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Analysis of the Influence of Office Building Operating Characteristics on Carbon Emissions in Cold Regions

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Abstract: Reducing buildings' operational carbon dioxide emissions has become a crucial element in China's efforts to achieve carbon peak and carbon neutrality targets. This study focus on the influence of office building operating characteristics on carbon emissions in cold regions. By utilizing DesignBuilder v7.0.0.096 to conduct numerical simulations of 10 different operating conditions for heating, ventilation and air-conditioning (HVAC) and lighting systems, this study solves the problems in the past of poor comfort and high energy consumption with manual management and achieves a win-win situation for health and environmental protection. The study shows that by implementing a mixed mode of mechanical ventilation and natural ventilation based on outdoor climate conditions and design requirements, unsatisfied hours can be reduced by 202 h compared to the traditional air condition heating operation mode for both winter and summer seasons. Furthermore, compared to a year-round HVAC operation mode, the air-conditioning energy consumption can be reduced by 19%, resulting in a carbon emissions reduction of 1.45 kg $CO_2/(m^2{\cdot}a)$. Additionally, for every 2 °C increase in the outdoor temperature, the cooling energy consumption decreases by 2–5%. In terms of lighting, the intelligent lighting mode can reduce energy consumption by 31.04%, leading to a carbon emissions reduction of 3.04 kg $CO_2/(m^2{\cdot}a)$. The coupling operation characteristics of mixed mode, intelligent lighting, and energy-saving lamps can achieve a maximum saving of 83.46 MWh of electricity and approximately CNY 72,000 every year, with a static payback period of approximately 2.7 years. This operational strategy, which fully considers the utilization of natural ventilation and daylighting in conjunction with traditional design approaches, improves indoor air quality and ventilation conditions, while also maximizing the energy-saving and carbon reduction potential. The study results provide valuable design and operational guidance for new and existing office buildings in cold regions, to effectively reduce carbon emissions, while offering significant investment returns.

Keywords: building energy; HVAC scheduling; building operation; energy efficiency measures

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1. Introduction

In order to assume its responsibilities in addressing the challenges of climate change, China declared its commitment to enhancing its nationally determined contributions and the adoption of more policies and measures at the 75th United Nations General Assembly on 22 September 2020. China aims to ensure that its carbon dioxide emissions peak by year 2030 and aims to achieve carbon neutrality before the year 2060 [1,2]. In the global effort to combat climate change, the building sector plays a critical role. In 2020, the total building stock in China reached 69.6 billion m^2, with 20% of it being public buildings. Public buildings serve as important platforms for the development of the tertiary sector in urban areas. With economic growth and improved living standards, the contribution of the tertiary sector to the economy continues to increase, leading to higher utilization rates of public buildings, such as office buildings and hospitals. The intensity of carbon emissions from public buildings (58.6 kg CO_2/m^2) is significantly higher than that of residential buildings (28.1 kg CO_2/m^2) and rural residential buildings (18.3 kg CO_2/m^2) [3]. Given the large volume and quantity of office buildings, which are only second to residential buildings in terms of construction, they exhibit high energy consumption. Therefore, this study focuses on office buildings in cold regions.

Energy-saving and carbon reduction in the building sector has two main aspects. On the one hand, building characteristics, such as building design [4,5], structural forms [6] and energy systems [7,8], are being explored. On the other hand, operational strategies [9–11] for achieving energy conservation and carbon reduction have tremendous potential. However, such methods primarily target commercial buildings [9], universities [10,12], dormitories [11], and residential buildings [13–15], with relatively fewer investigations conducted on office buildings. In this paper, the operational characteristics of office buildings in cold regions are studied, applying the principles of comfort and cost-efficiency with the objectives of energy-saving and carbon reduction.

Carbon emissions influenced by operational modes primarily reflect the operation of heating ventilation and air-conditioning (HVAC) systems and lighting systems. This study considers HVAC systems and lighting systems in the following respects:

- With the advancement of intelligent lighting systems, there has been a preliminary deployment of associated fixtures. In comparison to conventional lighting fixtures, what specific level of energy savings and emissions reductions can be achieved through the use of intelligent lighting systems?
- In HVAC systems, carbon reduction is primarily determined by three factors: ventilation, the indoor environment, and the operating duration. It is worthwhile to explore effective strategies for integrating these three facets in order to design an efficient approach.
- The effects of integrating HVAC systems, intelligent lighting systems and energy-saving lamps merit investigation.

To address the above issues, this study considers office buildings in cold regions as the research object, applying the principles of comfort and cost-efficiency with the objective of energy-saving and carbon reduction. Numerical simulations utilizing the Designbuilder software are conducted to investigate the influence of operational characteristics on carbon emissions for ten different HVAC conditions and lighting systems during the operational stage. The study aims to reveal the impacts and propose targeted measures for energy-saving and carbon reduction. The findings of this research can provide design and operational guidance for both newly constructed and existing office buildings in cold regions, leading to effective carbon reduction and offering valuable insights. The contributions of this study can be summarized as follows:

- Energy-efficient fixtures and intelligent lighting modes are used in the lighting system. This approach helps to avoid energy waste and to achieve energy-saving and carbon reduction goals.
- A hybrid mode is adopted in an HVAC system. By ensuring indoor comfort requirements, improving air quality, and maximizing window opening time, the operational stage aims to achieve maximum natural ventilation, reduce the energy consumption of mechanical ventilation, and, ultimately, achieve energy-saving and carbon reduction goals.
- The operational characteristics of the hybrid mode, energy-efficient fixtures, and intelligent lighting coupling represent an energy-saving and environmentally friendly approach. The approach not only extends the lifespan of equipment and lighting fixtures but also reduces operational costs and maintenance expenses.

The remainder of this study is organized as follows: Section 2 presents a literature review. Section 3 includes three parts: Section 3.1 introduces the data setting of the target building. Section 3.2 introduces different operating conditions. Section 3.3 provides an assessment from the perspective of economics. Section 4 presents the results and discussion, which also contains three parts, namely, comfort analysis (Section 4.1), energy saving and carbon reduction analysis (Section 4.2), and economic analysis (Section 4.3). Section 5 presents the conclusions of the paper.

2. Literature Review

Energy-saving and carbon reduction in the building sector have two main aspects. On the one hand, building characteristics, such as building design [4,5], structural forms [6] and energy systems [7,8], are being explored. Regarding building design, multiple perspectives [4,5], including floor plan layout, the building shape coefficient, building orientation, roof form, the heat transfer coefficient of the building envelope, and shading devices, are considered to characterize the basic patterns of carbon emissions in office buildings. This leads to the determination of optimal low-carbon values and ranges, resulting in low-carbon building solutions. With regard to building structures, studies [6] have shown that the carbon footprints of three common structural types—shear wall structures, frame structures, and masonry structures—do not differ significantly. Regarding energy systems, most research currently focuses on selecting representative green buildings [7,8] and near-zero energy buildings [16] as case studies, analyzing different types of HVAC systems [17] and their actual operational data [18], and proposing low-carbon retrofit and optimization measures.

On the other hand, when considering the operational process, the main focus is on energy conservation and carbon reduction in lighting systems and HVAC. Regarding lighting, research findings indicate that among the three influencing factors of lighting power density, luminaire installation methods, and lighting control methods, both lighting power density and lighting control methods have a similar impact of around 20% on the total energy consumption, while luminaire installation methods have little effect [19,20]. Although some studies have already suggested energy-saving efficiency measures in terms of lighting power density and control methods, traditional lighting fixtures and control strategies have become outdated as time has progressed and technology has advanced. According to Usama Perwez et al. [21], a comparison of various measures indicated that the most significant demand-side efficiency measures are improving system efficiency and upgrading lighting and appliances. Therefore, this paper investigates the field of intelligent lighting and energy-efficient luminaires to explore their potential for carbon reduction.

With regard to HVAC, studies [22,23] have shown that nighttime ventilation in summer is more energy-efficient than daytime ventilation or no ventilation. Moreover, the energy-saving effect is more significant in high-rise buildings compared to low-rise buildings. West- and south-facing offices exhibit greater energy-saving effects compared to other orientations. The impact of ventilation levels on air-conditioning energy consumption mainly manifests in terms of the operating-on/off time of air-conditioning systems. Ventilation levels I–III (air exchange rates of 0–2/2–4/>4) correspond to air-conditioning operating times that account for approximately 50%, 67%, and 100% of the total operating time, respectively; air-conditioning energy consumption increases by around 13–15% with each increase in ventilation level [24]. Regarding indoor environmental conditions, studies [25,26] have shown a consistent trend in both small and large office buildings with fan coil systems. In summer, for every 1 °C increase in indoor control temperature, energy consumption can be reduced by approximately 5–10%. For every 10% decrease in relative humidity, energy consumption increases by around 6–7%. In winter, for every 1 °C decrease in indoor control temperature, energy consumption can be reduced by approximately 8–10%. The phenomenon of cold winters and hot summers is a natural adaptation for humans. Within the range of 18–27 °C, lowering the room temperature in winter and raising it in summer has minimal impact on comfort but yields significant energy savings. Under the same occupant density, reducing the summer air-conditioning set temperature by 2 °C from the energy-saving temperature of 26 °C results in increases of 58.99%, 39.02%, and 28.83% in annual air-conditioning cooling loads. Similarly, for every 2 °C increase in the winter air-conditioning set temperature starting from 20 °C, there is an increase of 35.52%, 33.22%, and 29.37% in annual air-conditioning heating loads [27]. By raising the temperature of a 1.5 p air-conditioner by 1 degree Celsius and running it continuously for 24 h, an average reduction of around 4.5 degrees in electricity consumption can be achieved [28]. Regarding operating duration, research shows that, by adjusting operational modes in six commercial office buildings across three climatic regions, an average total energy saving of 2.7% can be achieved [29]. However, up until now, energy conservation and carbon reduction investigations in HVAC systems have primarily focused on individual factors, such as ventilation, indoor environment, and operating duration, without effectively integrating them. Moreover, compared to previous manual management approaches, this paper aims to achieve precise control through an intelligent perspective, avoiding inadequate manual management. By prioritizing both cost-effectiveness and energy conservation and carbon reduction goals, this research seeks to strike a balance between these aspects.

3. Materials and Methods

3.1. Building Data

This study considers an office building located in the Binhai New Area, Tianjin, China as the analysis subject. The building has a total floor area of 10,211.34 m^2 and features a reinforced concrete frame with shear walls. The shape factor is 0.2, and the basic parameters of the building envelope structure are shown in Table 1. The model is illustrated in Figure 1, and the cross-section is depicted in Figure 2.

The building is primarily used for office purposes and showcasing product images for enterprises. It includes functional rooms, such as offices, conference rooms, and exhibition halls. The personnel density and indoor temperature parameters in different functional rooms have a significant impact on the air-conditioning load. The room zoning parameters are shown in Table 2. A multi-split air-conditioning system with a comprehensive energy efficiency ratio of 3.5 is adopted, and heat recovery is employed for the exhaust air of the air-conditioning system. The heat and cold energy in the exhaust air is used for preprocessing the fresh air. mechanical ventilation heat recovery (MVHR) with heat recovery efficiency of 60%.

Table 1. The building envelope structure parameters.

Enclosure Structure	Heat Transfer Coefficient/[W/(m^2·K)]
ground floor	0.41
outer wall	0.40
partition	0.90
internal floor	0.834
external floor	0.557
external window	2.20
roof skylight	2.20
transparent curtain wall	2.20

Table 2. The building room zoning parameters.

Room	Light Thermal Disturbance (W/m^2)	Equipment Thermal Disturbance (W/m^2)	Occupancy Density (Person/m^2)	Personnel Heat Dissipation (W/Person)	Fresh Air (l/s·Person)	Summer Temperature (°C)	Winter Temperature (°C)
office	9	15	0.125	134	8.33	26	20
meeting room	9	15	0.4	108	3.88	26	18
antechamber	9	15	0.125	134	8.33	26	20
report room	9	15	0.4	108	3.88	26	18
show room	9	15	0.4	108	8.33	26	20
corridor hall	5	15	0.02	134	5.55	26	16
toilet	6	15	0.05	134	5.55	28	18

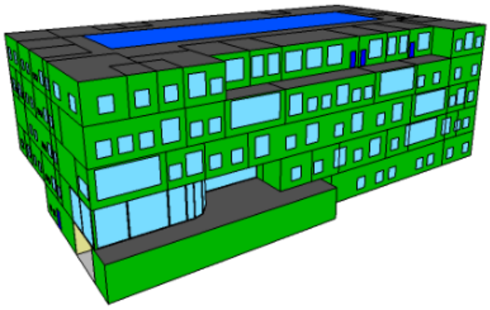

Figure 1. Building Model.

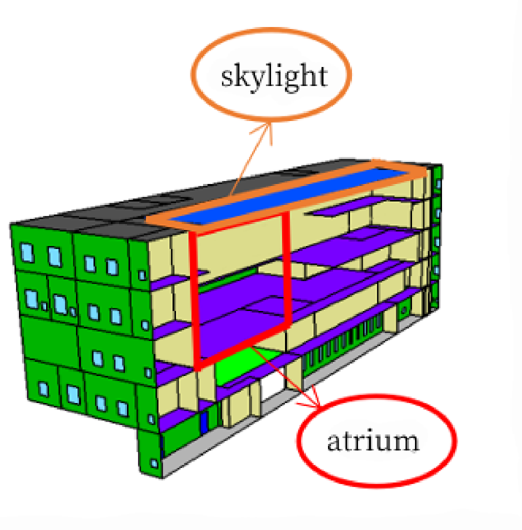

Figure 2. Cross-section.

3.2. Operating Condition

The energy consumption in office buildings primarily consists of lighting energy consumption, air-conditioning heating energy consumption, and office equipment energy consumption. Among them, air-conditioning heating accounts for 40% of the building's energy consumption [30]. In comparison to air-conditioning heating energy consumption, lighting energy efficiency is an aspect that people tend to overlook in their daily lives and in building design. It represents approximately 20% to 30% of the building's energy consumption, with a significant portion attributed to human behavior, both actively and passively [31]. Currently, manual management is the mainstream approach in office buildings, but it often leads to issues of poor comfort and high energy consumption. Conversely, human behavior can also have a substantial impact on operational efficiency. Therefore, from the perspective of operational characteristics, in addition to minimizing the use of high-energy-consuming equipment, it is necessary to optimize and improve operational methods and management details. This will allow people to use buildings in a more comfortable, healthier and more energy-efficient way. Consequently, this study focuses on analyzing the impact of energy consumption and carbon emissions by considering ten different conditions of HVAC heating and lighting systems during the operational stage.

Conditions 1 and 2 are established as the baseline scenarios, representing the operational characteristics of a typical office building. Condition 1 is based on the settings described in reference [29], while Condition 2 is derived from an actual condition study. Condition 1 represents the year-round operation of the air-conditioning system, while condition 2 represents the air-conditioning system operating only in winter and summer seasons. Conditions 3 to 5 focus on energy-saving and carbon reduction optimization for lighting modes. Condition 3 represents the use of energy-saving lamps. Condition 4 represents intelligent lighting and condition 5 represents the combination of energy-saving lamps and intelligent lighting. In the intelligent lighting condition, illuminance sensors are installed within the rooms, and the target illuminance value for the office areas is set at 300 lux, following the Architectural Lighting Design Standard GB50034-2020 [32]. When the indoor illuminance achieved through natural daylight exceeds 300 lux, the lighting fixtures are automatically turned off. When the illuminance falls below 300 lux, the lighting fixtures supplement the lighting to maintain a good illuminance environment indoors. This approach maximizes the utilization of natural daylight during the operational stage, resulting in energy-saving and carbon reduction.

Conditions 6 to 10 represent the energy-saving and carbon-reduction optimization in the hybrid mode. In the hybrid mode, an intelligent control system is implemented to achieve alternating operation between natural ventilation and mechanical ventilation, thereby avoiding any detrimental interference between the two kinds of ventilation. When the indoor temperature exceeds 26 °C, the air-conditioning system is activated, and the windows are closed. When the indoor temperature falls below 26 °C and meets the conditions for natural ventilation (e.g., appropriate outdoor temperature), the windows are opened, and the air-conditioning system is turned off. As there are no specific design standards for hybrid ventilation and its application is still limited, the selection of suitable control parameters to implement a hybrid ventilation scheme is under exploration and harnessing its advantages becomes crucial. This study considers the entire year, and conditions 6 to 8 analyze the impact of indoor temperature variations under natural ventilation conditions on energy-saving and carbon reduction. Conditions 7, 9, and 10 assess the influence of outdoor temperature variations under natural ventilation conditions on energy-saving and carbon reduction. Natural ventilation within this temperature range reduces cooling energy consumption without the need for heating due to excessively low input temperatures, thereby preventing energy waste. By meeting indoor comfort requirements, improving indoor airflow, enhancing air quality, and allowing for maximum window opening time, the operational stage can achieve optimal natural ventilation, thereby realizing energy-saving and carbon reduction objectives. Please refer to Table 3 for specific condition details.

Table 3. Operating condition.

Run Phase		**Operation Mode**	**B.C.**		**L.U.**			**Full Potential**				
			C.1	**C.2**	**C.3**	**C.4**	**C.5**	**C.6**	**C.7**	**C.8**	**C.9**	**C.10**
HVAC		Working day: 7:00–18:00 Holidays: turn off	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Heating season: 11.15–3.15	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Cooling season: 6.1–8.31	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Transition season: 3.16–5.31/9.1–11.14	✓		✓	✓	✓	✓	✓	✓	✓	✓
Lighting		Standard value (9 W/m^2)	✓	✓		✓						
		Linear value (8 W/m^2)			✓		✓	✓	✓	✓	✓	✓
		Intelligent lighting				✓	✓	✓	✓	✓	✓	✓
Mixed ventilation	Natural ventilation opening conditions (indoor temperature)	—	✓	✓	✓	✓	✓					
		20 °C						✓				
		22 °C							✓		✓	✓
		24 °C								✓		
	Natural vebtilation opening conditions (outdoor temperature)	—	✓	✓	✓	✓	✓					
		20–22 °C						✓	✓	✓		
		20–24 °C									✓	
		20–26 °C										✓

B.C denotes basic conditions. C denotes condition. L.U. denotes lighting upgrade. Full Potential denotes both lighting upgrade and hybrid ventilation mode being used. ✓represents condition matches the corresponding description in Operation Mode.

3.3. Economic Calculation

This section discusses the condition study based on an office building with a total area of approximately 10,200 m^2. The average unit electricity price P_{ue} is 0.9 ¥/KWh. Based on project experience, the estimated unit cost for the renovation (or construction) is $20/\text{m}^2$. The total renovation investment I can be calculated using the Formula (1).

$$I = P_{uc} \times \ Area \tag{1}$$

Compared to the coupling effect without the use of hybrid mode, intelligent lighting, and energy-efficient lighting fixtures, the total economic savings P_{ae} can be calculated by multiplying the annual saved electrical energy ES_{all} with the unit price of electricity P_{ue}:

$$P_{ae} = \ ES_{all} \times \ P_{ue} \tag{2}$$

The annual saved electrical energy ES_{all} can be expressed as follows:

$$ES_{all} = \ ES_{light} + ES_{ac} + ES_{other} \tag{3}$$

ES_{light} represents the electricity saved due to lighting adjustments, ES_{ac} represents the electricity saved due to air-conditioning adjustments, and ES_{other} represents the electricity saved due to adjustments from other factors (such as air-conditioning fans, etc.).

The static payback period T can be determined by the total investment cost I divided by the average annual net cost savings P_{ae}. Refer to Equation (4):

$$T = I/P_{ae} \tag{4}$$

From Equations (1)–(4), we can derive the following equation:

$$T = \frac{P_{uc} \ \times \ Area}{\left(ES_{light} \ + \ ES_{ac} \ + \ ES_{other}\right) \ \times \ P_{ue}} \tag{5}$$

4. Results and Discussion

4.1. Comfort Analysis

Based on Figures 3–5, it can be observed that condition 2 (air-conditioning operating only in winter and summer seasons) exhibits significantly higher room temperatures during the transitional seasons compared to other conditions, with a difference of approximately 3–8 °C, which leads to extreme discomfort. Based on the statistical analysis of the comfort zone graph, the hybrid mode (conditions 6–10) shows an average reduction of 108.55 h in the unsatisfactory hours compared to the baseline conditions (conditions 1–2). Among them, condition 10 has the lowest number of unsatisfactory hours, achieving a reduction of 36.5 h and 202 h compared to condition 1 (year-round operation of air-conditioning) and condition 2, respectively. With an increase in indoor–outdoor temperature conditions for window opening, the unsatisfactory hours initially decrease and then increase. This is because the intermediate range of temperature values under natural ventilation conditions is more likely to meet comfort requirements.

The temperature variation trend throughout a day, as shown in Figure 6; the left side represents condition 2. The indoor temperature reaches its peak at around 3 PM, reaching a maximum of 36 °C, requiring the air-conditioning to effectively cool the space. The right side represents condition 10. During the morning period, window ventilation is employed when the indoor temperature falls below 26 °C, maintaining it within the range of 22–26 °C. In the afternoon period, when the indoor temperature exceeds 26 °C, the air-conditioning is activated to maintain the temperature at 26 °C. Additionally, due to the impact of thermal pressure (atrium) and thermal radiation (skylights), the temperature in the five-floor office space is higher than the other floors [33], with a temperature decrease observed at 12:00. This is because lighting usage and occupancy decrease during this period. Therefore, it is recommended to utilize thermal pressure ventilation in the high-ceiling space above pedestrian areas to enhance the exhaust of indoor hot air and improve thermal comfort while achieving carbon emissions reduction.

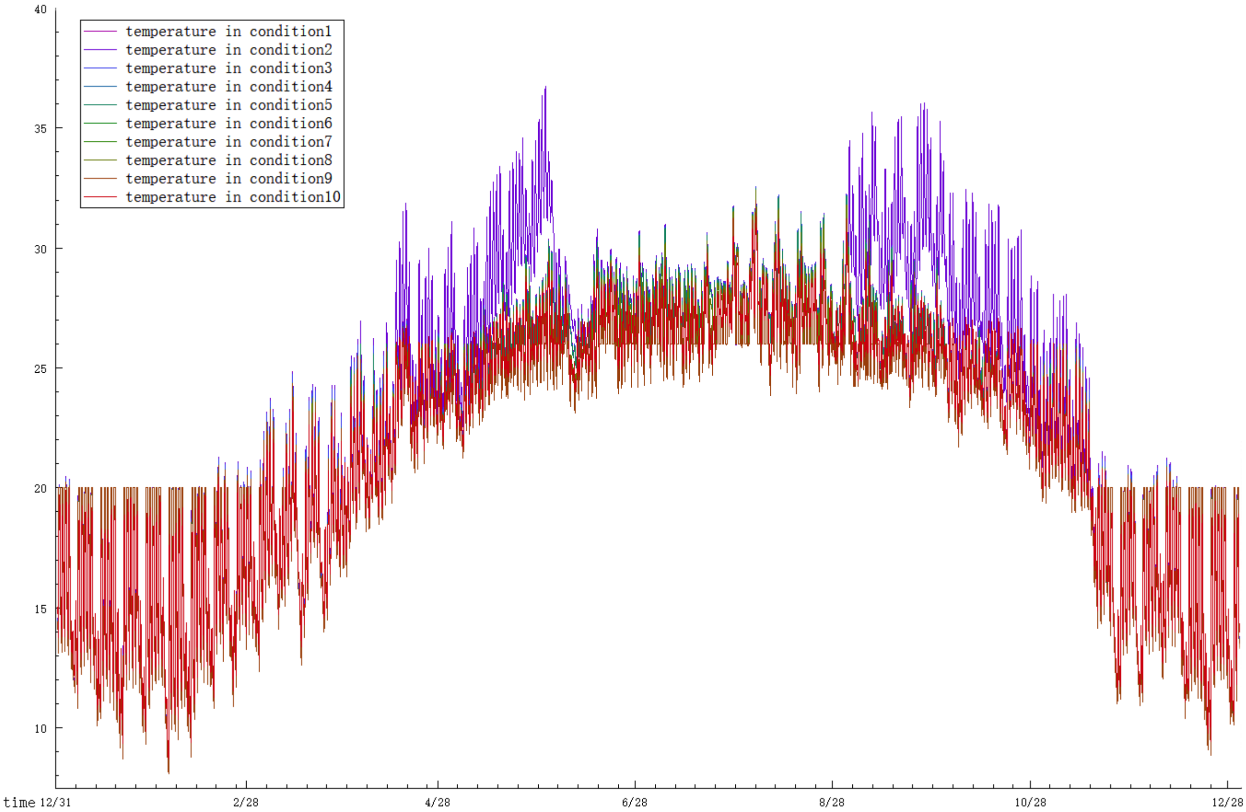

Figure 3. Year-round temperature simulation.

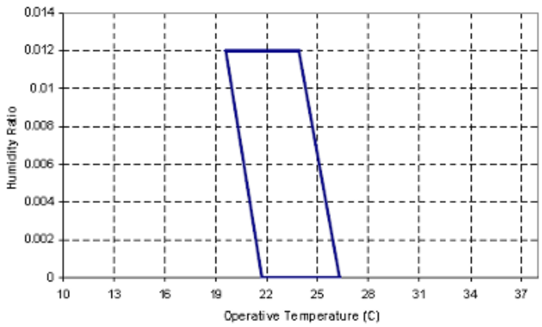

Figure 4. Graphic comfort zone winter (1.0 Clo).

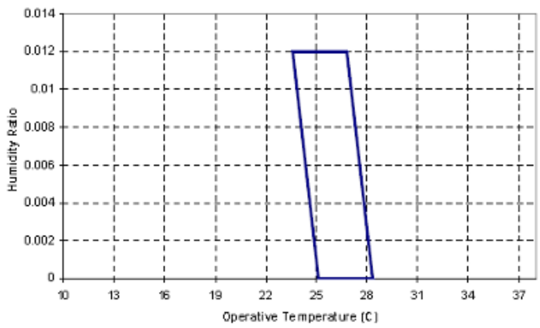

Figure 5. Graphic comfort zone summer (0.5 Clo).

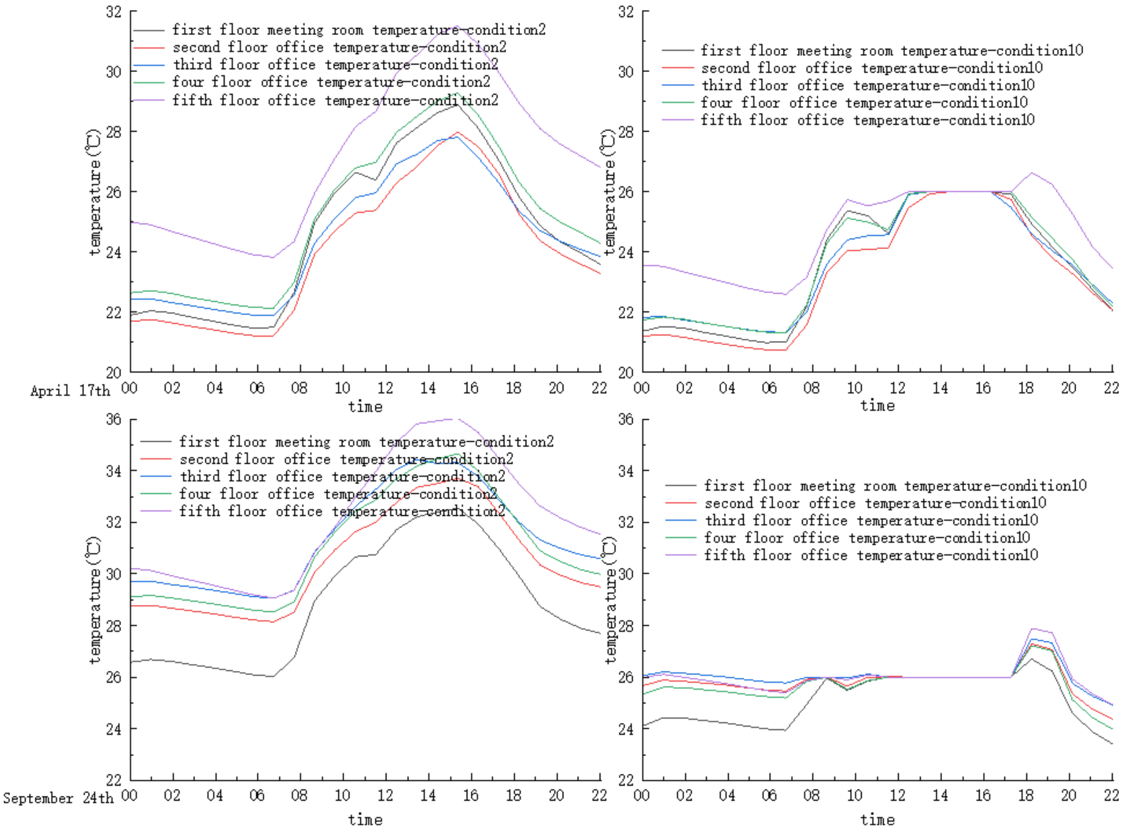

Figure 6. Temperatures of condition 2 and condition 10 in 24 h.

4.2. Energy Saving and Carbon Reduction Analysis

4.2.1. Lighting System

By comparing condition 3 with condition 1, it can be observed that in the main functional rooms, such as offices, meeting rooms, and reception areas, using energy-saving lamps reduces the lighting power density from the standard value of 9 W/m^2 to the restricted value of 8 W/m^2. This results in a reduction of 17.05 MWh in lighting energy consumption, which corresponds to a 10.61% decrease. The carbon emissions are reduced by 1.02 kg CO_2/(m^2·a) per unit area per year. The heat generated by the lighting system influences the load and subsequently affects the energy consumption of other systems, such as fans, cooling, and heating. Comparing condition 4 with condition 1, it is evident that by adopting the intelligent lighting mode alone, lighting energy consumption can be reduced by 49.87 MWh, representing a decrease of 31.04%. This translates to a carbon emissions decrease of 3.04 kg CO_2/(m^2·a) per unit area per year. These results indicate that the carbon reduction effect of the intelligent lighting mode is remarkable compared to using energy-saving lamps. By comparing condition 5 with condition 3, it can be observed that by combining intelligent lighting with reduced lighting power density, lighting energy consumption can be reduced by 42.22 MWh, representing a decrease of 29.40%. This corresponds to a carbon emissions decrease of 2.40 kg CO_2/(m^2·a) per unit area per year. These results indicate that there is still room for significant improvement even when using energy-saving lamps. Moreover, conditions 3 to 5 show no reduction in lighting duration, suggesting that the indoor illuminance environment cannot rely solely on natural daylighting. Instead, artificial lighting is supplemented by automatic adjustment based on external weather conditions to achieve energy-saving and carbon reduction goals. By comparing condition 5 with condition 1, it can be observed that the combination of energy-saving lamps and intelligent lighting in the lighting system results in a carbon reduction of 3.37 kg CO_2/(m^2·a) per unit area per year. The energy consumption for cooling decreases, while the energy consumption for heating increases, resulting in a carbon reduction of 3.42 kg $CO_2/(m^2{\cdot}a)$ per unit area per year. This indicates a significant carbon reduction effect on lighting energy consumption. To ensure a good illuminance environment, maximizing the utilization of natural daylighting is recommended. In architectural floor design, a decentralized core arrangement can be adopted, along with the effective utilization of intelligent lighting systems. The annual simulation results of sub-energy consumption are shown in Figure 7.

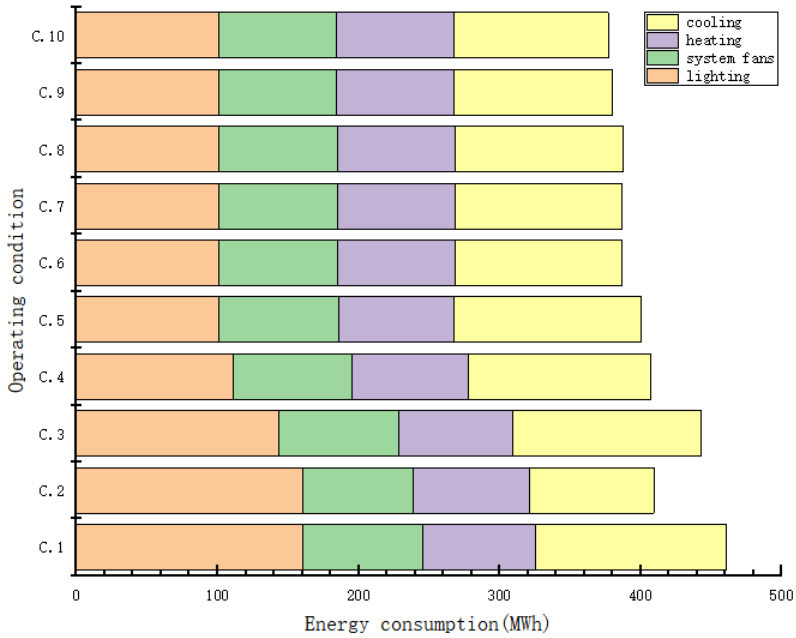

Figure 7. Annual sub-energy consumption simulation results.

4.2.2. HVAC System

From the comparison between condition 2 and condition 1, it can be observed that when the air-conditioning operation is shifted from year-round to winter and summer seasons, cooling energy consumption decreases by 46.48 MWh, representing a reduction of 34.43%. Additionally, fan energy consumption decreases by 6.82 MWh, resulting in an annual carbon reduction of 29,638.0 kg CO_2/a and a unit area annual carbon reduction of 2.90 kg $CO_2/(m^2{\cdot}a)$. The energy-saving and carbon-reduction effects are significant. However, this approach does not guarantee thermal comfort during the transitional seasons, leading to extreme discomfort. Therefore, sacrificing thermal comfort during transitional seasons for the sake of energy saving and carbon reduction is not recommended. From conditions 6 to 8, it can be observed that when the outdoor temperature range for natural ventilation remains constant, each 2 °C increase in indoor temperature does not significantly affect cooling energy consumption. The unit area carbon emissions for cooling remain around 22 kg $CO_2/(m^2{\cdot}a)$. This is because the temperature range set in condition 6 already covers conditions 7 and 8, and the increase in indoor temperature does not result in a significant change in operational hours. Thus, optimizing indoor temperature monitoring has minimal impact on cooling energy consumption. By comparing conditions 7, 9, and 10, it can be observed that when the indoor temperature remains constant under natural ventilation conditions, each 2 °C increase in outdoor temperature leads to a 2% to 5% decrease in cooling energy consumption. The unit area annual carbon emissions can be reduced to approximately 21.42 kg $CO_2/(m^2{\cdot}a)$. Therefore, it is recommended to adopt a hybrid mode with precise window opening control. The control system parameters should be set to an indoor temperature of 22 °C and window opening conditions of outdoor temperature ranging from 20 °C to 26 °C. This approach results in a unit area annual carbon reduction of 1.37 kg $CO_2/(m^2{\cdot}a)$ for the HVAC system. It ensures maximal window opening time, enables the highest degree of natural ventilation during the operational phase, and minimizes unsatisfied hours, thus achieving the most optimal energy-saving and carbon-reduction effect. In summary, by emphasizing seasonality and utilizing the coupled operational characteristics of energy-saving lighting fixtures, intelligent lighting, and hybrid mode, total energy consumption can be reduced by 83.46 MWh. Compared to the traditional mode, energy consumption during the operational phase can be reduced by 18.12%, with a unit area energy consumption of 36.98 kWh/(m^2·a). The unit area annual carbon reduction is 4.74 kg CO_2/(m^2·a). The unit area energy consumption and carbon emission results are shown in Figure 8.

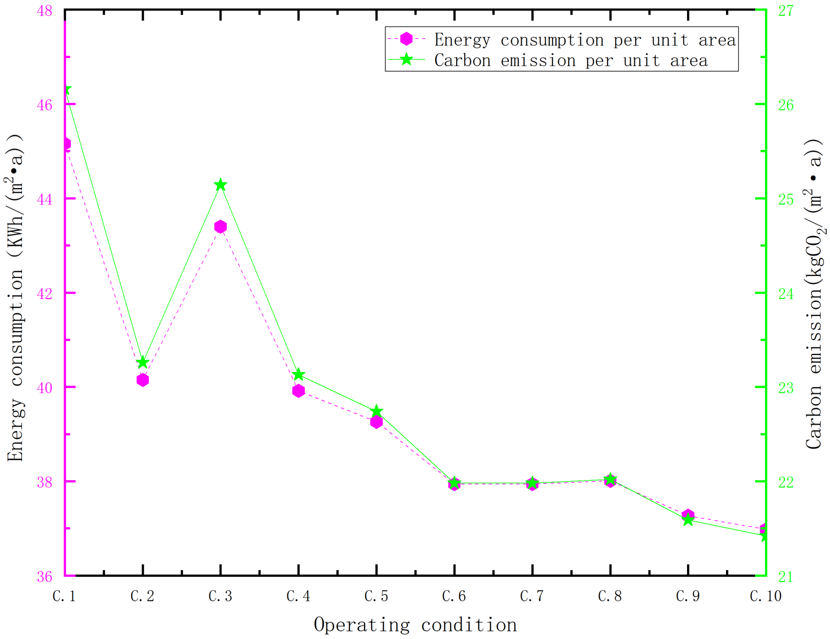

Figure 8. Unit area energy consumption and carbon emission results.

While countries like the United States [20,29] have made efforts to reduce energy consumption, operational costs, and carbon emissions to some extent, they have not fully utilized the coupling of intelligent lighting with a hybrid mode to achieve maximum natural daylighting and ventilation during office hours. Compared with research undertaken on the operational characteristics of office buildings in China [34–38], this study focuses on analyzing a neglected operational mode and management detail during the operational phase. By implementing energy-saving and user-oriented measures, the study aims to encourage energy-saving behavior among users. The aims are to maximize the window-opening time and improve the energy efficiency of office buildings by reducing the indoor temperature during nights and weekends to alleviate air-conditioning loads. Additionally, this research emphasizes the advantages of energy conservation and carbon reduction, as well as investment returns, based on the corresponding improvement measures. This further highlights the feasibility and practicality of the proposed approach. In light of the current situation, the following recommendations are proposed:

(a) Further research on the operational characteristics of Chinese office buildings. It is necessary to conduct more in-depth research on the operation mode and management mechanism of Chinese office buildings in order to formulate targeted improvement measures.
(b) Integrating smart technologies and the Internet of Things (IoT.). The application of smart technology and the IoT. has great energy-saving potential in building operations, such as smart lighting, automation control and sensing technology, etc.
(c) Auxiliary decision support systems. The development and application of auxiliary decision support systems will help operation managers to better monitor, analyze and

optimize the energy consumption and operation status of buildings, guide managers to make decisions, and achieve the building's energy-saving and carbon-reducing goals.

(d) Enhance user participation awareness. The user's behavior, habits and awareness are crucial to the effect of energy saving and carbon reduction. It is recommended to raise users' awareness of the importance of energy conservation through education and participation activities and to encourage them to adopt energy-saving behaviors in office buildings.

4.3. Economic Analysis

Figure 9 presents the static payback periods for various operating conditions; the results can be derived using Equation 5. It can be deduced that the static payback periods across different operating conditions average around 3 years except for operating conditions 4 and 5. This variation can be ascribed to the absence of the HVAC intelligent control system in conditions 3–5, which facilitates the alternating operation between natural ventilation and mechanical ventilation. Consequently, the total renovation investments in these three conditions are significantly lower compared to others, resulting in shorter static payback periods in conditions 4 and 5. However, it is important to note that such conditions may be accompanied by suboptimal indoor air quality. In conditions 6–10, diverse ventilation strategies yield varying static payback periods, despite having equal total renovation investments. Among all the operating conditions, condition 10 exhibits the shortest payback period, which is around 2.7 years, making it a valuable guidance principle for resource conservation in practical projects.

Moreover, this calculation of the static payback period T only considers the savings in electricity resources. It is observed that the use of intelligent lighting control systems can successfully extend the lifespan of lamps by 2–4 times, resulting in significant cost savings in lamp procurement and a substantial reduction in the workload of lamp replacements. This also leads to an approximately 30% reduction in maintenance personnel costs (considering difficult-to-install lamps and expensive lamps, this cost may further increase). Taking these factors into account, the actual static payback period T will be shorter than the static payback period illustrated in Figure 9, indicating a significant investment return.

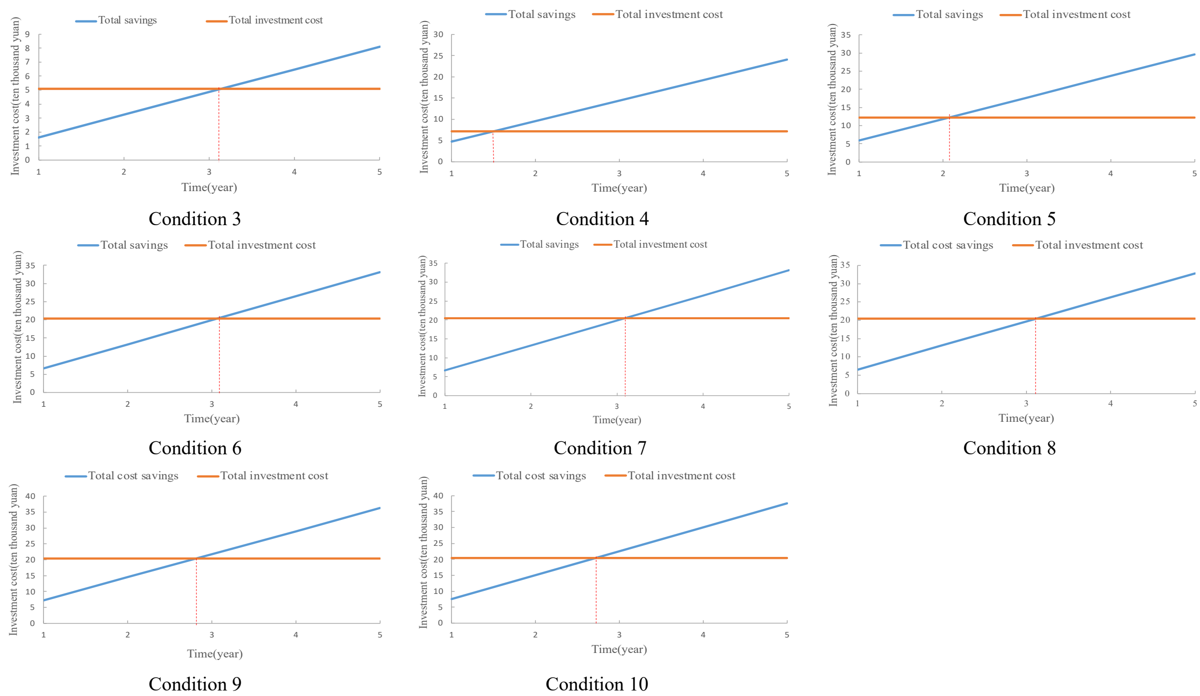

Figure 9. Static payback periods for different operating conditions.

5. Conclusions

This paper focuses on office buildings in cold regions, with comfort and cost-effectiveness as the premise and energy-saving and carbon reduction as the goal. DesignBuilder software was used to numerically simulate a total of 10 operating conditions of the HVAC and lighting systems during the operational stage. The study sought to reveal the influence of operational characteristics of office buildings in cold climate zones on carbon emissions and propose targeted energy-saving and carbon reduction measures. The main conclusions are as follows:

1. Regarding the HAVC, a hybrid mode is adopted with the control system parameters set at an indoor temperature of 22 °C and window opening conditions ranging from an outdoor temperature of 20 to 26 °C. The annual carbon reduction of the HVAC heating system per unit area is 1.37 kg $CO_2/(m^2 \cdot a)$. Uncertain meteorological parameters are taken into account to determine the control system and parameters. By ensuring indoor comfort requirements, improving air quality, and maximizing window opening time, the operational stage aims to achieve maximum natural ventilation, reduce the energy consumption of mechanical ventilation, and ultimately achieve energy-saving and carbon reduction goals.
2. Regarding the lighting system, energy-efficient fixtures and intelligent lighting modes are used, with an annual carbon reduction of 3.37 kg $CO_2/(m^2 \cdot a)$ per unit area of the lighting system. By automatically adjusting or turning off lighting devices based on the perceived natural light intensity, the operational stage aims to achieve maximum natural daylighting while maintaining a well-lit indoor environment. This approach helps to avoid energy waste and achieve energy-saving and carbon reduction goals.
3. The operational characteristics of the hybrid mode, energy-efficient fixtures, and intelligent lighting coupling represent an energy-saving and environmentally friendly approach. It not only extends the lifespan of equipment and lighting fixtures but also reduces operational costs and maintenance expenses. Furthermore, it improves indoor air quality, which is beneficial for addressing China's indoor air quality and energy issues. This approach provides more reasonable technical support for exploring the pathway to carbon neutrality and the practical application of projects.

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