Exploring the Ecological Design of Office Building Envelopes

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Abstract. In the whole life cycle of a building, carbon emissions from the operation phase are dominant and play a key role in the country's total emissions. Therefore, reducing carbon emissions in this phase is crucial for environmental protection. Especially for office buildings, optimizing envelope design and improving energy efficiency are effective means to achieve energy conservation and emission reduction. Therefore, this study aims to explore the ecological design applicable to different components of office building envelopes through classic examples of excellence in energy efficiency. The evaluation standards of China, the United States and the United Kingdom are selected, and the differences and similarities of the evaluation standards are tabulated to assess the impact of different evaluation standards on green buildings. This paper concludes that a generalized building envelope design methodology can be explored through a comprehensive study of key elements such as high-performance curtain walls, eco-materials and innovative technologies, shading, ventilation and lighting design, and by combining the comparison of energy efficiency before and after retrofitting, detailed data and design detail analysis in specific cases. This paper can provide a feasible and effective program for the ecological design of office building envelope.

Keywords: Office building envelope; ecological design; building energy efficiency; green building.

1. Introduction

The full life cycle of construction is divided into the production and transportation stage of building materials, the construction transportation stage and the construction stage. Relevant reports indicate that the carbon emissions of the whole life cycle of buildings account for 38.2% of the national carbon emissions. Among them, the carbon emissions in the building operation stage account for about 56.6% of the carbon emissions in the whole life cycle of buildings[1]. Therefore, reducing carbon emissions in the operation phase of buildings can not only alleviate the tense situation of energy supply but also solve the serious problems of environmental pollution and greenhouse gas emissions, which have a far-reaching impact on global warming.

With the rapid growth of the economy and the acceleration of urbanization, the scale of office buildings continues to expand, resulting in a sharp rise in energy consumption, which is gradually becoming an important part of energy consumption. In many office buildings, many buildings constructed at an earlier age are generally faced with problems such as no insulation measures for the envelope and old equipment systems. These problems not only affect the energy efficiency of the building but also lead to a large amount of energy waste. As a barrier between the building and the external environment, the design of the envelope directly affects the performance of the building in terms of heat preservation, insulation, lighting, ventilation, etc., which determines the energy efficiency level of the building. Therefore, optimizing the design of the envelope to improve the energy efficiency of the building is the key to energy saving and emission reduction.

Many scholars have conducted in-depth research on building envelopes, exploring how to respond to different environmental demands through algorithms, data models, and optimal designs, and making significant progress in energy efficiency and comfort, especially in energy saving and comfort. Zhichao Tian et al.[2] constructed a data-driven model through 6720 non-residential buildings, so that the relevant designers can make energy-saving designs according to their own needed variables. To find the best energy-efficient design for office buildings, Xing Shi[3] used a genetic algorithm to construct an energy simulation program. Lotfi Yomna et al.[4] used a simulation model to evaluate the effect of green envelopes on the interior in hot and arid climates, and the results showed that green roofs are more effective than green walls. In order to improve building comfort and reduce energy consumption, Trombadore Antonella et al.[5] designed a green façade and a vertical farm for a tower building. Gutai Matyas et al.[6] evaluated the impact of smart water-filled glazing on the energy consumption of a building. Although these studies have made progress in the areas of green design, climate resilience and building energy efficiency, there is still a lack of universal energy-efficient design for office buildings.

Against this background, this paper summarizes the profiles of office building energy consumption in China, the United States, and the United Kingdom, and compares and analyzes the relevant provisions of the green building evaluation standards of these three countries. On this basis, the paper summarizes the ecological design of high-performance curtain walls, eco-materials and innovative technologies, sun shading, ventilation and lighting design in combination with specific classic building cases, and finally puts forward the challenges in the development of green office buildings and the outlook of intelligent and innovative ecological design in the future.

2. Analysis of the current situation of energy consumption in office buildings

As an important part of urban energy consumption, the energy consumption patterns and characteristics of office buildings have received widespread attention. In China, as early as 2018, the energy consumption of the building operation phase accounted for 21.7% of the total national energy consumption, while the carbon emissions of the building operation phase alone accounted for 21.9% of the share of the national energy carbon emissions. The purpose of this paper is to compare and analyze the energy consumption of office buildings in China, the United States and the United Kingdom as an example.

According to data from the National Bureau of Statistics, the energy consumption structure of public buildings in China mainly focuses on air conditioning, lighting, elevators and office equipment. Among them, air conditioning energy consumption accounts for the largest proportion, especially during the high temperatures in summer, while the energy consumption of lighting and elevators and other equipment should not be ignored. In the U.S., according to the U.S. Energy Information Administration (EIA) data, the U.S. building energy consumption accounted for about 40% of the total energy consumption and is a year-on-year growth trend, in which residential buildings accounted for 21-22%, public buildings accounted for about 20%, and the energy consumption of the office building is about 270kw·h/m^2. The United Kingdom, with its long history of construction and stringent environmental protection laws and regulations, has demonstrated a unique advantage in the management of energy consumption in office buildings. New buildings, like those to be constructed from 2023 onwards, have a carbon footprint of 29% of the average emissions of existing houses. Nonetheless, office buildings still account for a certain percentage of the nation's energy consumption.

As a whole, building energy consumption in the US and UK is generally higher than that in China. This is because of their high level of urbanization, high building density, and the fact that many buildings are designed and constructed to high energy consumption standards. In contrast, China's building density is low, and many buildings are designed and constructed according to low energy consumption standards. In terms of specific building types, commercial and public buildings in the US and UK consume more energy than buildings in China. This is mainly due to the larger scale of the buildings, which require a large amount of energy to maintain their operation. In addition, from the point of view of energy utilization efficiency, buildings in the United States and the United Kingdom are also generally more efficient than those in China.

3. Comparison of major evaluation standards for green office buildings

3.1. Introduction to evaluation standards in China, the United States and the United Kingdom

The China Green Building Evaluation Standard (GBES) is the most authoritative and widely used green building evaluation system in China, covering a wide range of building types, including residential buildings, office buildings, schools, hospitals, etc., as well as commercial complexes, exhibition halls, stadiums, and industrial buildings, and covering the whole life cycle of a building, from planning and design to construction, operation and maintenance. It also covers the whole life cycle of buildings, from planning and design to construction, operation and maintenance. With the continuous updating of the standards, GBES pays more attention to the overall performance and user experience of green buildings than other evaluation standards, and at the same time strengthens the requirements for the use of renewable energy, ecological and environmental protection, and intelligent management.

LEED is the most widely used green building evaluation standard, developed by the U.S. Green Building Council (USGBC) based on BREEAM. LEED covers a wide range of building types, including residential buildings, office buildings, medical buildings, educational buildings, factories, warehouses, etc., which basically includes all types of buildings, and even includes interior design and construction. It even includes interior design and construction.

BREEAM is the world's first green building assessment standard, released by the Building Research Establishment (BRE) in 1990, and is a milestone in the development of international green building standards. BREEAM is the most widely used assessment system in the world, covering 86 countries and certifying more than 15,000 projects/250,000 buildings worldwide.

3.2. Comparative analysis of evaluation criteria

An in-depth comparative analysis of China's green building evaluation standards, LEED and BREEAM reveals that there are both commonalities and differences in their requirements for energy saving, environmental protection and health. For example, in terms of energy saving, each standard emphasizes improving the energy efficiency ratio and reducing carbon emissions, but the specific methods and technical paths are different; in terms of health, LEED and BREEAM pay more attention to the overall quality of the built environment. Through Table 1, the similarities and differences of these standards can be analyzed, and the evolution trend and development direction of the green building evaluation system can be explored in depth.

Table 1. Comparison of Green Building Evaluation Standards GB/T50378-2019, LEED V4.1, BREEAM V6

Name	GB/T50378-2019	LEED V4.1	BREEAM V6
target audience	Civilian single buildings or complexes, evaluated after completion of construction work	All types of buildings that have been fully operational for at least 1 year,such as offices,restaurants,schools,etc.	Commercial and residential buildings,especially existing ones
Core concepts	Green, Conservation,Livability	Efficient,Sustainable ,Healthy	Comprehensive,Systematic ,Sustainable
Evaluation content	Safety and Durability,Health and Comfort,Convenience,Resource Conservation,Livability,Enhancement,Innovation	Integration of Design,Site Selection and Transportation	Environmental quality and performance of buildings (Q), external environmental loads of

		(LT),Sustainable Sites (SS),Water Efficiency (WE),Energy and Atmosphere (EA),Materials and Resources (MR),and Indoor Environmental Quality (EQ),with bonus points for Innovation (IN),and Region (RP)	buildings (L),Q includes indoor environment (Q1),service quality (Q2),external environment within the region (Q3).L includes energy (LR1), resources and materials (LR2), external environment of the region (LR3)
economic benefit	Less embodied	Throughout the process	Throughout the process
clout	The most authoritative and widely used green building assessment system in China	One of the most widely recognized green building evaluation standards in the world	The world's first green building evaluation standard

4. Ecological design of the envelope

After examining the similarities and differences between the evaluation standards of the three countries and their guiding significance for sustainable development, it can be found that these evaluation standards not only provide a clear measure for building design but also emphasize the important position of eco-design in building design. Especially in the field of office buildings, the rationality of the design of the envelope, as the key interface between the building and the external environment, has a direct impact on the level of energy consumption, the quality of the indoor environment and the overall ecological environment of the building. Therefore, an in-depth study of more innovative and universal design strategies for the office building envelope is not only a positive response to the practical requirements of green evaluation standards but also an inevitable choice to promote the development of the construction industry in the direction of lower carbon and environmental protection.

4.1. High-Performance Curtain Wall

The architectural envelope serves as a pivotal link between the internal and external domains of a structure, functioning as both a protective barrier and a conduit for communication with the external environment. The design of this envelope transcends mere aesthetic considerations, exerting a direct influence on the energy consumption rates and the indoor environmental quality of the edifice. Typically, high-performance curtain walls are constructed using advanced heat-insulating materials, such as double or triple-glazed insulating glass and low-emissivity coated glass, integrated with sun-shading systems and ventilation apparatuses to achieve superior thermal retention, insulation, acoustic insulation, and waterproofing properties. Concurrently, an intelligent control system is employed to automatically modulate the curtain wall's operable state in response to indoor and outdoor environmental fluctuations, thereby facilitating refined energy consumption management.

For instance, the east and west elevations of the GSW headquarters building feature continuously horizontal and transparent expansive glass curtain walls that not only afford exceptional bidirectional natural illumination but also significantly curtail the dependency on artificial lighting, ensuring the building's interior is well-lit. The eco-energy system's most critical component within the building is also embodied by these two glass curtain walls. The sun shading panels are capable of automatic adjustment by the central control system based on light intensity, while also allowing for manual local control tailored to individual preferences, thus combining flexibility with intelligence. The tripartite curtain wall on the west facade acts as a massive solar chimney, harnessing the "chimney effect" to facilitate efficient natural ventilation throughout the structure, enabling the building to rely solely on natural ventilation for 70% of the year. The ventilation system is governed by a cutting-edge Building Management System (BMS) that meticulously regulates the opening and closing of valves at the upper and lower extremities of the building, providing precise ventilation control. Given that Berlin experiences more extreme temperatures, with hotter summers and colder winters compared to the rest of Europe, the multi-layered curtain wall on the west side maintains an indoor temperature of 27°C when the external temperature reaches 32°C, with the internal climate being managed by a system of valves positioned at the building's zenith and nadir.

4.2. Eco-materials and innovative technologies

The integration of environmentally friendly materials is a crucial trend in the evolution of sustainable construction. When designing building envelopes, emphasis should be placed on the selection of renewable, decomposable, non-toxic, and non-hazardous substances, including materials such as bamboo, repurposed plastics, and bio-derived finishes. Moreover, the deployment of cutting-edge technologies is pivotal in slashing energy consumption in buildings and enhancing their environmental impact. For instance, the cohesive design of solar PV panels and curtain walls satisfies both architectural and aesthetic standards and facilitates the capture and utilization of solar energy. The conjunction of rainwater harvesting systems with landscape architecture and greenery promotes the reuse of water resources. Furthermore, an intelligent building management system leverages tools like big data and the IoT(Internet of Things) to enable continuous monitoring and optimal control of energy consumption within the structure.

Consider the new Freiburg City Hall as a case in point; this elliptically shaped edifice stands six stories above ground with an additional basement level, replacing a governmental structure built in 1960. A standout feature of its design is the generous external atrium located centrally. The facade incorporates locally sourced, full-height pine wood for its sun protection louvers, which are as visually appealing as they are functional. Concurrently, vertical BIPV components are affixed to these sun-exposed screens, providing a dual-purpose solution for sun shading and PV energy production. Additionally, the building's envelope is constructed from advanced materials boasting a thermal conductivity rating of $0.1W/m^2\Delta K$ for opaque sections and $0.8W/m^2\Delta K$ for the triple-glazed windows, significantly enhancing energy efficiency. Glazed hybrid PV-thermal solar collectors (PVT) offer a solution to the challenges of installing PV or solar thermal systems on limited roof space. While PVT collectors generate slightly less electricity per square meter than PV panels, they also produce thermal energy, leading to a superior primary energy ratio. Arrays of PVT collectors are engineered to match solar yields. By substituting traditional solar collectors with glazed PVT collectors, the building can boost electrical output in a specific area by 180% while maintaining consistent thermal production, achieving a net energy surplus and becoming the world's first public edifice to meet this "energy surplus" benchmark.

4.3. Shading, ventilation and lighting design

Sun shading strategies represent an efficacious method for mitigating the effects of solar radiation within the confines of edifices. By employing stationary sunshades, retractable shading curtains, and blinds, among other devices, in synergy with architectural orientation and seasonal fluctuations, a meticulously crafted sun shading system can effectively obstruct direct solar incidence while guaranteeing an adequate influx of natural indoor light. Ventilation schemes enhance indoor air quality and curtail the operational duration of air-conditioning systems by integrating both natural and mechanical modes of air circulation. Illumination design underscores the maximization of natural light utilization, via skylights and elevated side windows, to augment indoor luminosity and diminish energy consumption for lighting. Moreover, the structure can capitalize on water resources to furnish auxiliary water supplies. Below the roof covering, drainage boards are installed to channel and conserve water, which can be employed to replenish the internal water supply of the building or to irrigate the surrounding landscape.

For instance, the Amsterdam Frontier Building, situated in the heart of the Zuidas district, boasts energy conservation features such as its orientation, facade configuration, and the north-facing super atrium. The building's alignment is the outcome of precise calculations on the sun's trajectory, and it incorporates an expansive atrium on the north side, which not only substantially increases the admission of natural light but also adeptly forestalls the penetration of direct sunlight from the southern flank, thereby markedly diminishing air-conditioning energy consumption while concurrently ensuring the northern office spaces are bathed in sufficient natural light. The glass curtain wall is fabricated from high-performance glass, adept at insulating against both sound and heat. The substantial atrium on the north side not only affords superior lighting but also contributes significantly to the building's ventilation. The elevated atrium generates a chimney effect, facilitating the unobstructed circulation of indoor air. Contaminated air is channeled through mesh partitions on each level and ultimately expelled via the rooftop exhaust system, while fresh air is continually introduced into the interior after being processed by specialized apparatus, thus creating an efficient natural air circulation system. Additionally, the edifice is outfitted with a heat exchange mechanism on its rooftop, capable of reclaiming surplus heat energy from the air. In the realm of facade design, the southern facade is equipped with calculated louvers to mitigate excessive sunlight and prevent glare, in contrast to the extensive transparent glass panes on the northern side. The reduced window apertures on the eastern and western elevations offer enhanced insulation and shading for the structure, and the window panes are designed to open freely to encourage indoor air ventilation.

5. Suggestion

With the rapid development of big data, artificial intelligence and other technologies, the intelligence and adaptivity of the enclosure structure will become a hot direction for future research. Through real-time monitoring of changes in the internal and external environment of the building, the intelligent control system can automatically adjust the operating status of equipment such as curtain walls, shading systems, ventilation devices, etc., and realize the fine management of building energy consumption. Meanwhile, through data mining and analysis, building design can be further optimized and green buildings can be accurately assessed, thus improving the energy efficiency and environmental performance of buildings.

New green materials and technologies are also a key force in promoting the development of green buildings. In the future, we can strengthen the R&D and application of renewable, biodegradable, high-performance and other green materials, explore more efficient and environmentally friendly building construction technologies, pay attention to the treatment and reuse of construction waste, and promote the development of a circular economy in the construction industry. Meanwhile, the development of green building requires interdisciplinary and cross-field cooperation and innovation. In the future, we can strengthen exchanges and cooperation with energy, transportation, electronic information, environmental protection and other fields to jointly promote the research, development and application of green building technology.

6. Conclusion

This paper explores in depth the ecological design of office building envelopes. The paper concludes that GBES excels in its focus on overall performance and user experience, LEED has advantages in terms of internationalization and flexibility, and BREEAM is known for its long history and wide international recognition. In terms of a universal eco-design approach for the building envelope, the curtain wall of a building should use highly efficient insulation materials and intelligent controls to achieve good performance and energy management; the materials of a building should prioritize the use of eco-materials and incorporate innovative technologies such as solar photovoltaic, rainwater harvesting and intelligent management systems to reduce energy consumption and improve environmental performance; the design of building shading, ventilation and lighting, combined with the use of water resources, can effectively reduce the impact of solar radiation, and reduce the impact of solar radiation and the impacts on the environment. The use of solar radiation can effectively reduce the impact of solar radiation, improve the indoor environment and reduce energy consumption.

Despite the increasing number of studies on energy consumption and green building design in office buildings in recent years, there are still many challenges to data collection and the actual practice of green building. On the one hand, due to the privacy of building energy consumption data, it is difficult to obtain comprehensive and accurate data. On the other hand, due to the limitations of technical cost, construction difficulty, and policy implementation, it is often difficult to achieve the expected results in the design and implementation of green buildings. In the future, it is necessary to study how to build intelligent simulation programs to automatically adjust the operation of curtain walls, sun shading, ventilation and other devices according to the external environment. By doing so, the technology can be used to solve more architectural design optimization problems. There is also important future work for architecture to strengthen integration and cooperation with other disciplines to promote the development of green materials and circular economy.

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