

Article

Green Building Performance Analysis and Energy-Saving Design Strategies in Dalian, China

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Abstract: In the face of global climate change, there is a pressing and significant need to find low-carbon solutions for China's construction industry. This research focuses on green public buildings in Dalian, a municipality situated in northern China. We investigated energy-saving design applications based on actual measured data. The results show that the common design aspects in the eco-friendly design of green public buildings encompass the conservation of building-derived energy, water use in buildings, and indoor environmental quality technologies. Optimized design strategies were proposed, focusing on three design elements—building orientation, greening, and shading—that are less considered in the case of buildings. It was found that the optimal orientation of the building is 35° southwest, and two vertical greening methods and three shading design methods were proposed. In addition, the incremental costs of green public buildings with different energy-saving technologies were discussed. This study aims to provide operational performance and feasible emission-reduction strategies for the construction industry in China and worldwide to meet the challenges under the dual carbon target.

Keywords: green public building; sustainable design; energy-saving technologies; incremental cost; optimized design strategies



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1. Introduction

Since the energy crises of the 1970s, the world has grappled with the consequences [1]. Approximately 40% of global energy consumption is attributed to the building industry [2]. In addition, the area of public buildings in China has tripled in the past two decades [3]. The proportion of energy consumption by the construction industry has increased from 36% in 2005 to the current 46% [4]. The proportion of operational energy consumption and carbon emissions in the industry represents 21%, experiencing a growth rate persistently above 9% per year for nearly 20 years and exceeding the growth rate of building areas [5].

On the other hand, the construction industry's high-energy-consumption characteristic significantly impacts climate change. According to the International Energy Agency (IEA), the construction industry generates nearly 40% of global carbon dioxide and 25% of gas emissions [2]. Since pre-industrial times, the global average temperature has risen by 1.1 °C [6]. The latest Intergovernmental Panel on Climate Change (IPCC) report indicates that the leading way to stabilize global surface temperature is to achieve zero carbon dioxide emissions [7]. As of April 2021, 33 countries or regions worldwide have implemented policies to curb the growth of carbon emissions [8]. Therefore, the international community must continue controlling high-emission sectors, especially the construction industry [9].

In recent years, China has taken proactive measures to achieve low-carbon and energy-saving goals in construction. The Government Work Report in 2018 clearly stated a goal of achieving a decrease of more than 3% in energy consumption per unit of GDP and adhering to green development [10]. The 14th Five-Year Plan in 2021 made “reducing energy consumption per unit of GDP by 13.5%” one of the major binding indicators for economic and social development while encouraging public data mining to enhance the service role of big data in various industries [11]. In summary, whether the construction industry can effectively solve the problem of high energy consumption directly relates to whether China can achieve a low-carbon transformation of its industrial structure. Actual operational performance data can directly and effectively improve a building’s holistic design and provide users with healthy, comfortable, and sustainable spaces [12]. However, large-scale data collection on building energy consumption in China faces difficulties. The actual energy consumption level of buildings needs more scientific evaluation methods, and the pursuit of design practices that result in high energy consumption, such as large glass curtain walls and central air-conditioning [13], poses a significant challenge for China regarding reducing carbon emissions in buildings.

This paper selects typical green public buildings in Dalian, a city in northern China, for a detailed analysis to understand the implementation and application of energy-efficient design in sustainable public buildings. The original contribution of this research is to summarize, based on measured data, the patterns and features of the economic benefits of energy-saving design and green technologies in public buildings in Dalian and propose energy-saving design optimization strategies suitable for the region. This research can provide a specific data foundation for studying energy-saving design in Dalian buildings to assist government departments in formulating targeted energy-saving policies.

2. Literature Review

With the rising problem of high energy consumption in the construction industry, scholars have begun to seek energy-saving design methods based on the factors that affect building energy consumption. This paper presents a literature review based on the following aspects: (1) passive building energy-saving design, (2) factors affecting building energy consumption, and (3) energy consumption statistics and analysis.

2.1. Passive Building Energy-Saving Design

Passive design is essential for reducing building greenhouse gas emissions [14]. Wang et al. [15] determined the best building orientation for a specific office building in Jilin City to be 3° southwest by referencing the energy-saving design standards of Jilin Province, combined with the Design-Builder v2.4.2.026 simulation software. In the Netherlands, van Hoof et al. [16,17] studied six passive design measures for Dutch row houses, concluding that external shading and natural ventilation strategies are the most effective methods to improve building performance. Kim D et al. [18] analyzed the impact of double-curtain walls with internal and external louvers on the indoor thermal environment and lighting. They found that these can reduce building air-conditioning and lighting energy consumption by 27–52%. Zheng X et al. [19] concluded from 89 related studies in 23 countries and regions worldwide that green roofs bring about an average energy-saving effect of approximately 30% in building cooling and an average cooling effect on the microclimate of about 2.9 °C. Nik et al. [20] evaluated the energy-saving potential of nine retrofitting measures for residential buildings in Sweden, and they found that the most effective measures were highly insulated building walls combined with windows. Zhang Y et al. [21] showed that using 200 mm thick B05 aerated concrete blocks and toughened vacuum glass windows with a 0.73 W/(m²·K) heat transfer coefficient for the external walls can achieve a 75% building energy-saving effect.

2.2. Factors Affecting Building Energy Consumption

Building energy consumption is not only intricately related to implementing green technology but is also influenced by factors such as climate, envelope structure, building equipment, and user behavior [22]. Su Y et al. [23] analyzed the energy consumption of green commercial buildings in cold coastal areas. They found that indoor illumination in different seasons was highly correlated with CO₂ on typical days. Research has been undertaken to rank the effect of passive factors on energy consumption, with climate factors reported as having the most significant impact [24]. Feng W et al. [25] scrutinized the relationship between the energy consumption of building air-conditioning systems and historical weather data in Shanghai, demonstrating that exterior temperature holds considerable influence. Passive factors also include the impact of the pandemic on building energy consumption, with restrictions on social distancing leading to a significant reduction in utilization and energy consumption in commercial buildings during COVID-19 [26].

A plethora of studies underlines the importance of elevating user awareness of energy saving as well as the transformation of energy-saving behaviors in a bid to lessen building energy consumption. Research shows that office equipment can change their energy use time through user behavior [27]. In office buildings, the power consumed by lighting can be accountable for a staggering 45% of total energy consumption. However, the deployment of a lighting control strategy reflecting user behaviors can result in a reduction of up to 60% in energy consumption [28]. Similarly, research suggests that opening windows in automated buildings has no significant repercussions on building energy consumption [29]. Therefore, it is apparent that the potential for energy saving can be identified by thoroughly exploring high-correlation factors through energy consumption impact factor analysis.

2.3. Energy Consumption Statistics and Analysis

The US Energy Information Administration has conducted an energy consumption survey for commercial and residential buildings, showing that the food-sales-type buildings in the US have the highest energy consumption at 102.8 kWh/ft² [30]. Yan R et al. studied the decarbonization patterns of residential buildings in China and India. They found that space heating has the most significant positive contribution to China's carbon intensity change [31]. Besides the macro-statistics at the national level, scholars also pay attention to the law of building energy consumption locally and explore ways to save energy. The energy bills of 119 public buildings in northern China were collected by Ma H et al. [32]. Their research found that hospital buildings consume more than office and school buildings. The Jiangsu Provincial Government [33] analyzed the current situation of energy utilization in various public buildings in the province. It was found that total energy consumption from lighting outlets and air-conditioning systems can account for 70–80% of total energy consumption in public buildings. The Shanghai Institute of Architectural Science [34] and others have recorded the electricity usage of major building types in the city during different seasons and found that office buildings, mall buildings, integrated buildings, and tourist hotels account for 86.0% of the total electricity consumption. In 2021, the China Academy of Building Science [35] investigated the annual energy usage characteristics and indoor environment of a near-zero-energy CABR structure located in a cold region. The study concluded that heating, ventilation, and air-conditioning (HVAC) systems most significantly affected a building's energy use.

The above literature shows the need to further improve buildings' energy efficiency and sustainability. It is necessary to strengthen the study of regional energy consumption patterns in China and explore the energy-saving potential of specific buildings by analyzing actual data based on different geographical areas. To fill the above gaps, this study conducted an in-depth analysis of typical green public building cases in Dalian, a city in northern China, from the aspects of energy-saving design methods, indoor thermal environment and incremental cost, and proposed passive design strategies to provide a basis for the optimization of public information disclosure system.

3. Research Object and Research Method

3.1. Meteorological Overview of Dalian City

According to China's Building Climate Zone Classification Standards, Dalian is a cold area. Dalian is in the southernmost part of China's Liaodong Peninsula, in the warm temperate zone of the Northern Hemisphere, surrounded by the sea on three sides—east, west, and south—and the sea breeze dramatically affects the climate. The average annual temperature in Dalian is about 10.5 °C, with the highest temperature from July to September at an average of 26 °C. The lowest temperatures occur in January, February, and December, with an average temperature of about −4 °C. The maximum temperature of the year is below 0 °C for about 35 days. The annual total precipitation is approximately 650 mm, with around ten days experiencing precipitation exceeding 25.4 mm.

3.2. Overview of Green Buildings in Dalian

The China Green Building Evaluation Standard categorizes green buildings into different levels based on the total scores. A one-star building requires an awarded score of 60, a two-star building requires an awarded score of 70, and a three-star building requires an awarded score of 85 [36]. Between 2011 and 2015, the number of green buildings in Dalian increased by 800%. Among them, public buildings accounted for 61%, with a total construction area of 920,800 square meters. In terms of star rating, there are seven one-star green buildings with an area of 583,400 square meters, five two-star green buildings with an area of 696,200 square meters, and six three-star green buildings with a total area of 460,500 square meters [37]. Green buildings in Dalian have developed rapidly in recent years. According to the latest report [38] released by the Dalian Housing and Urban-Rural Development Bureau, in 2022, 23.0063 million square meters of green buildings were constructed in Dalian, an increase of 4.989 million square meters over the 2020 data. Among them, green building identification projects account for 6,046,800 square meters. All new urban and rural residential buildings in the city are being constructed following green building standards.

3.3. Research Object

This study primarily focuses on green public buildings in Dalian for research. Through field investigations, alongside the measurement and collection of data, the study meticulously examines the energy-saving design practices and fundamental characteristics of these green public buildings. Table 1 summarizes the basic information about green public buildings. Among them are five three-star projects and three buildings each with two-star and one-star ratings. The case buildings are mainly high rises, some of which have reached the super-high-rise level. More than 80% of the project's total construction area exceeds 20,000 square meters, and nine buildings have adopted central air conditioning, defined as large public buildings. This type of building in China accounts for about 6% of the total area of public buildings, but its energy consumption accounts for about 22% of the total social energy consumption [39]. The characteristics such as high energy consumption, and operational management challenges indicate that large public buildings have great energy-saving potential.

3.4. Research Method

Based on the survey and measured data, the paper analyzes the energy-saving design application, indoor environmental quality, incremental cost, and building energy consumption of the case buildings. The investigation of the application of energy-saving design is based on the China Green Building Evaluation Standard adopted when a case building applies for the green building design mark. The energy consumption data in the case building are sourced from the SmartPiEMS platform, a monitoring system that tracks a building's energy usage hourly, enabling precise quantification and analysis of the data [40]. Indoor and outdoor environmental parameters are derived from on-site monitoring and online data collection, covering the typical months of the 2019–2020 summer. According

to the building space type, number of floors, personnel ratio, and other factors, 17 test instruments are set up.

Table 1. Summary of basic information research on green public buildings.

Stars of the Building	Location of the Surveyed Building	Building Projects	Completion Date	Building Height (m)	Number of Floors	Green Area Ratio (%)	Total Floor Area (10 ksqm ²)
Three-star building		P1	2010	59	7	30%	14.68
		P2	2015	63	15	38%	13.09
		P3	2016	121.1	27	23.55%	7.61
		P4	2015	69.5	17	25%	6.37
		P5	2013	16.8	4	26%	0.15
Two-star building		P6	2016	24	5	10.1%	8.73

Table 1. Cont.

Stars of the Building	Location of the Surveyed Building	Building Projects	Completion Date	Building Height (m)	Number of Floors	Green Area Ratio (%)	Total Floor Area (10 ksqm ²)
Two-star building		P7	2013	31.3	6	1.47%	16.74
		P8	2013	18.6	4	35%	1.22
One-star building		P9	2017	24	5	10%	8.79
		P10	2012	31.3	3	30%	2.94
		P11	2015	30.7	4	10%	3

4. Energy-Saving Design Analysis

The classification of energy-saving design in this section refers to the Green Building Evaluation Standard GBT50378-2006 [41], which is the basis for the case buildings to apply for the green label. This section covers five categories: land space and outdoor environment, energy-saving design, material-saving design, water-saving design, and indoor environmental quality.

4.1. Land Space and Outdoor Environment

Figure 1 shows the design statistics of the case buildings' land space and outdoor environment. In terms of maintaining the surrounding environment, all case buildings were built on empty sites and did not affect the local natural environment. These terms also include architectural glass curtain wall design and material selection, where the visible light reflectance ratio of the curtain wall is not greater than 0.3, and attention is paid to the division of windows and the restricted use of glass area. Tempered hollow low-E glass

is the curtain wall material used in most projects, and most projects choose the model of 6 mm + 12 A + 6 mm, which meets the requirements of the Green Building Evaluation Standard. When selecting a site, all case buildings were selected to be surrounded by roads, public buildings, and green landscapes far away from residential buildings and do not affect the sunlight needs of surrounding residential buildings. All case buildings have considered the convenience of the site and surrounding transportation, and the walking distance from the main entrance of the building to the nearest public stop is no more than 500 m. Therefore, in terms of maintaining the surrounding environment, light pollution, surrounding sunlight needs, and environmental noise reduction, the compliance rate is 100%.

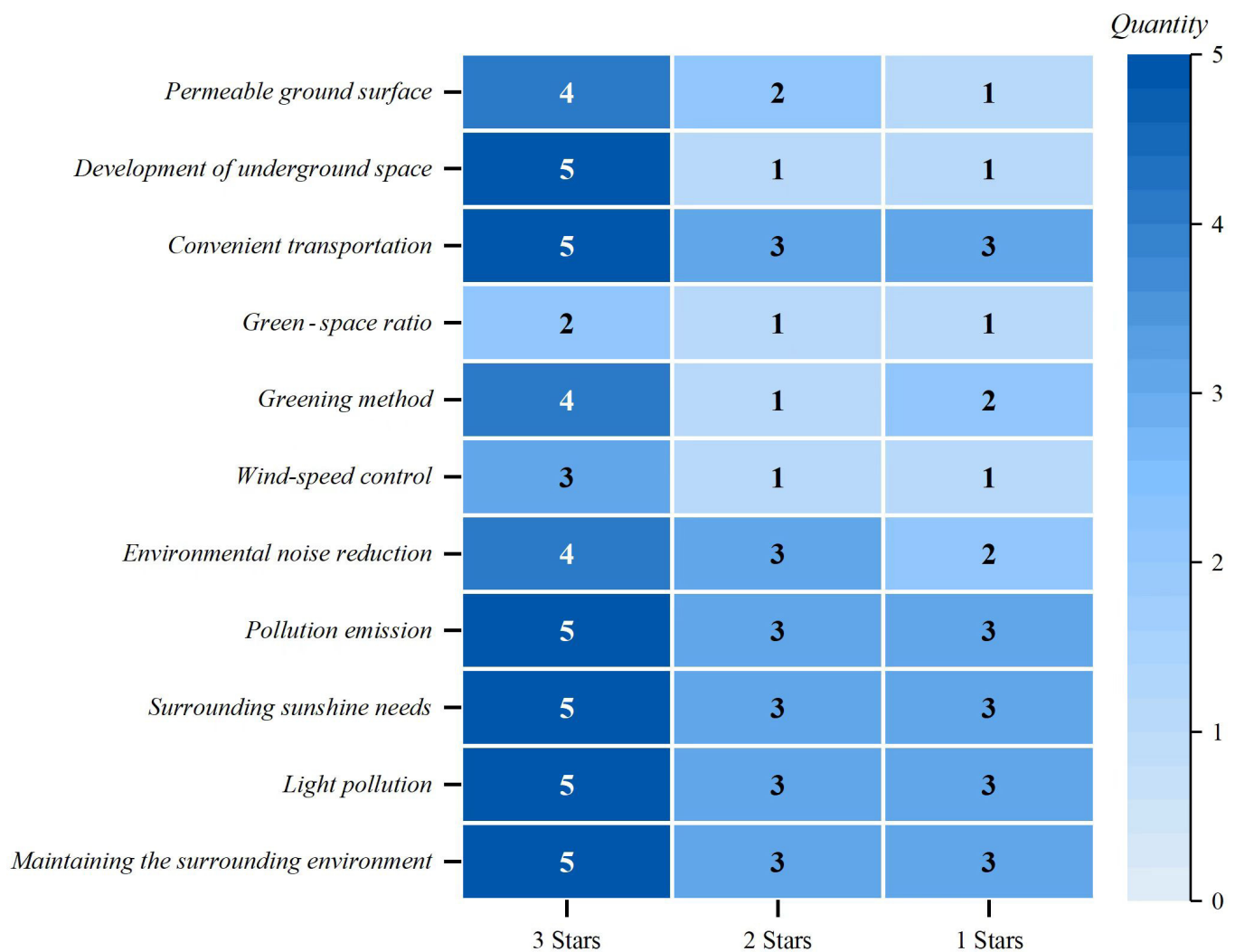


Figure 1. Land space and outdoor environment.

Only five buildings met the peripheral wind-speed control item standard, with a compliance rate of 45%. The reason is related to Dalian's particular geographical location and the projects' generally low green-space rate. The wind rose diagram for Dalian is shown in Figure 2. The Dalian area is in the continental climate area of the Northern Hemisphere, the annual variation of monsoon is evident, and the wind speed is high [42], with the annual occurrence of 90–140 days of level 6 or higher wind speeds. There is quite a bit of time throughout the year when the wind speed is above 5 m/s, which impacts the comfort of pedestrians outdoors. At the same time, most buildings have a low green-space rate, with the lowest being less than 2%. The Green Building Evaluation Standard requires

at least a 30% green-space rate, but only four of the case buildings met the standard, with a compliance rate of 36%.

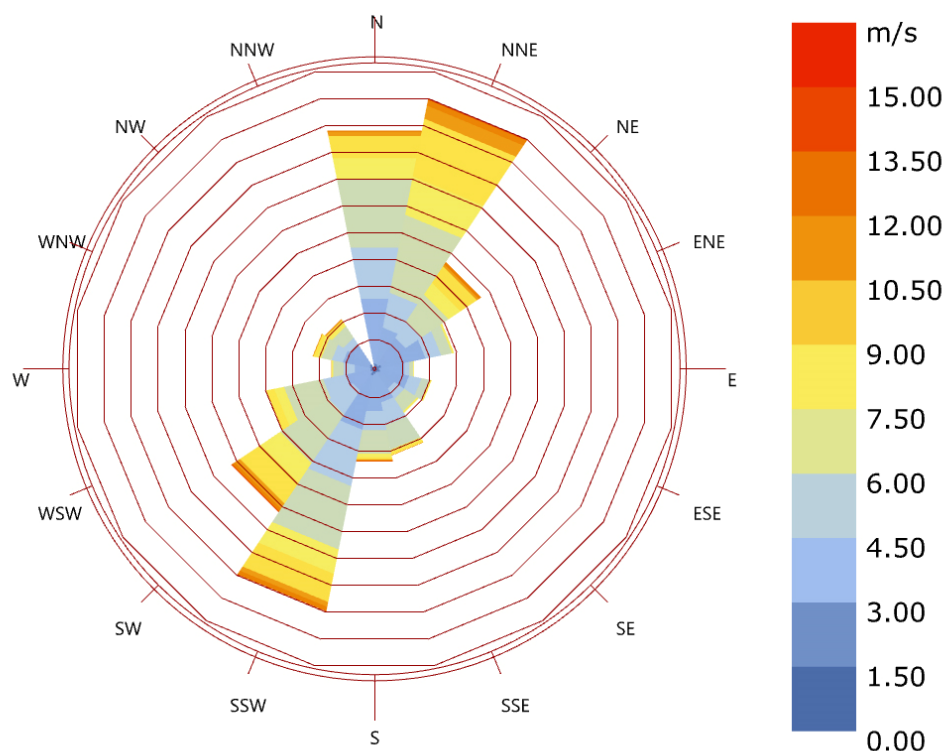


Figure 2. Wind rose of Dalian's typical meteorological year (Source: Dalian Typical Annual Meteorological Data of the United States Department of Energy).

4.2. Building Energy-Saving Design

Figure 3 shows the statistics of energy-saving design. The compliance rate of building thermal performance of enclosures, fresh air load control, and energy-saving elevator projects is 72.7%. The compliance rates of air-conditioning and heating energy efficiency, lighting power density, and independent energy consumption items are 100%. On the other hand, cold and heat storage design, waste heat utilization, and distributed tri-generation have not been adopted, with a compliance rate of 0%. Among the case buildings, 72% have carried out fresh air load control energy-saving design, and usually, heat recovery type fresh air ventilation units are set up to recover heat from the indoor return air to pre-heat or pre-cool the fresh air, reducing the operating energy consumption of the unit itself. Most of the surveyed projects that use this equipment can recover the investment cost within five years, the fastest being three years.

4.3. Building Material-Saving Design

Figure 4 shows the statistics of material savings, divided into 11 sub-items. The facades of all case buildings are relatively simple, without excessive decorative components. The poured concrete of the projects utilizes pre-mixed concrete and integrates design and construction to shorten the construction period. The rate of application for building material safety, light weight, and material recycling is only 34.4%. The proportion of building materials made from waste has not met the requirements. The typical practices for external walls of the surveyed projects combine small hollow concrete blocks or aerated concrete blocks. Rock wool insulation boards are the most common external wall materials, with 82% of the case buildings using these materials.

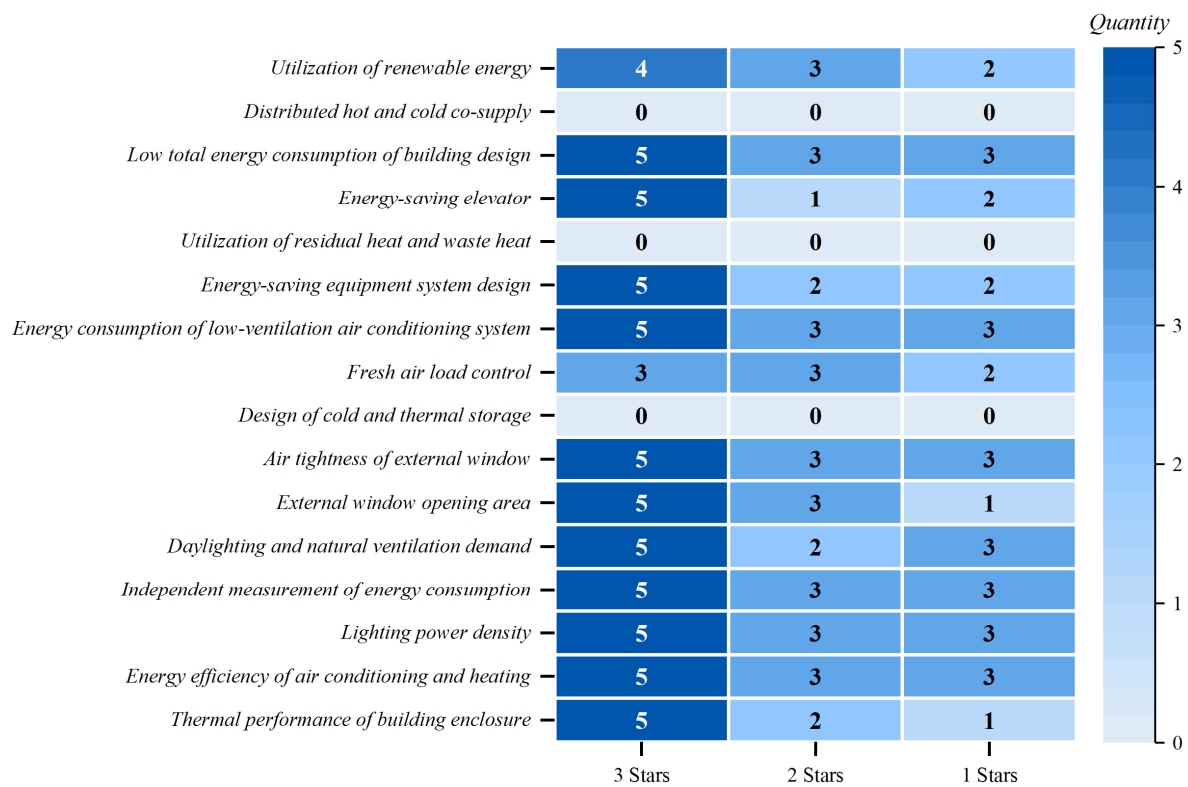


Figure 3. Building energy-saving design.

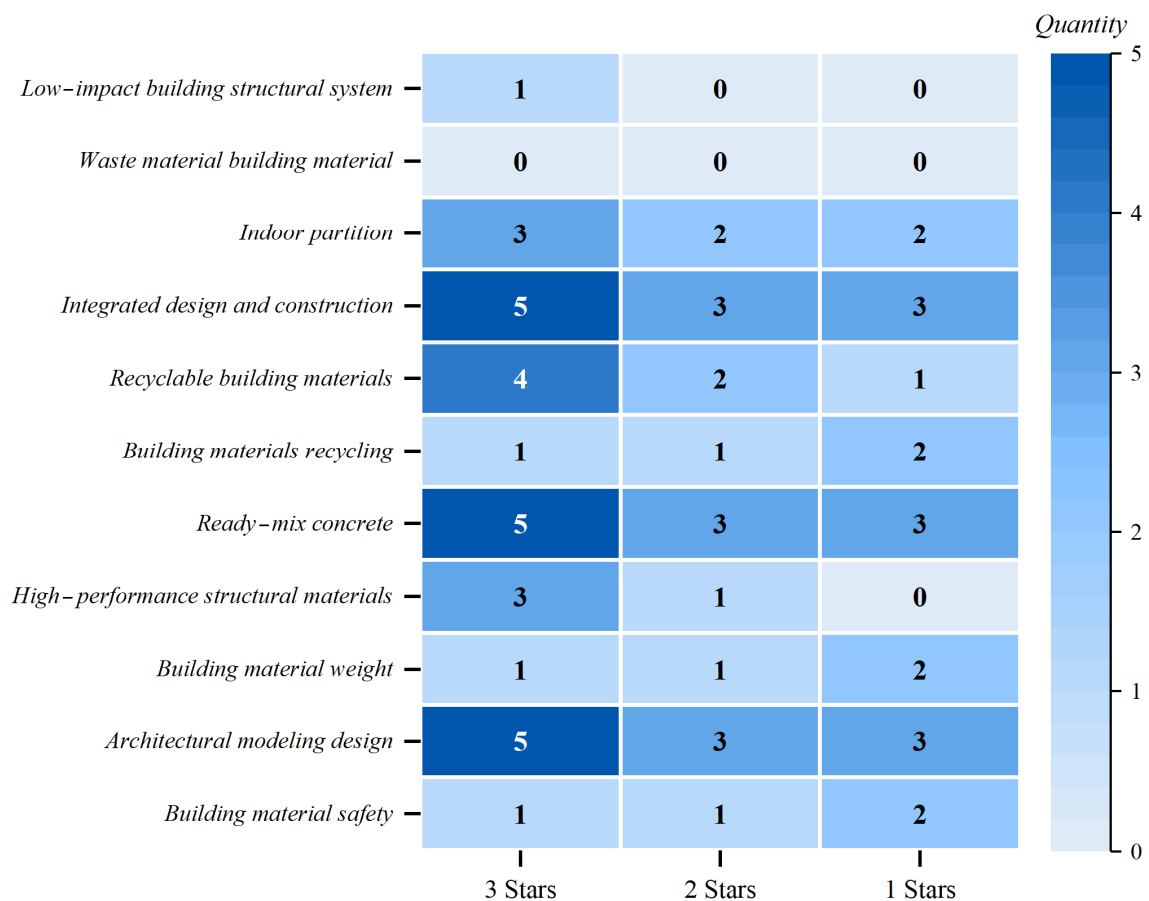


Figure 4. Building material-saving design.

4.4. Building Water Conservation Design

Figure 5 shows the situation of water-saving design, and the overall application rate of water-saving design is high. Among the factors, the design of rainwater accumulation and treatment is the least commonly employed, with a compliance rate of less than 50%. The annual precipitation in Dalian city is about 600 mm, and the monthly precipitation is very uneven, with the lowest in February being less than 10 mm, and the highest in August being about 150 mm. Most projects consider that if the design of rainwater accumulation and treatment for reuse is used for landscape irrigation, basement washing, etc., there may be nine months a year when the rainfall cannot meet the demand for water use, and the utilization rate of non-traditional water sources will decrease accordingly. Dalian city provides municipal reclaimed water. Most projects choose to connect the reclaimed water from the municipal reclaimed water network, which is used for outdoor green-space irrigation, road square washing, etc.

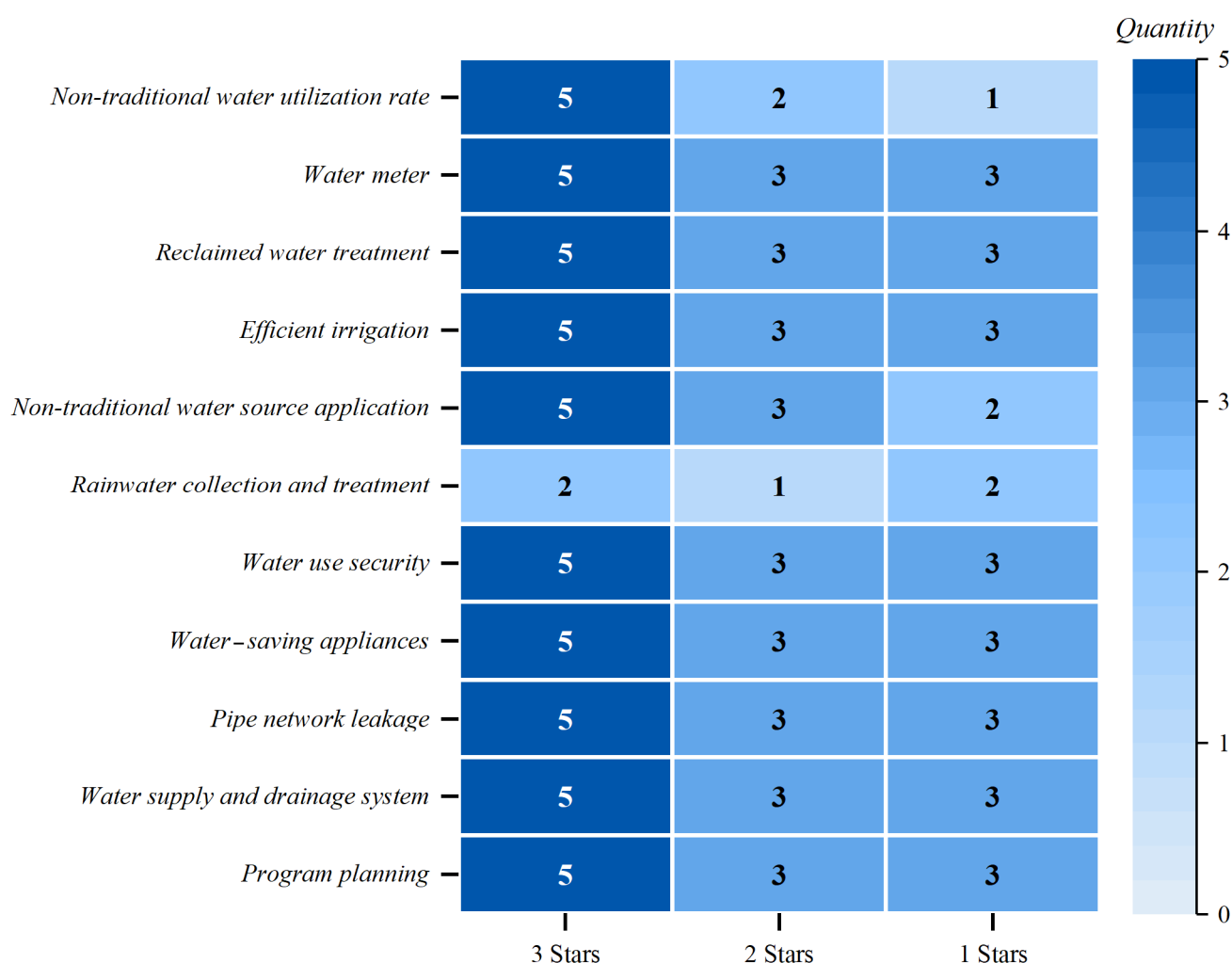


Figure 5. Building water conservation design.

4.5. Indoor Environmental Quality

Figure 6 shows the indoor environment quality design. Most projects do not consider indoor air pollutants during the design stage and control them more during the operation and management stage. Only two projects have applied adjustable external shading devices, and some use fixed shading. Some projects fail to meet the requirements for natural ventilation and daylighting coefficient in the main function rooms. If the project area is large, it will lead to excessive depth, and both natural ventilation and daylighting will be limited.

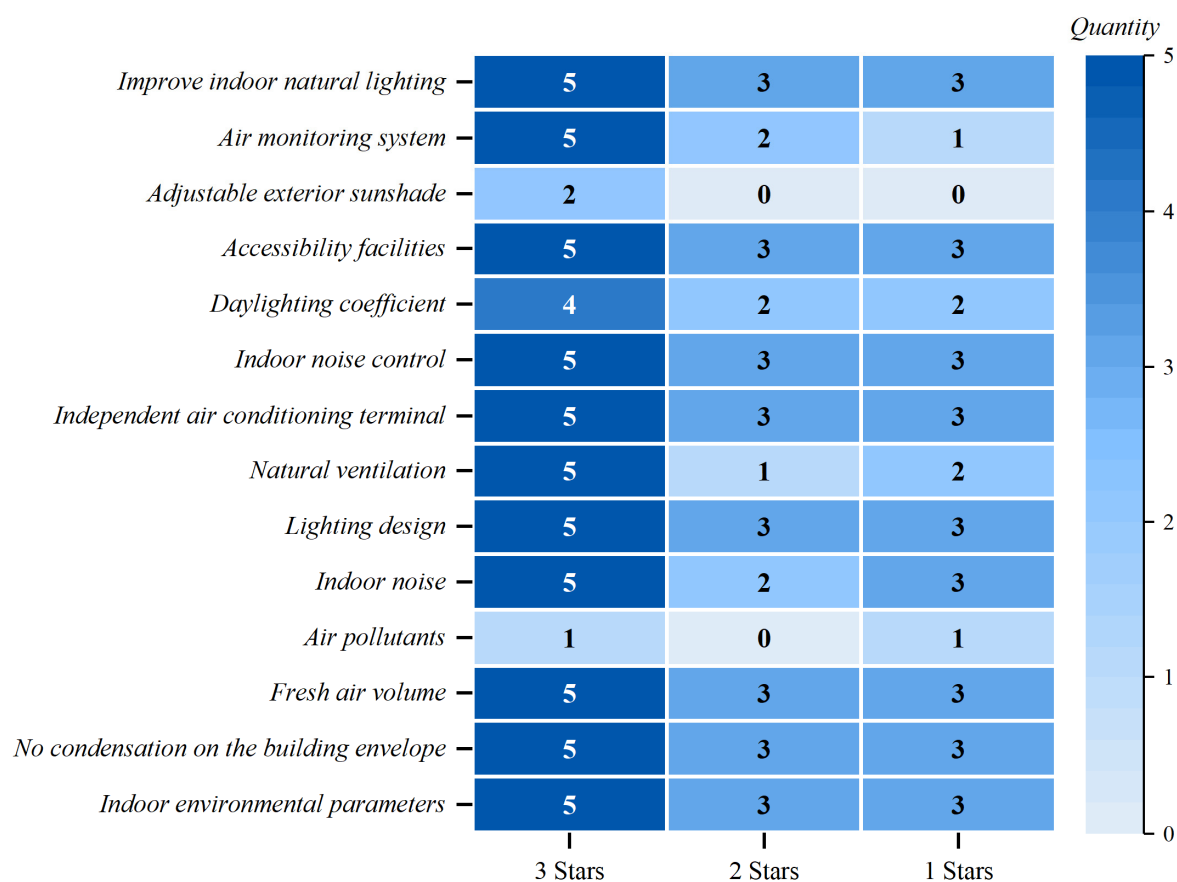


Figure 6. Indoor environmental quality.

The air monitoring systems in the surveyed projects are primarily set up with carbon dioxide sensors linked to the operation of fresh air ventilators incorporated into the building equipment monitoring system to save energy and maintain indoor air quality. Although the air-conditioning system design parameters of each project meet the required standards, it is unclear whether they meet expectations during the actual operation and management stage. Therefore, this paper conducts an analysis through actual measurement.

5. Indoor Air Quality Case Study

5.1. Office Air Quality

This study selected P8 as the case building. Figure 7 shows the results of a one-month indoor air quality monitoring conducted on different floors of the P8 building in summer. The actual measurement uses an IBEM environmental quality tester [43], and the test data include temperature, humidity, CO₂ concentration, and PM_{2.5} particle concentration. The basic parameters and measurement accuracy of the measuring instrument are shown in Table 2. The instrument is placed in an office space with different orientations and different areas, and the instrument is located at a height of 0.75 m or 1.2 m. The test time refers to the typical high-temperature months in Dalian, and the measured time is from 21 June to 21 July 2019. Data are recorded at five-minute intervals. Only the data from the working hours (8:00 to 18:00) are saved.

We found that the first floor had the highest carbon dioxide and PM_{2.5} concentrations, between 379.8–700.9 ppm and 7.9–201.4 µg/m³, respectively. In contrast, some high-rise offices are vacant, and the air quality is relatively stable. The ground floor has a high density of occupants, and the selected points include multiple open office areas and large spaces. During summer working hours, outdoor weather is hot, and doors and windows are closed, resulting in a lack of natural ventilation.

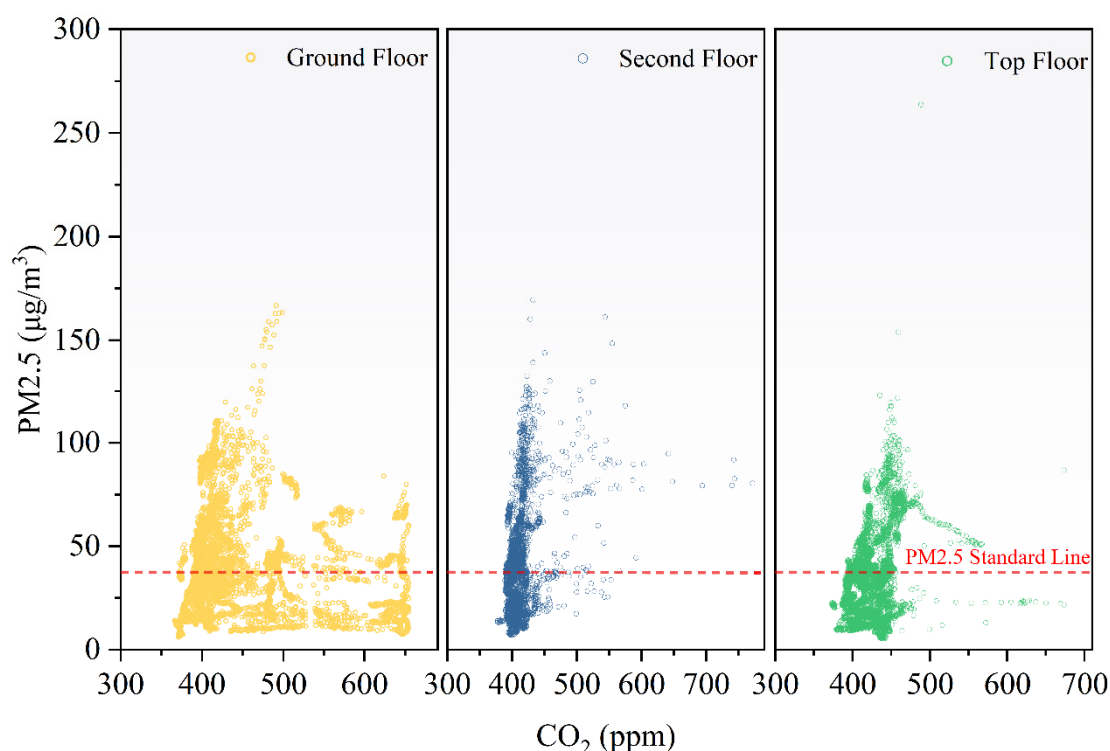


Figure 7. Air quality distribution in the office area of the P8 building.

Table 2. Basic parameters and measurement accuracy of the measure instrument.

Parameter Name	Range
Temperature	−40–80 °C
Humidity	0–99.9%
Illuminance	0–20,000 lx
PM _{2.5}	0–999.9 µg/m ³
CO ₂	0–2000 ppm

Figure 8 presents the comparison of CO₂ and PM_{2.5} concentrations on different floors in the office area. During the working period, the CO₂ concentration in this region showed a flat trend with time. The highest concentration of the top layer was 431.1 ppm, the lowest concentration was 414.2 ppm, and the change was evident at around 15:00. This is because the points on this floor are primarily located in meeting rooms, corridors, etc. Combined with the actual investigation, it was found that activities such as meetings are often held in this period, and the gathering time causes CO₂ levels to rise.

PM_{2.5} concentrations on the first floor fell below the standard from 10:00. The lowest value appeared at 08:00, at 34.6 µg/m³, and the highest concentration was reached at 17:00, at 46.7 µg/m³, exhibiting a relatively pronounced trend. Two of the monitoring points were situated in glass-partitioned offices that had been left vacant for an extended period, and the doors and windows of these spaces were firmly shut. As a result of the lack of use, a large amount of dust had accumulated on the furniture, leading to consistently high PM_{2.5} concentrations. There might also be a possibility of PM_{2.5} concentration increases being caused by smokers entering the indoor area. The highest PM_{2.5} concentration on the second floor was 37.6 µg/m³. During this measurement period, there was a monitoring point on the second floor under renovation with heavy personnel traffic. Top-floor concentrations remained generally stable.

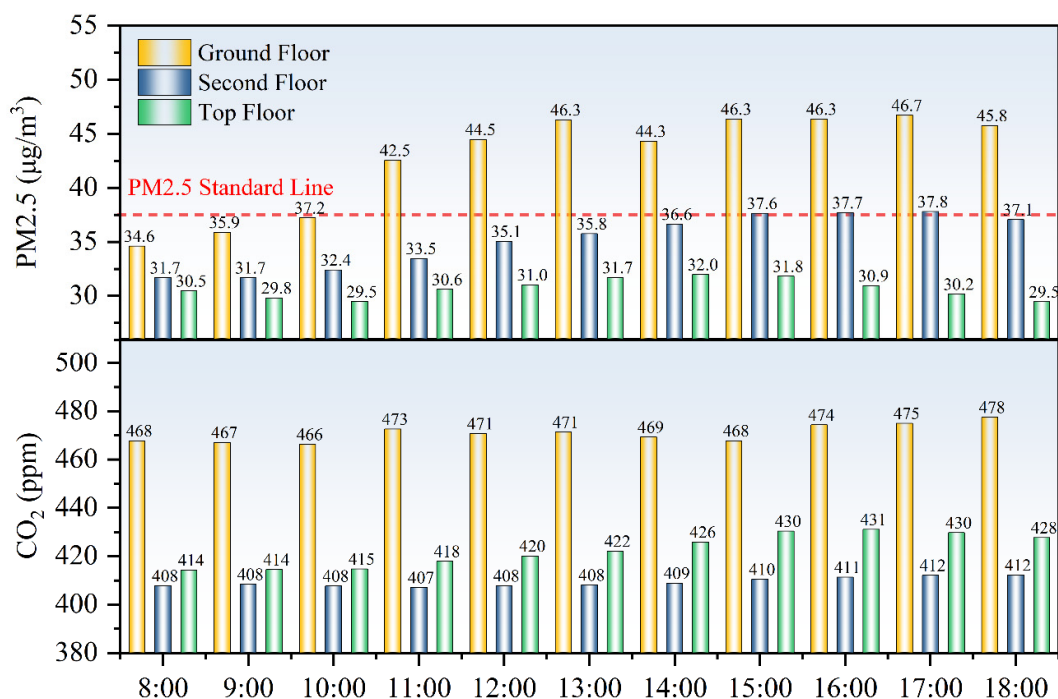


Figure 8. Comparison of hourly average CO₂ and PM_{2.5} concentrations in the office area of the P8 building.

5.2. Indoor Thermal Environment

Figure 9 shows the results of the indoor thermal environment measurements. The maximum indoor temperature recorded was 28.0 °C, while the minimum was 25.1 °C, maintaining an average between 26.0 and 27.1 °C. The indoor temperature was highest during the midday period, which is also the warmest part of the day, hence impacting the indoor temperature significantly. Generally, the indoor temperature remained consistent.

The highest indoor humidity level recorded was 72.4%, the lowest was 61.0%, and the average ranged between 67.0 and 68.5%. The indoor humidity was less affected by outer environmental conditions. However, upon deeper analysis, it was found that a significant portion of the humidity data lies near the critical point, and this is mainly due to the project's location in a coastal city, where the air humidity is relatively high.

When comparing relevant standards, it is observed that the average carbon dioxide concentration within the P8 building's office area adheres to the stipulated requirements of less than 1000 parts per million (ppm), as specified in the Indoor Air Quality Standards GB/T18883-2002 [44], and this compliance is achieved with a rate of 100%. However, the overall compliance rate for indoor PM_{2.5} concentration is less than 60%. Specifically, the first-floor office area fails to satisfy the requirements of the Health Building Assessment Standard T/ASC02-2021 [45], which states that the “daily average PM_{2.5} concentration should not exceed 37.5 µg/m³” during work hours from 11:00 to 18:00. The exceedance rate during the peak period is 24%, and the indoor PM_{2.5} concentration of the second floor also exceeds the standard at 15:00–17:00 by roughly 1%.

According to the Design Standards for Heating Ventilation and Air Conditioning of Civil Buildings GB50376-2012 [46], the case building's temperature compliance rate is 50.3%, and the humidity compliance rate is 57.8%. The building operation should consider enhancing indoor ventilation to optimize air quality, improving the performance of dehumidification equipment, and controlling the air-conditioning supply temperature to prevent overcooling situations, ultimately achieving indoor comfort and health.

Long-term actual measurements allow for the detection of problems in building operation management and the implementation of solutions while improving the indoor environment, which can effectively exploit the potential for energy savings.

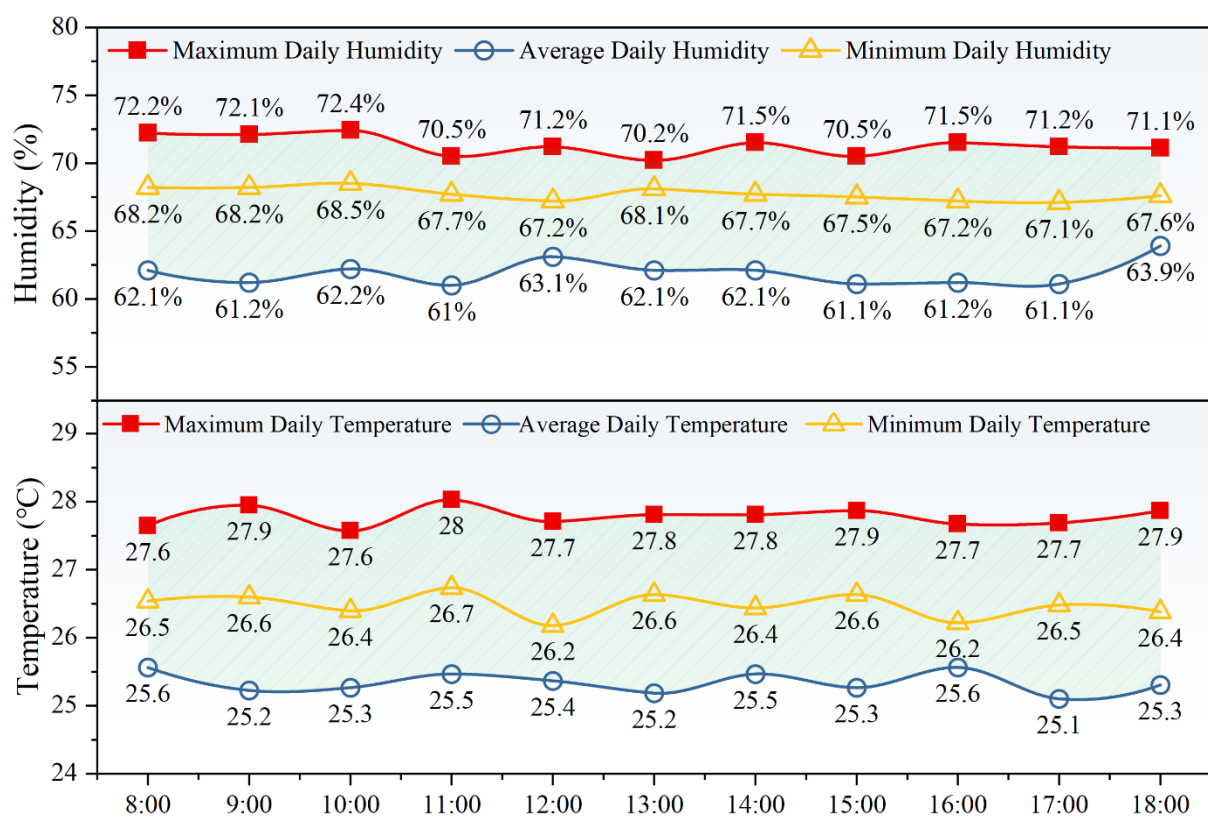


Figure 9. P8 building indoor humidity and temperature.

6. Localized Building Energy-Saving Design System and Optimization Strategy

6.1. Energy-Saving Design System

The implementation of energy-efficient design in selected case buildings has been analyzed. The survey included 36 commonly used design items and 7 less commonly used design items [47], and the specific sub-items of these are summarized as shown in Table 3.

The highest proportion of commonly used designs in case buildings is building water, with a total of 11 design sub-items. Among the sub-items, nine were commonly used designs, accounting for 81.8%, and none were less-used designs. This is followed by the indoor environment, where 64.3% of commonly used designs and 14.3% of less-used designs are applied. In building energy, 62.5% of commonly used designs and 18.8% of less-used designs are used in case buildings. In the 11 subcategories of outdoor and outdoor environment, 45.5% of the commonly used designs were applied in the case buildings, and none of the less-used designs were used. Among the 11 sub-items of building materials, 3 were commonly used designs, accounting for 27.3%, and 2 were less-used designs, accounting for 18.2%. Architectural energy conservation, water, and indoor environmental quality were the high-frequency areas of the energy-saving design commonly used in Dalian green public buildings.

Table 3. Summary of commonly used designs and less-used design in case buildings.

	Land Space and Outdoor Environment	Building Energy-Saving Design	Building Material-Saving Design	Building Water Conservation Design	Indoor Environmental Quality
Commonly used designs	Maintaining the surrounding environment	Energy efficiency of air conditioning and heating	Architectural modeling design	Program planning	Indoor environmental parameters
	Light pollution	Lighting power density	Ready-xix concrete	Water supply and drainage system	No condensation on the building envelope
	Surrounding sunshine needs	Independent measurement of energy consumption	Integrated design and construction	Pipe network leakage	Fresh air volume
	Pollution emission	Daylighting and natural ventilation demand		Water-saving appliances	Indoor noise
	Convenient transportation	External window opening area		Water use security	Lighting design
		Air tightness of external window		Non-traditional water source application	Independent air-conditioning terminal
		Energy consumption of low-ventilation air-conditioning system		Efficient irrigation	Indoor noise control
		Energy-saving equipment system design		Reclaimed water treatment	Accessibility facilities
		Low total energy consumption of building design		Water meter	Improved indoor natural lighting
		Utilization of renewable energy			
Less-used design		Design of cold and thermal storage	Waste material building material		Air pollutants
		Utilization of residual heat and waste heat	Low-impact building structural system		Adjustable exterior sunshade
		Distributed hot and cold co-supply			

Figure 10 shows the statistics of the research buildings' commonly used and less-used designs. P1, P2, P6, and P11 buildings used 36 commonly used designs, of which three-star buildings accounted for 50%. Six buildings applied 35 commonly used designs, and three-star buildings accounted for 17%. Seven projects did not apply less-used designs, of which three-star buildings accounted for 29%.

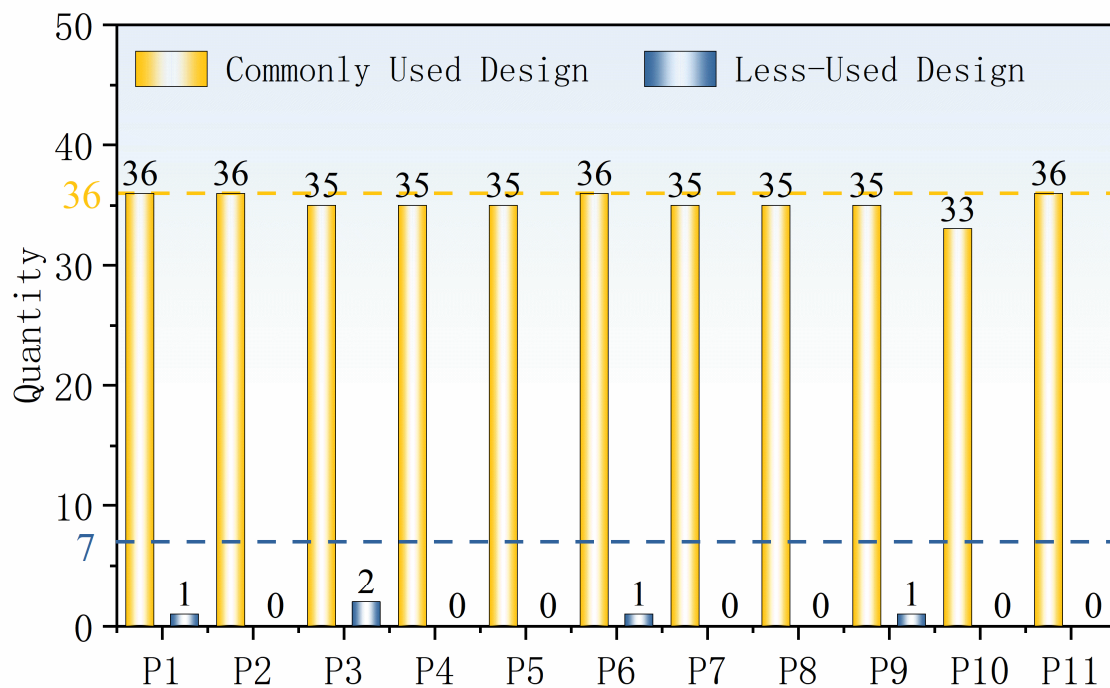


Figure 10. Comparison of building energy-saving design.

6.2. Energy-Saving Design Optimization Strategy

6.2.1. Building Orientation

In cold regions, careful consideration should be given to building orientation to minimize north-facing aspects. However, this aspect should have been more noticed in the buildings surveyed. Figure 11 displays the optimal orientation in Dalian. The area enclosed by the green thin line represents the annual average solar radiation conditions. The area enclosed by the red thin line represents the overheated period solar radiation conditions, while the blue line represents underheat period. The yellow arrow denotes the best orientation of the building. It suggests that when the building in Dalian faces south-west at an angle of 35 degrees, it receives the least solar radiation in summer and the most solar radiation in winter.

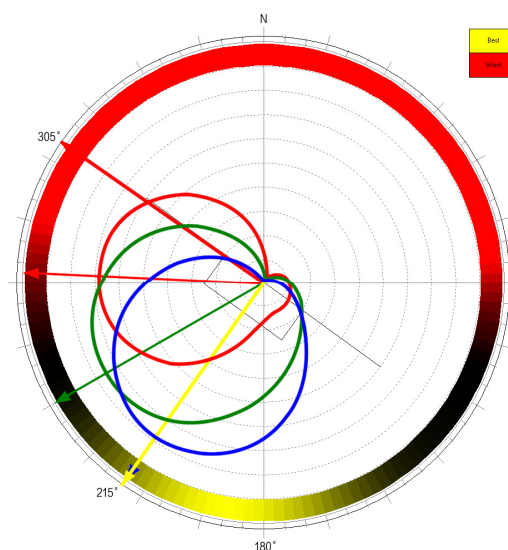


Figure 11. The best orientation in Dalian.

According to the survey, only two case buildings are close to the best building orientation in Dalian. Most buildings surveyed have their main facades or entrances facing north-east. It is recommended that newly built green buildings consider the building orientation comprehensively in conjunction with its actual usage from the energy-saving perspective.

6.2.2. Building Greening

All the case buildings have relatively low standards for green-space ratio and wind-speed control. For a northern city like Dalian, the role of plants in improving the wind environment is critical. There is limited vertical greening in the projects surveyed. Regarding the unique features of green public buildings in Dalian, vertical greening can be implemented through two distinct methods, as illustrated in Figure 12. The first method, as depicted on the left side of the figure, involves creating planting slots directly on the facade of the building. The second method, as demonstrated on the right side of the figure, entails installing supportive components on the external walls of the building to facilitate the growth and support of climbing plants. This approach requires careful consideration of the selection and design of components to ensure harmony with the overall architectural style. It can also be used as a stylistic element or given certain functional features, such as a sun shield.

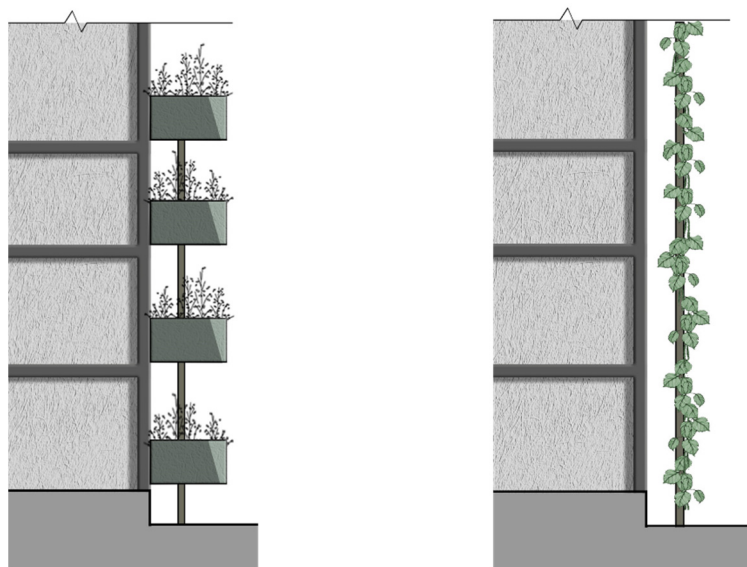


Figure 12. Vertical greening design.

6.2.3. Building Shading

The study found that the application of adjustable external sunshade facilities in green public buildings is less common, and most of the case buildings generally use fixed vertical sunshades to express the effect of building facades. Three common sunshade systems can be formed through transformation, as shown in Figure 13.

System ① integrates adjustable perforated metal grilles that users can modify to meet their varying needs for shade and privacy throughout the year, adapting to the sun's seasonal shifts. This is particularly effective when the proportion of glass in the facade is high, as seen in system ②. For such cases, a foldable louvered shading mechanism is proposed. These louvers can be compacted into their roll tube in winter, maximizing sunlight exposure. Conversely, in summer, the shading level can be adjusted flexibly to manage solar heat gain efficiently. System ③ introduces the concept of installing baffles above the windows on the building's interior side. This strategy aims to diminish glare and enhance the penetration of natural light deep into the building's core. By optimizing shading solutions from the outset, the necessity for later adjustments can be significantly reduced, leading to a more sustainable and user-friendly design.

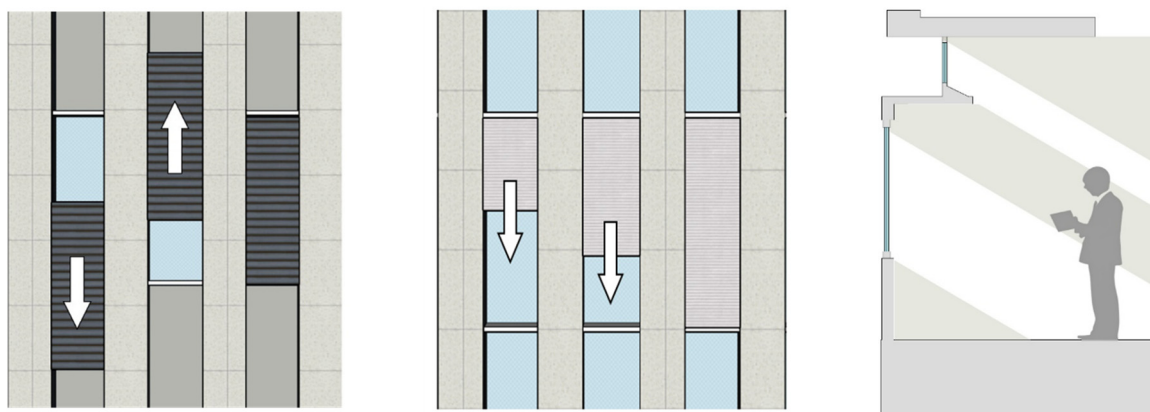


Figure 13. Building shade design.

The Chinese government has announced a climate target of carbon neutrality by 2060 [48], and to achieve this goal, an entire building's energy consumption needs to be reduced by 23.6% [4]. Therefore, China has issued several regulations on building energy efficiency, such as the Public Building Energy Efficiency Design Standard (GB/T50189) [49,50] and the Technical Standards for Near-Zero Energy Buildings in China [51], among others. The research shows an overall downward trend in national carbon intensity between 2020 and 2022, which may be influenced by national environmental policies [52]. After reviewing passive design's critical impact on building energy efficiency, we put forward relevant optimization strategies. We found that China's green building evaluation standard for passive design requirements and points is not considered. If the above issues are considered in the green building evaluation, it will help China's sustainable development.

7. Discussion

Investigations into the technical performance of green buildings should encompass more than just energy-saving procedures. Economic costs stemming from these measures also constitute a pivotal aspect of such studies.

The incremental costs for 11 green public buildings are summarized in Table 4. Among this selection, five are three-star green buildings, boasting an average unit area energy consumption of $264.28 \text{ MJ/m}^2 \cdot \text{yr}$ and an average unit cost increment of 151.77 yuan/m^2 . Three two-star green buildings have an average unit area energy consumption of $192.66 \text{ MJ/m}^2 \cdot \text{yr}$ and an average unit cost increment of 54.63 yuan/m^2 . The three one-star buildings average a unit area energy consumption of $172.565 \text{ MJ/m}^2 \cdot \text{yr}$ with an average unit cost increment of 15.15 yuan/m^2 . The building with the lowest average energy consumption per unit area is P10. The P10 building is a sales office and was vacant during the test period. The use of the building has a greater impact on energy consumption.

In summary, a building's incremental cost escalates with its star rating. The enormous price disparity between the highest and lowest unit area incremental costs is 399.59 yuan/m^2 . The highest initial investment was the three-star building P1, which reached 14.38 million yuan. The lowest is the one-star building P11 at 320,000 yuan. Furthermore, the use of green technology can lead to savings in operating costs of 300,000 yuan/year. The average unit area energy consumption per unit building area of the P11 building is only 2.47% higher than that of three-star building P2. There is also a significant difference in the payback periods, where the building with the longest period is P2, taking 92 years, while the one with the shortest period recovers the initial investment in just 2 years. Field research identified the P2 building of a three-star building, adopting the most energy-saving equipment and design methods among the study sample, totaling 11 items. The costliest item is the sewage heat pump system, which has a 4,581,200 yuan price tag.

Considering the investment required for greener construction, buildings rated with two stars only need to allocate 36.0% of the additional cost compared to those with three

stars, while one-star buildings require just 9.98% of that incremental expense. This highlights the considerable potential of one-star and two-star green buildings in balancing economic investment with environmental benefits. Meanwhile, the construction of three-star buildings entails the adoption of advanced energy-saving designs. However, their higher costs and energy demands call for more comprehensive research to fully assess the environmental friendliness of green buildings.

Table 4. Incremental cost statistics of green buildings in different regions.

Stars of the Building	Building Project	Energy Saving Rate (%)	Energy Consumption per Unit Area of Building (MJ/m ² ·yr)	Incremental Cost per Unit Area (yuan/m ²)	Incremental Cost (10 k yuan)	Initial Investment Cost Recovery (yr)	Savings in Operating Costs (10 k yuan/yr)	Number of Key Energy-Saving Technologies
Three-star building	P1	24.9	206.41	97.9	1438	31	47.2	3
	P2	74.78	187.89	80.26	1050.53	92	11.5	11
	P3	70.15	348.21	129.91	988.1	9	53.03	9
	P4	64.15	370.17	40.87	260.2	15	17.96	5
	P5	72.1	208.73	409.89	61.17	8	9.36	8
Two-star building	P6	65	316.94	34.4	301	11	27.8	10
	P7	62.4	64.98	12.7	212.46	19	11.3	6
	P8	63	196.08	116.8	116.8	11	13.51	4
One-star building	P9	65	325.07	10.3	90.37	7	13.89	8
	P10	50	0.095	24.51	72.01	14	5.5	3
	P11	65	192.53	10.66	32	2	30	5

It is estimated that by 2050, China's construction industry will contribute to 56% of carbon reduction [53]. Whether or not the dual-carbon goal can be achieved depends on how deeply the construction industry carries out energy conservation and emission-reduction work. This paper summarizes 36 commonly used designs and 7 less-used designs. From the passive point of view and regional characteristics, the optimization strategy of energy-saving design is put forward according to local conditions. At the macro level, relevant departments need to promulgate and implement more stringent green building evaluation standards to restrict building energy consumption. At the micro level, they need to control building energy-saving design strategies by region to achieve local conditions. Promoting commonly used designs could facilitate cost sharing, enhance developers' enthusiasm to implement energy-saving measures, and further broaden the application of green practices.

8. Conclusions

This paper examines and categorizes green designs, specifically focusing on green public buildings in Dalian. The main aim is to comprehend the norms of green building developments and the current state in the northern regions. With the rapid acceleration in the development of green buildings, there is an apparent need for more actual operational data, underscoring the need to collect and analyze building performance data during the operational phase.

Through field research and data collection on 11 constructed case buildings in Dalian, it analyzes the application of energy-efficient design in these projects by referring to the standards used when they applied for the green building label. These designs are examined from five perspectives: land space and outdoor environment, building energy conservation, building materials, building water usage, and indoor environmental quality. A total of 63 sub-items have been categorized based on their application rates into standard designs, which are those with an application rate greater than 80%, and low-usage designs, where the application rate is less than 20%. This classification has led to the identification of 36 standard and 7 low-usage designs. This paper analyzes the application of green design in the case of buildings in Dalian city and discusses its incremental cost. The research shows that building energy efficiency, water use, and indoor environmental quality are

the high-utilization areas of green design in the case of buildings. There is a substantial difference in the incremental costs between one-star and two-star buildings, as well as three-star buildings. In conjunction with the preceding analysis of the application rate of energy-saving designs, this paper proposes design optimization strategies from the standpoint of passive design for building orientation, greening, and shading to address the existing issues with energy-saving designs in research buildings.

With the establishment of China's dual-carbon goal, building energy conservation has become one of the important means to achieve the goal, and the cognition of building energy consumption structure and law has become key. Many factors affect the energy consumption of green buildings. Based on the above considerations, this paper mainly focuses on building energy-saving design strategy, indoor environment, and incremental cost and carries out an analysis. In future research, we will combine the use of questionnaire surveys to emphasize the influence of climate and building practices on buildings, users, and owners. By improving the green building evaluation standard, we aim to further expand our understanding and analysis of the regulatory environment and building operational performance.

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