-ratio Scheme C exhibits a higher average room temperature than the low-window-to-wall-ratio Scheme D. For the four schemes with skylights, the July average temperature exhibits a trend of first increasing and then decreasing with increasing window-to-floor ratio.

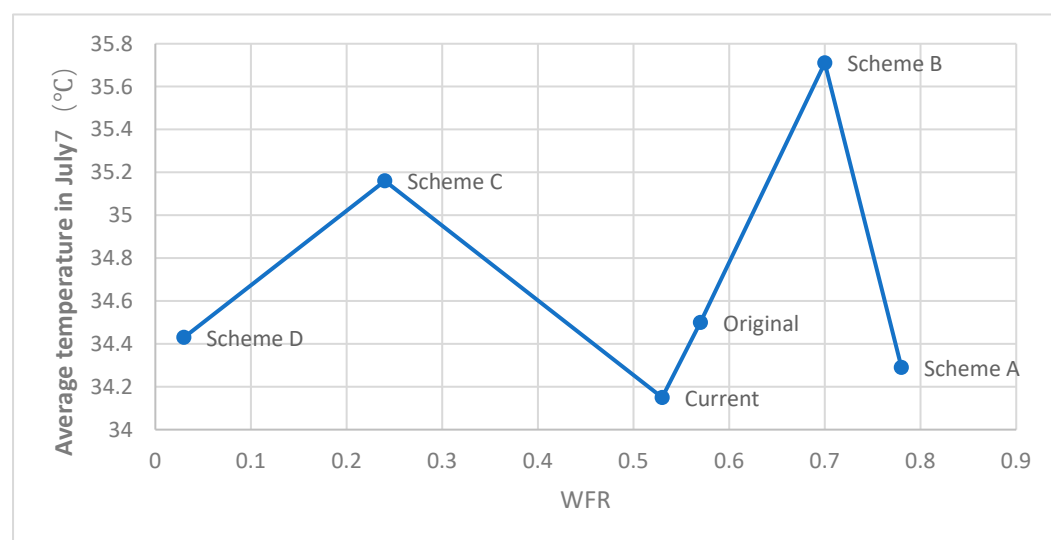
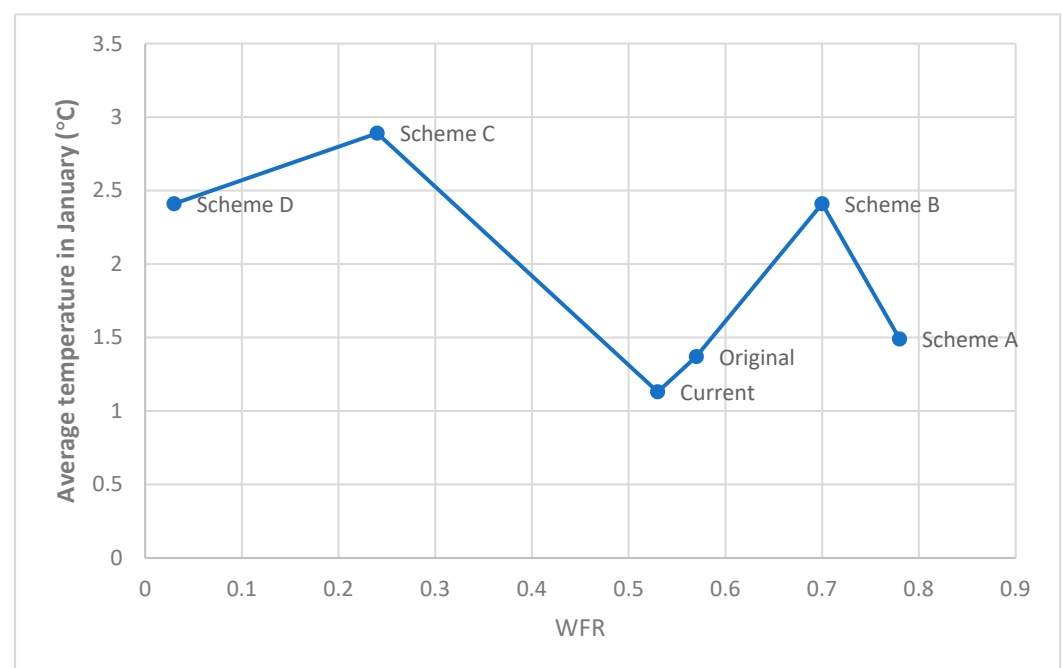


Figure 16. Relationship between window-to-floor ratio (WFR) and the indoor average temperature in July for the building.

Table 6. Average monthly indoor temperatures during the autumn semester usage period for the six schemes.

Scheme Name	Average Monthly Indoor Temperature During the Autumn Semester (°C)				
	September	October	November	December	January
Original	30.28	22.27	12.11	4.57	1.37
Current	29.92	21.96	11.87	4.36	1.13
Scheme A	30.08	22.28	12.16	4.65	1.49
Scheme B	31.66	23.48	13.09	5.44	2.41
Scheme C	31.34	23.76	13.7	6.27	2.89
Scheme D	30.65	23.15	13.28	5.92	2.41

During the autumn semester, indoor temperatures decrease continuously with falling outdoor temperatures, with the annual minimum mean value occurring in January (Figure 17). The temperature differences among schemes are relatively small; the highest January mean temperature is 2.89 °C (Scheme C), while the lowest is only 1.13 °C (current scheme), with a difference of 1.76 °C between the two. Among the six schemes, Schemes C and D, both without skylights, exhibit higher annual average room temperatures. For the four schemes with skylights, the January average temperature exhibits a trend of first increasing and then decreasing with increasing window-to-floor ratio.

**Figure 17.** Relationship between window-to-floor ratio (WFR) and the indoor average temperature in January for the building.

(2) Statistical Results of Comfortable Hours for Each Scheme

To accurately evaluate the actual impact of each scheme on users' thermal environment, this study calculates the hourly thermal comfort duration for each scenario. Referring to existing studies on sports venues, the lower limit of acceptable temperature for ball sports in cold regions is 7.5–14 °C [42], while the acceptable temperature range for occupants in hot-summer and cold-winter regions is 25–31 °C [43]. By synthesizing the findings of these two studies, this paper defines the period during which indoor temperatures fall within the range of 7.5–31 °C as the effective comfortable hours, while all other periods are classified as thermally uncomfortable.

Among all schemes in the spring semester, Scheme D achieved the highest total comfortable hours, reaching 848 h, followed by the current scheme with 845 h. Scheme A ranked third, with 4 h fewer than the current scheme. Scheme B had the lowest total comfortable hours, with 92 h fewer than the current scheme (Table 7).

Table 7. Monthly comfortable hours during the spring semester.

Scheme Name	Monthly Comfortable Hours During the Spring Semester (Hours)					
	March	April	May	June	July	Total
Original	266	266	173	72	46	823
Current	264	267	184	76	54	845
Scheme A	265	266	185	75	50	841
Scheme B	270	253	156	49	25	753
Scheme C	271	267	184	54	23	799
Scheme D	270	269	209	67	33	848

In the autumn semester, Scheme D still achieved the highest total comfortable hours, reaching 731 h, closely followed by Scheme C with only 1 h less than Scheme D. Scheme A ranked third with 701 h. Scheme B again had the lowest total comfortable hours, with 689 h (Table 8).

Table 8. Monthly comfortable hours during the autumn semester.

Scheme Name	Monthly Comfortable Hours During the Autumn Semester (Hours)					
	September	October	November	December	January	Total
Original	146	279	219	37	11	692
Current	157	279	214	36	10	696
Scheme A	155	278	218	39	11	701
Scheme B	114	272	230	56	17	689
Scheme C	117	275	240	79	19	730
Scheme D	137	279	237	64	14	731

Based on the annual statistical results of the two semesters, the cumulative thermal comfort hours of each scheme are ranked as follows: Scheme D ranks first with a total of 1579 comfortable hours; Scheme A ranks second with 1542 h, merely 1 h more than the current scheme; the current scheme ranks third with 1541 h; Scheme C ranks fourth with 1529 h, which is 12 h fewer than the current scheme.

3. Statistical Results after Changing Window-to-Floor Ratio and Window Thermal Performance

(1) Monthly Average Temperatures

After optimizing the optical and thermal performance parameters of the window glazing for the four renovation schemes, the simulated monthly average temperature results for each scheme are presented in Tables 9 and 10. For the convenience of horizontal comparison, the monthly temperature data of the original scheme and the current scheme are also included in the tables.

Table 9. Monthly indoor average temperatures during the spring semester after changing window material properties.

Scheme Name	Average Monthly Indoor Temperature During the Spring Semester (°C)				
	March	April	May	June	July
Original	14.32	23.1	28.99	33.64	34.5
Current	13.96	22.72	28.65	33.28	34.15

Scheme A	23.93	33.87	39.92	44.53	44.74
Scheme B	22.59	32.28	38.26	42.91	43.18
Scheme C	18.27	26.84	32.23	37.19	38.16
Scheme D	14.54	22.75	28.34	33.16	34.40

Table 10. Monthly indoor average temperatures during the autumn semester after changing window material properties.

Scheme Name	Average Monthly Indoor Temperature During the Autumn Semester (°C)				
	September	October	November	December	January
Original	30.28	22.27	12.11	4.57	1.37
Current	29.92	21.96	11.87	4.36	1.13
Scheme A	40.87	30.94	19.11	10.76	7.95
Scheme B	39.34	29.66	18.17	9.98	7.09
Scheme C	34.53	26.46	15.89	8.19	4.91
Scheme D	30.63	23.15	13.30	5.94	2.42

The data results indicate that optimizing the thermal performance of side window and skylight glazing can significantly increase indoor average temperatures in winter: Scheme A achieves a January average room temperature of 7.95 °C, which is approximately four times that of the current scheme (1.13 °C), with a temperature difference of 6.82 °C between the two, effectively improving the indoor thermal environment for winter activities. However, this also exacerbates indoor heat accumulation in summer. Scheme A reaches a July average temperature of 44.74 °C, which is 10.59 °C higher than the current scheme (34.15 °C), representing an increase of 31%.

(2) Statistical Results of Comfortable Hours for Each Scheme

In the spring semester, Scheme D achieved the highest cumulative comfortable hours, reaching 852 h; however, its daylighting performance failed to meet the relevant requirements of Chinese national standards. The current scheme and original scheme followed closely, with 845 h and 823 h, respectively. Scheme C ranked fourth with 620 h. Notably, during the hottest months of June and July, both Scheme A and Scheme B recorded zero thermally comfortable hours (Table 11).

Table 11. Monthly comfortable hours of each scheme during the spring semester after changing window material properties.

Scheme Name	Monthly Comfortable Hours During the Spring Semester (Hours)					
	March	April	May	June	July	Total
Original	266	266	173	72	46	823
Current	264	267	184	76	54	845
Scheme A	249	83	20	0	0	352
Scheme B	266	109	22	0	0	397
Scheme C	276	224	106	12	2	620
Scheme D	270	270	210	69	33	852

In the autumn semester, the monthly comfortable hours of the four retrofit schemes all increased significantly. Among them, Scheme C achieved the highest cumulative comfortable hours, reaching 809 h, closely followed by Scheme B and Scheme A with 805 h and 800 h, respectively. The overall performance of these three schemes was relatively close. However, examining the monthly data for the coldest winter months (December and January), Scheme A performed best, with a total of 386 comfortable hours over the two months, followed by Scheme B with 345 h, while Scheme C dropped to 227 h. During these two months, Scheme A exceeded Scheme C by 159 comfortable hours (Table 12).

Table 12. Monthly comfortable hours of each scheme during the autumn semester after changing window material properties.

Scheme Name	Monthly Comfortable Hours During the Autumn Semester (Hours)					
	September	October	November	December	January	Total
Original	146	279	219	37	11	692
Current	157	279	214	36	10	696
Scheme A	15	138	261	236	150	800
Scheme B	27	171	262	222	123	805
Scheme C	68	256	258	166	61	809
Scheme D	139	279	237	65	13	733

From the annual perspective, Scheme D achieved the highest number of thermally comfortable hours, followed by the current scheme and the original scheme. Among the remaining retrofit schemes, Scheme C had the most thermally comfortable hours, reaching 1429 h, while Scheme B and Scheme A recorded 1202 h and 1152 h, respectively. Further analysis of the specific data reveals that the primary reason for Scheme C's relatively high thermally comfortable hours is its effective reduction in indoor temperature by eliminating skylights, thereby preventing indoor overheating and the consequent loss of thermal comfort.

4. Further Optimization Simulation for Schemes A and C

Given the significant seasonal differences in natural ventilation frequency of the building, adopting a uniform annual air change rate setting does not reflect the actual physical process. In winter, due to low indoor occupancy intensity (the venue has no fixed seating, and is used by sports personnel only for the vast majority of the time), the frequency of actively opening windows is relatively low, resulting in correspondingly lower natural ventilation rates. In summer, however, to alleviate severe indoor heat accumulation, users open all operable windows and, when necessary, simultaneously open the four large door openings (5 m × 5 m) on the north and south sides to enhance cross-ventilation.

To objectively verify the improvement effects of Schemes A and C on indoor comfortable hours in the simulation, this study does not adopt a real-time dynamic ventilation strategy. Instead, a relatively conservative upper- and lower-limit assessment method is employed: the annual natural ventilation rate is set at the minimum (0.5 ACH) and maximum (5 ACH) scenarios for simulation. Comfortable hours under both scenarios are extracted on a monthly basis, and the maximum of the two is taken as the final monthly value. The resulting annual cumulative comfortable hours obtained by this method are lower than those under a real-time dynamic ventilation strategy, thus serving as the minimum achievable comfortable hours for the building under the renovation schemes.

The comfortable hours for Schemes A and C under the maximum ventilation rate scenario are presented in Table 13.

Table 13. Monthly comfortable hours for Schemes A and C after modifying ventilation rates.

Scheme Name	Annual Monthly Comfortable Hours Statistics (Hours)										
	March	April	May	June	July	September	October	November	December	January	Total
Scheme A	227	266	250	132	93	200	270	210	59	18	1725
Scheme C	205	269	279	158	142	230	276	204	43	10	1816

Comparing with Tables 11 and 12 above, it can be observed that during the 10-month usage period, months with higher comfortable hours under the maximum ventilation rate scenario include April, May, June, July, September, and October—totaling 6 months—

while for the remaining 4 months, the minimum ventilation rate scenario yields more comfortable hours.

Taking the scenario with more comfortable hours for each month and summing them month by month, Scheme A achieves 2107 comfortable hours during the 10-month usage period, while Scheme C achieves 2115 comfortable hours (Table 14). Compared to the current scheme, the two schemes increase comfortable hours by 566 h and 574 h, respectively, representing growth rates of 36.7% and 37.2%. That is, when combined with optimal natural ventilation strategies, Schemes A and C increase annual comfortable hours by at least 36.7% and 37.2%.

Table 14. Monthly optimal comfortable hours for Schemes A and C under two ventilation scenarios (hours).

Scheme Name	Monthly Optimal Comfortable Hours Statistics (Hours)										
	March	April	May	June	July	September	October	November	December	January	Total
Scheme A	249	266	250	132	93	200	270	261	236	150	2107
Scheme C	276	269	279	158	142	230	276	258	166	61	2115

3.3. Comparison and Selection of Optimal Schemes

Based on a comprehensive analysis of the daylighting environment and annual thermal comfort performance, the following conclusions can be drawn: If the design objective focuses solely on improving indoor thermal comfort during cold seasons, Scheme A is the optimal choice. By incorporating large-area high-performance side windows, retaining complete skylights, and optimizing the thermal performance of the skylights, this scheme maximizes the utilization of solar radiation heat gain in winter, significantly raising the indoor air temperature during cold seasons and substantially increasing the comfortable hours in autumn and winter. Meanwhile, Scheme A exhibits the best natural daylighting performance among all retrofit schemes, with an average daylight factor of 10.71%, an average illuminance of 820.14 lx, and the best illuminance uniformity. It can thoroughly resolve the issues of insufficient natural lighting and uneven illumination in the venue, with daylighting quality significantly superior to that of the original scheme and other comparison schemes. However, this scheme has an evident drawback: the large glazing area results in excessive solar heat gain in summer, leading to prominent indoor overheating issues, with comfortable conditions essentially lost during hot summer periods. If the building is to be used normally in summer, enhanced ventilation and heat dissipation are required to improve indoor comfort during this season.

If the building is intended for year-round normal operation, with consideration for both winter and summer thermal comfort and a balance between daylighting and energy performance, Scheme C offers more prominent comprehensive advantages. In terms of daylighting, Scheme C eliminates skylights and retains only large-area side windows. Although the daylight factor and average illuminance are significantly lower than those of Scheme A, the scheme still maintains a basic level of natural daylighting, offering clear advantages over the windowless Scheme D and the current benchmark scheme, and is capable of meeting the fundamental natural lighting requirements of the venue. In terms of thermal environment, Scheme C effectively avoids the severe summer overheating defects of Schemes A and B, while retaining the winter solar heat gain advantages of side windows, effectively improving the cold and gloomy indoor conditions in winter. The annual comfortable hours remain at a relatively high level, and the heating and cooling loads are more balanced across all operating conditions. Overall, Scheme C sacrifices some of the extreme daylighting performance in exchange for a well-balanced winter–summer thermal comfort, resulting in a more balanced and reliable overall retrofit performance.

4. Discussion

4.1. Daylighting Performance

(1) There is a significant correlation between the window-to-floor ratio (WFR) and both the daylight factor and illuminance uniformity. In general, the larger the WFR, the higher the daylight factor and average illuminance (Figure 18). Among all schemes, Scheme A has the highest WFR of 0.78, and accordingly achieves the highest daylight factor (10.71%) and average illuminance (820.14 lx). In contrast, Scheme D has the lowest WFR of 0.03, and correspondingly yields the lowest daylight factor (0.18%) and average illuminance (90.20 lx). It should be noted that in the calculation of WFR, the contribution of skylight area is significantly greater than that of side windows. Excluding Schemes C and D, the daylight factors of the remaining schemes exhibit an approximately linear relationship with WFR overall; however, once the WFR exceeds 0.7, the increasing trend of daylight factor with WFR markedly slows down. This finding does not contradict the conclusion of Krarti et al. [17] who pointed out that further increasing the WFR beyond 0.5 no longer yields significant lighting energy savings. Their conclusion was based on the premise that indoor illuminance is maintained above a certain level, under which condition the artificial lighting system would automatically switch off; therefore, further increasing the WFR would not result in additional lighting energy savings.

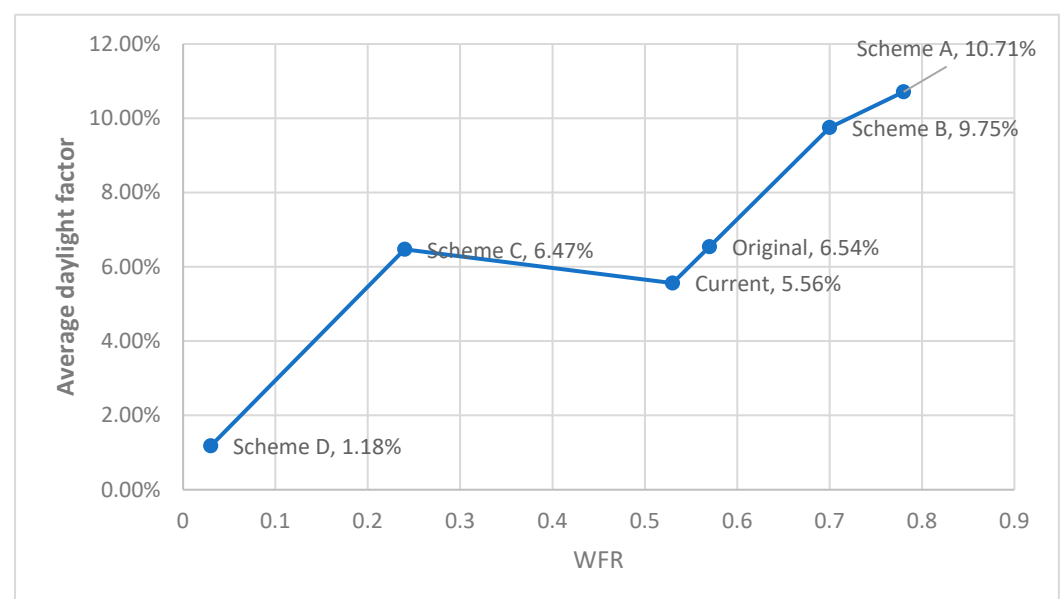


Figure 18. Relationship between window-to-floor ratio (WFR) and daylight factor.

(2) Relationship between illuminance uniformity U1 and U2. By analyzing the illuminance uniformity U1 and U2 values from the six simulation schemes and the field measurements, it was found that there is no obvious linear relationship between U1 and U2. Scheme D has a relatively good U1 value (0.35) but a poor U2 value (0.05). This indicates the presence of locally over-bright areas, which is related to the fact that after removing the skylights, relying solely on low side windows for daylighting creates areas with excessive local brightness. Considering its low average illuminance (90.2 lx), this suggests that the relatively good U1 value of Scheme D represents a case of “uniformity under low illuminance” that does not meet daylighting requirements. Meanwhile, Scheme C also has low values for both U1 (0.08) and U2 (0.04). These findings illustrate that the two different illuminance uniformity calculation methods can yield significantly different results and must be used together to comprehensively evaluate indoor daylighting quality. This result is consistent with the recommendation of the CIBSE Guide [44], which suggests that the

two metrics, U1 and U2, should be used in combination: U1 focuses on overall consistency, while U2 helps prevent excessively dark areas.

(3) Characteristics of illuminance uniformity in schemes without skylights. After removing the skylights, Schemes C and D exhibit, respectively, the minimum and maximum U1 values among the six schemes. Although Scheme C does not have skylights, its use of large-area high side windows still achieves a relatively good daylight factor (6.47%). Scheme D, whose WFR and daylight factor fail to meet relevant Chinese codes [16], paradoxically has the highest U1 value among the six schemes. This may be because the overall low indoor illuminance level makes the indoor uniformity appear relatively higher. The fact that Scheme C has the lowest U1 value demonstrates that skylights contribute more to indoor illuminance uniformity than side windows.

(4) Daylighting characteristics of schemes with skylights. Even with zero side window area (the current scheme), the scheme with skylights achieves a daylight factor of 5.56% and an illuminance of 425 lx, which can basically meet usage requirements. The U1 values for schemes with skylights range from 0.13 to 0.26. The schemes combining both skylights and side windows have U1 values of 0.24, 0.24, and 0.26, respectively. Considering the measured U1 value (0.40), this indicates that the combination of skylights and side windows can provide the best illuminance uniformity. This conclusion is consistent with the findings of Lee et al. [45] and Ali et al. [46], both of which reported that hybrid types (skylights + side windows) achieve significantly better daylighting performance compared to using only skylights or only side windows.

(5) LUO et al. [47] indicated that 1000 lx serves as a critical threshold for the shift in the primary cause of glare: below this value, glare is mainly attributed to luminance contrast, while above it, glare is predominantly caused by absolute luminance levels. Song et al. [48] further demonstrated that glare risk increases significantly when horizontal illuminance exceeds 1500 lx or vertical illuminance exceeds 2000 lx. In addition, Elsiana et al. found that a high daylight factor is directly associated with high glare risk, and that side-window-only schemes tend to result in elevated DGP values due to excessively high DF.

Among the six schemes in this study, Schemes C and D adopt side-window daylighting. Scheme C has a moderate daylight factor of 6.47%, but its maximum indoor illuminance reaches 1040 lx, indicating a certain degree of glare risk. Scheme A has the highest daylight factor, with a maximum indoor illuminance of 1410 lx, posing an even greater glare risk. However, since direct sunlight primarily occurs in the afternoon (with fewer occupants in the morning and a high solar altitude angle at noon), and because a five-story teaching building is located 50 m to the west of the sports hall with numerous tall trees in between providing substantial shading, the actual glare impact caused by direct sunlight entering the interior is relatively low.

4.2. Thermal Performance

4.2.1. Case of Varying Window-to-Floor Ratio Only

(1) Analysis of summer temperature variation. The highest summer temperature occurred in Scheme B (35.71 °C), which has skylights, rather than in the skylight-less Scheme C (35.16 °C) or Scheme A (34.29 °C). This indicates that reducing the west-facing window-to-wall ratio (WWR) paradoxically led to an increase in the average indoor temperature. A possible reason is that the thermal transmittance (U-value) of the wall (2.42 W/(m²·°C)) is lower than that of the window (5.11 W/(m²·°C)). Under natural conditions, Scheme B has lower heat retention and heat dissipation capacity in summer evenings, resulting in higher indoor temperatures. This also demonstrates that a west-facing WWR of zero does not guarantee a cooler summer. This finding is consistent with the conclusions of Bagheri et al. [28], who found an optimal west-facing WWR of 58% for residential buildings in a humid temperate climate, and Tawfeeq et al. [49], who found an optimal west-facing

WWR of 30% for a low-rise residential building in a hot summer Mediterranean climate. A lower west-facing WWR is not necessarily more beneficial for energy efficiency.

(2) Analysis of winter temperature variation. The average indoor temperatures in January for the skylight-less schemes (Scheme C and Scheme D) were higher than those for the other four schemes with skylights. Among the four schemes with skylights, the average indoor temperature initially increased with increasing window-to-floor ratio (WFR), but when the WFR exceeded a certain value (0.7), the average indoor temperature began to decrease. This indicates that for this model, when the WFR exceeds 0.7, the total heat gain of the envelope is less than the total heat loss, resulting in a decrease in the average indoor temperature.

(3) The fully enclosed facade scheme (current) exhibits a large winter–summer temperature difference (33.02 °C), while the large side window scheme (Scheme C) has a smaller winter–summer temperature difference (32.27 °C). The latter is closer to a passive tendency of “warm in winter and also warm in summer.” The winter–summer temperature differences of the skylight-less schemes (Schemes C and D) are smaller than those of the schemes with skylights, indicating that skylights, due to their higher thermal transmittance, tend to cause excessively high temperatures in summer and excessively low temperatures in winter. This finding is consistent with the conclusions of Psomas et al. [50], whose field study of a two-story residential building demonstrated the decisive impact of skylight control on the indoor thermal environment. That study pointed out that manually controlled passive cooling systems cannot guarantee a high-quality indoor environment, that user behavior is a key factor for successful operation, and that automated skylight control systems can significantly reduce the risk of overheating.

4.2.2. Case of Varying Window-to-Floor Ratio and Window Material Properties

(1) From the perspective of indoor temperature distribution, the six schemes exhibit distinctly different thermal characteristics in spring and autumn. In the spring semester, the indoor monthly mean temperatures of Scheme A and Scheme B are significantly higher, reaching 39.92 °C and 38.26 °C in May, respectively, and exceeding 40 °C in June and July, far beyond the human thermal comfort range. This directly results in nearly zero comfortable hours for these two schemes after May. In contrast, the temperatures of Scheme C fall between the original/current schemes and Schemes A/B, with monthly mean temperatures approximately 5–7 °C lower than those of Scheme A in spring, and its corresponding comfortable hours are also significantly higher, totaling 620 h for the spring semester.

(2) A similar pattern is observed in the autumn semester. The indoor temperatures of Scheme A and Scheme B remain as high as approximately 40 °C in September and only drop to around 19 °C in November, further decreasing to 7–10 °C in December and January. This indicates that although these two schemes delay the indoor cooling process through thermal storage effects, resulting in significantly higher winter comfortable hours (150–222 h) than other schemes, the excessively high temperatures during the transitional seasons (September–October) severely constrain their overall thermal comfort performance. Scheme C demonstrates better balance in autumn, with moderate monthly temperatures of 34.53 °C in September and 26.46 °C in October, followed by a gradual decline after November. Its total annual comfortable hours reach 809 h in autumn and 620 h in spring, showing strong seasonal adaptability.

(3) In terms of total annual comfortable hours, Scheme D ranks first with 1585 h, followed by Scheme C with approximately 1429 h. Scheme C’s autumn performance is particularly outstanding, with comfortable hours increasing month by month from September to November, and still reaching 166 h in December, demonstrating favorable thermal inertia advantages. It is worth noting that although Scheme A and Scheme B have ex-

tremely low comfortable hours in spring (352 h and 397 h, respectively), their autumn performance rebounds significantly, with Scheme A reaching 800 h and Scheme B reaching 805 h in autumn. This indicates that these two schemes exhibit a clear seasonal shift—comfortable periods are transferred from summer to winter.

(4) According to the Code for Thermal Design of Civil Buildings (GB 50176-2016) [51], the climatic design of buildings in this region must prioritize winter insulation while also addressing summer heat protection. Based on this requirement, the present study adjusts the relevant window parameters of the building under non-air-conditioned conditions. The simulation results indicate that Scheme A increases indoor comfortable hours during the winter period (November to January) from 260 h (benchmark scheme) to 647 h, representing an increase of 387 h and a growth rate of 149%, significantly improving the thermal environment for sports activities during cold seasons. However, during the remaining seven months (spring, summer, and autumn), comfortable hours drop sharply from 1281 h to 505 h, a decrease of 776 h and a reduction of 60%. It is thus evident that the passive warming strategy of merely enlarging the window-to-floor ratio and optimizing glass solar heat gain performance suffers from a significant seasonal imbalance—while it effectively addresses low winter temperatures, it exacerbates indoor thermal conditions during spring, summer, and autumn by enhancing excessive solar radiation heat gain, resulting in a substantial reduction in annual comprehensive thermal comfort hours.

4.2.3. Performance After Increasing Ventilation Frequency

After increasing the air change rate to 5 ACH, the monthly comfortable hours of Schemes A and C increased by 11.9% and 17.8%, respectively, compared to the current scheme. Furthermore, based on the upper- and lower-limit assessment method, the cumulative annual comfortable hours of the two schemes increased by 36.7% and 37.2%, respectively. The analysis also reveals that during the building's 10-month annual usage period, six months exhibit optimal comfortable hours under the high-ventilation scenario (5 ACH), with these six months concentrated in the warm seasons from late spring to early autumn.

The above results clearly demonstrate that in this type of sports building, the cooling benefits of natural ventilation are not uniformly distributed throughout the year, but are highly concentrated in periods with strong solar radiation and significant indoor heat accumulation. The annual cumulative contribution can exceed 30%, substantially surpassing the marginal improvements achieved solely through optimizing envelope thermal performance. This indicates that enhancing envelope insulation performance exhibits notable diminishing returns in this climate zone and large-space buildings, while adequate ventilation remains the critical passive measure for mitigating overheating risks during warm seasons.

Based on these findings, it is recommended that in the design of large-space sports buildings in similar climate zones, a passive design principle of “ventilation-oriented, insulation as the baseline” should be established. In standard formulation and design decision-making, natural ventilation potential—such as operable window area, cross-ventilation pathways, and stack-effect exhaust conditions—should be prioritized over the sole pursuit of improving envelope thermal parameters

4.3. Limitations and Future Work

(1) The conclusions of this study are primarily based on the comparative simulation analysis of six schemes. The coverage of samples and conditions is relatively limited, and the empirical observational data for daylighting and temperature are insufficient in volume, with a relatively short measurement period. This methodologically constrains the accuracy of model validation. Therefore, the findings of this study are only applicable to the building model and simulation conditions of this specific sports hall. The generaliza-

bility of the relevant patterns and optimization strategies is subject to certain limitations and does not currently meet the conditions for widespread application.

(2) In the analysis of the luminous environment for each scheme, this study did not provide a more systematic and comprehensive assessment of visual comfort performance under natural daylighting, nor did it include a quantitative evaluation of the risk of glare occurrence for each scheme. This constitutes a deficiency in the evaluation framework for comparing the luminous environmental quality among the schemes.

(3) This study establishes only four practically feasible renovation schemes, conducting a comparative analysis of the changes in daylighting and thermal environments across schemes while examining the underlying causal mechanisms. However, it does not delve into the coupled effects of envelope parameters—such as visible transmittance of glazing and the heat transfer coefficient of walls—with skylight and side window areas on the annual daylighting-thermal response mechanisms. This aspect can serve as a key direction for future in-depth research.

(4) This study focused only on the simulation and measurement of indoor daylighting quality and temperature conditions. It did not incorporate survey analyses of user satisfaction regarding indoor daylighting quality and thermal environment. This is another direction for further research optimization.

4.4. Innovation Points

This study takes a sports hall without air conditioning and heating systems as a case study to explore how passive measures can improve indoor daylighting and thermal environmental quality in this building type. This research fills several important gaps in the existing literature regarding natural daylighting and passive energy strategies for sports hall buildings.

First, this study addresses the research gap concerning “sports halls” as a specific building subtype. Most existing studies on passive design for sports buildings focus on large-scale venues that meet competition standards, while research on smaller, more frequently used sports halls with prominent shelter functions remains extremely scarce. By taking the non-air-conditioned, non-heated “sports hall” as an independent research object, this study directly confronts the core contradiction of “coexisting summer overheating and winter overcooling” without active regulation equipment, forming a sharp contrast with the existing literature.

Second, this study responds to and supplements the methodological gap regarding the neglect of the unique spatial characteristics of sports buildings. The existing literature indicates a lack of detailed exploration into how passive design strategies can be matched with the “unique spatial attributes” of sports buildings. By focusing on the building’s self-regulating capacity under “non-air-conditioned” conditions, the quantitative analysis results of this study more directly serve this specific spatial type, providing scarce field measurement or simulation validation data for the synergistic optimization of wind, daylighting, and thermal environments.

Third, this study points out that current building energy efficiency design standards are primarily oriented toward buildings equipped with heating and cooling systems, with their evaluation systems centered on envelope thermal performance and only providing general principles for natural ventilation. However, for non-air-conditioned large-space sports buildings, natural ventilation serves as the key passive means of regulating indoor thermal environments during warm seasons. To this end, this study proposes that natural ventilation capacity should be incorporated as a mandatory evaluation parameter, given equal weight alongside envelope thermal performance, to remedy the structural deficiency in current codes where the contribution of ventilation cooling in this building type is systematically underestimated.

5. Conclusions

This study takes a wind and rain sports hall as the research object, establishes six natural daylighting retrofit schemes with different combinations of side windows and skylights, and systematically investigates the influence patterns of different window opening forms, window-to-floor ratios (WFR), and skylight configurations on indoor daylighting performance and indoor temperature variation through a combination of natural daylighting simulations, on-site measurements, and annual thermal simulations. The passive daylighting and thermal environment optimization strategies suitable for this type of wind and rain sports hall are clarified. The main research conclusions are as follows:

In terms of indoor daylighting environment:

(1) When skylights and side windows are combined, the average daylight factor and average illuminance increase with the rise in the window-to-floor ratio (WFR) when WFR is below 0.7, and a significant linear relationship exists between them. When WFR reaches or exceeds 0.7, the increase in the average daylight factor and average illuminance decreases with further enlargement of WFR.

(2) There is no obvious linear correlation between the two calculation methods for illuminance uniformity: minimum illuminance/average illuminance (U1) and minimum illuminance/maximum illuminance (U2). Both indicators need to be used in combination to comprehensively evaluate indoor daylighting quality.

(3) Skylights contribute more to illuminance uniformity than side windows. The combined window opening form of skylights and side windows can effectively improve indoor illuminance uniformity, achieving higher quality than using only skylights or only side windows.

In terms of indoor thermal environment:

(1) For large-space buildings that rely on passive solar heat gain, when the window-to-floor ratio (WFR) is below 0.7, indoor temperature increases with the rise in WFR; when WFR exceeds 0.7, heat dissipation through the building envelope surpasses heat gain, resulting in a decrease in indoor temperature with further increase in WFR.

(2) For each scheme under the condition of varying the window-to-floor ratio only, the overall variation in annual indoor temperature differences among the schemes is relatively small. For large-space buildings such as wind and rain sports halls, the effect of passively improving winter indoor temperature solely by increasing the WFR and window-to-wall ratio (WWR) to enhance visible light transmittance is not significant.

(3) The effects of window-to-floor ratio and window material properties on the indoor thermal environment exhibit three major characteristics: nonlinearity, coupling effects, and seasonal shift. Under the condition of simultaneously varying the window-to-floor ratio and window material properties, Scheme C emerges as the optimal alternative for achieving balanced year-round thermal comfort, while Scheme A is the preferred option for winter insulation-oriented design, albeit at the cost of summer overheating, which necessitates the implementation of appropriate auxiliary cooling measures.

(4) In the design of large-space sports buildings in cold regions, the passive design principle of “ventilation-oriented, insulation as the baseline” should be established, and natural ventilation potential should be prioritized in standard formulation and design decision-making.

This study is based on a comparative simulation of six operating conditions. Due to the limited volume of measured data and the relatively short measurement period, the accuracy of model validation is subject to certain limitations. Consequently, the findings are only applicable to the building model and simulation conditions of this specific case and are not yet suitable for widespread generalization. In addition, this study does not include a quantitative assessment of glare risk, nor does it deeply explore the quantitative relationships between key parameters—such as glass transmittance and the wall heat

transfer coefficient—and the indoor luminous and thermal environments. Furthermore, it lacks survey-based support regarding occupant satisfaction with the indoor environmental quality. These identified gaps represent key directions for future research optimization.

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