Carbon emission measurement of the envelope of a university teaching building in Hefei City

Shenqi Gan[1,2,*], Jiawang Feng[1,2,†], Bigen Fang[1,2] and Wenxiang Chen[1,2]
[1]School of Architecture and Urban Planning, Anhui Jianzhu University, No.292 Ziyun Road, Shushan District, Hefei 230601, China; [2]Built Environment and Health Research Center, Anhui Jianzhu University, No.292 Ziyun Road, Shushan District, Hefei 230601, China

Abstract

In response to the challenges posed by global warming, China has formulated dual carbon goals. In this context, the construction industry, a key carbon emitter, is vital for implementing energy-saving and emission-reducing strategies. This study zeroes in on the pivotal role of building envelope structures in carbon emissions, with a focus on a university building in Hefei. Commencing with onsite measurements to gather initial data, the study leverages simulation software to conduct an in-depth analysis. Employing orthogonal experimental design and variance analysis, it meticulously assesses the carbon emissions associated with different materials used in exterior walls, roofs and windows, considering both the material production and building operation phases. The research scrutinizes the impact of these materials on carbon emissions, with a special focus on the performance of seven distinct building retrofit schemes. Key findings of the study underscore that the type and thickness of exterior wall materials substantially influence carbon emissions during the production phase. Conversely, the choice of window materials emerges as more critical in reducing emissions during the building operation phase. The implementation of the various retrofit schemes demonstrates a tangible reduction in overall building carbon emissions. Specifically, these schemes yield a yearly reduction in carbon emissions of 2.96–3.62 tons during operation and a substantial decrease of 30.36–165.97 tons in the production phase, compared to the original structure of the case study building. These insights not only offer practical and viable strategies for the construction industry's low-carbon development but also provide theoretical underpinnings and references for future building designs and retrofits.

Keywords: analysis of variance; carbon emission measurement; DesignBuilder; enclosure structure; green transformation; orthogonal experiment; reconstruction cost

*Corresponding author: 46726519@qq.com

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1 INTRODUCTION

On 22 September 2020, at the general debate of the 75th session of the United Nations General Assembly, the Chinese government solemnly pledged to adopt bolder policies and measures to ensure that the peak in carbon dioxide emissions is reached before 2030 and carbon neutrality is achieved before 2060 [1]. In recent years, global carbon emissions have continued to rise, of which the construction industry accounts for the largest proportion, so carrying out research on building carbon emissions plays an important role in promoting the implementation of China's 'double carbon' goal. The Research Report on China's Building Energy Consumption and Carbon Emission (2022) published by the China Building Energy Efficiency Association points out that the total carbon emissions of the whole building process in China in 2020 will be 5.08 billion tCO_2, accounting for 50.9% of the national carbon emissions [2]. The heat loss caused by the building envelope is higher than 20%, among which the heat loss caused by windows and external walls accounts for the highest proportion [3]. Therefore, it is of great significance to focus on carbon emission

†, https://orcid.org/0009-0005-6822-1488
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research on the building envelope structure to reduce building carbon emissions and realize the aforementioned dual carbon goal as soon as possible in China.

Since the dual carbon goal was proposed in 2020, China has conducted extensive and in-depth studies on building carbon emissions and low-carbon development [4–15]. Related research on urban green renewal and carbon emission calculation, Ding *et al.* [16] analyzed the link between the epidemic and urban green space, focusing on the significance and advantages of China's national garden city policy. The research shows that the selection criteria of China's national garden city have changed from quantity to quality, and the disaster preparedness capacity of the city has been strengthened. It provides valuable experience for the green development of the city. Ren *et al.* [17] summarized the development history, hot spots and trends of urban public open space and carried out statistical analysis through the bibliometric method. The research indicates that in the future, urban public open space research should change the design concept, strengthen the people-oriented concept and provide a theoretical basis for the low-carbon transformation of the city. Yao *et al.* [18] conducted a bibliometric analysis of high-density cities, explained their development track and summarized the research hotspots in this field after the 21st century, providing valuable experience for the green renewal of cities. Xinhui *et al.* [19] took the Yangtze River Economic Belt as an example, and on the basis of elaborating the mechanism of urban form on carbon emissions, they quantitatively assessed urban form with multi-source data and evaluated the impact of urban form on carbon emissions at global and subregional scales from 2005 to 2020 by using spatial econometric models and geographic detectors, respectively. Based on the panel data of China's super large cities from 2007 to 2020, Huixiang [20] conducted an empirical study on the impact of urban production, technology and life factors on carbon emissions by using a STIRPAT model and concluded four 'two-carbon' development models through comparative analysis.

In the field of building carbon emission accounting research, Beijia *et al.* [21] compared the carbon emissions of residential buildings and non-residential buildings in Shanghai, studied the trend in building carbon emissions in Shanghai and proposed corresponding emission reduction countermeasures. Mingchao *et al.* [22] took prefabricated buildings as the research object, calculated the carbon emissions in the whole life cycle of prefabricated buildings by establishing a carbon emission accounting model and analyzed the distribution relationship of carbon emissions at each stage. Liu Yueli and Wei [23] calculated the carbon emissions of public service buildings in China using two methods and analyzed the influencing factors of carbon emissions in this industry using the logarithmic mean divisia index (LMDI) model. Min *et al.* [24] elaborated the division and accounting methods of carbon emission accounting for the construction sector at home and abroad and pointed out the problems existing in the existing carbon emission accounting boundaries. Zhu *et al.* [25], relying on the core collection of Web of Science, discovered that establishing a zero-carbon community is primarily associated with decisions regarding building structure and the selection of building materials. Wu *et al.* [26] conducted a bibliometric analysis of literatures related to resilient cities to analyze their related research progress, fields, hotspots and strategies. And the analysis provides suggestions for the low-carbon urban renewal.

Aiming at the research on carbon emissions in the physical and chemical stage of buildings, Mengmeng *et al.* [27] established a calculation model of carbon emissions in the physical and chemical stage of prefabricated buildings by means of a carbon emission coefficient method. On the basis of data quantification, from the perspective of project management, a structural equation model (SEM) is used to deeply analyze the influencing factors of carbon emissions in the physical and chemical stage of prefabricated buildings. Yu *et al.* [28] calculated and compared the carbon emissions of traditional buildings, prefabricated buildings and green buildings in the materialization stage. Yanli *et al.* [29] analyzed the differences in carbon emissions between prefabricated buildings and traditional buildings in the physical and chemical stage, evaluated the emission reduction in the former and provided a basis for the formulation of building emission reduction programs. Hongmin *et al.* [30] studied the carbon cycle of light-wood-structure and bamboo-structure buildings in the physical and chemical stage; proposed a calculation method of carbon emissions of bamboo and wood structures that considered the contribution of metal connectors; explored their contribution degree across the physical and chemical stages of buildings; and then compared the results of carbon emissions of bamboo and wood structures, concrete structures and steel structures. Cheng *et al.* [31] set up the carbon emission accounting system in the physical and chemical stages of buildings using the carbon emission factor method. The carbon emissions of 15 houses in Shaanxi Province were calculated using this system. The results show that the carbon emissions in the production stage of building materials range from 372.43 to 525.88 $kgCO_2/m^2$, accounting for 94.27% of the total emissions.

In order to analyze the influencing factors of carbon emissions in the stage of building operation, many scholars have conducted in-depth studies in this field: Yuanyuan *et al.* [32] showed that energy-saving technological transformation of hospital equipment and facilities in the stage of hospital operation can reduce carbon emissions in the stage of hospital operation and can also provide technical support for the subsequent energy management of the hospital. Mingzhu *et al.* [33] started with the carbon emission sources of public buildings in the operation stage, based on the questionnaire data and the proposed hypothesis, and used the SEM method and AMOS software to build the driving SEM of carbon emission reduction in the operation stage of public buildings. The results showed that the policy factors and ecological value factors were related. The standardized path coefficient is the highest. Based on Wuhan Statistical Yearbook and public building energy audit data, Fangwei *et al.* [34] analyzed the carbon emissions of various public buildings, established regression equations of carbon emissions and floor area of relevant public buildings and proposed two calculation methods for total carbon emissions of public buildings. Junjie *et al.* [35] used the population, affluence and Technology Random Effects Regression (STIRPAT) method to investigate the contribution of various drivers to carbon emissions from public buildings, and they simulated seven scenarios to predict the change trend of carbon emissions during the operation phase of public buildings. Yuchong *et al.* [36] proposed a low-intervention carbon footprint accounting system based on the digital twin management platform to measure carbon emissions in the building operation stage.

Aiming at the research and application of low-carbon building technology, Zhu H *et al.* constructed a residential building model of Changsha City based on actual research data and screened out decision parameters that have an important impact on carbon emissions and thermal comfort based on a comprehensive sensitivity analysis method. The filtered data set is used to train the backpropagation neural network model, and the feasibility of the model is verified using multiple indexes. Finally, based on the Pareto frontier set results, non-dominated sorting genetic algorithm III is selected and combined with the backpropagation neural network model to solve the multi-objective optimization problem [37]. Based on the data of the energy-monitoring center, Yanghui *et al.* [38] calculated the carbon emission of a university building in Jiangxi during its operation period from 2017 to 2021, predicted the change trend of carbon emission from campus building operation in 2022–2035 and put forward targeted carbon reduction suggestions. Yixin *et al.* [39] explored sustainable retrofit design strategies and technological methods for constructing intelligent educational buildings with near-zero energy consumption and excellent indoor environmental quality and functionality in the cold climate of northern Germany, using the Energy School Project as an example. Ding Xiaoxin *et al.* [40] took prefabricated components as research objects and established SEM models based on the principle of multivariate data analysis, revealing that prefabricated components are affected by multiple factors.

The above research shows that China's research and practice in building low energy consumption and green development have been at the forefront of the world. This paper mainly studies the green transformation and low-carbon design of existing buildings and takes a teaching building of a university as a case to specifically analyze the impact of the change of the envelope structure on the carbon emissions in the physical and operational stages of the building, so as to provide theoretical basis and design reference for the green transformation and low-carbon design of buildings. The technical roadmap depicted in Figure 1 illustrates the approach taken in this paper.

2 CALCULATION METHOD OF CARBON EMISSION

Aiming at the stage division of building life cycle theory [41], the China Building Energy Consumption Research Report pointed out that carbon emissions in the building material manufacturing stage accounted for 55.2% of building life cycle carbon emissions, the construction stage accounted for 2% of building life cycle carbon emissions and the building operation stage accounted for 42.8% of building life cycle carbon emissions [42]. It can be seen that most of the carbon emissions of buildings come from the building material manufacturing stage and the building operation stage. The carbon emission research in this paper mainly focuses on these two stages. The carbon emission factor method [43] is chosen as the carbon emission calculation method, and the calculation Standard for Building Carbon Emission (GB/T51366-2019) is referred to Ref. [44]. The specific calculation formula is as follows:

$$\mathrm{C_{SC}} = \sum\nolimits_{i=1}^{n} \mathrm{M_i F_i} \#(1)$$

$$\mathrm{C_M} = \frac{\left[\sum_{i=1}^{n} \mathrm{E_i EF_i}\right] \mathrm{y}}{\mathrm{A}} \#(2)$$

where C_{SC} is the carbon emissions in the building material production stage, kgCO$_2$e; F_i is the consumption of the i main building materials; F_i is the carbon emission factor of the i main building materials, kgCO$_2$e/unit quantity of building materials; C_M is carbon emission per unit building area in the operation stage of the building, kgCO$_2$/m^2; E_i is the annual consumption of Class i energy, in unit/a; E#x1D439;$_i$ is the carbon emission factor of Class i energy; y is the design life of the building, a; and A is the building area, m^2.

3 CASE ANALYSIS

3.1 Case introduction

The case selected is a teaching building of a university in Hefei, Anhui province. Built in 2012, the main body of the building adopts a cast-in-place reinforced concrete frame structure, and the roof has a cast-in-place reinforced concrete beam and slab structure. The whole building plan is formed by two 'mouth' fonts interlocking, connected by a corridor, enclosing two courtyard spaces. The building has a total of five floors, the building height is 21.6 m, the building area is 23 288 m^2, there is no underground layer and the building design service life is 50 years. The teaching building has a total of 71 classrooms, including 20 classrooms for 160 people, 51 classrooms for 120 people and 17 auxiliary rooms (offices, duty rooms, etc.). The case building envelope structure and thermal parameters are shown in Table 1.

3.2 Feasibility of case building energy conservation and emission reduction

The parameters in Table 1 are compared with the thermal parameters of public building envelope stipulated in Technical Standard for Near Zero Energy Buildings (GB/T51350-2019) [45] and General Code for Building Energy Efficiency and Renewable Energy Utilization (GB55015-2021) [46], as shown in Table 2. It can be seen that there is a certain gap between the thermal parameters of the case building and the values of the two codes, so the thermal performance of the outer envelope of the selected case building really needs to be reformed.

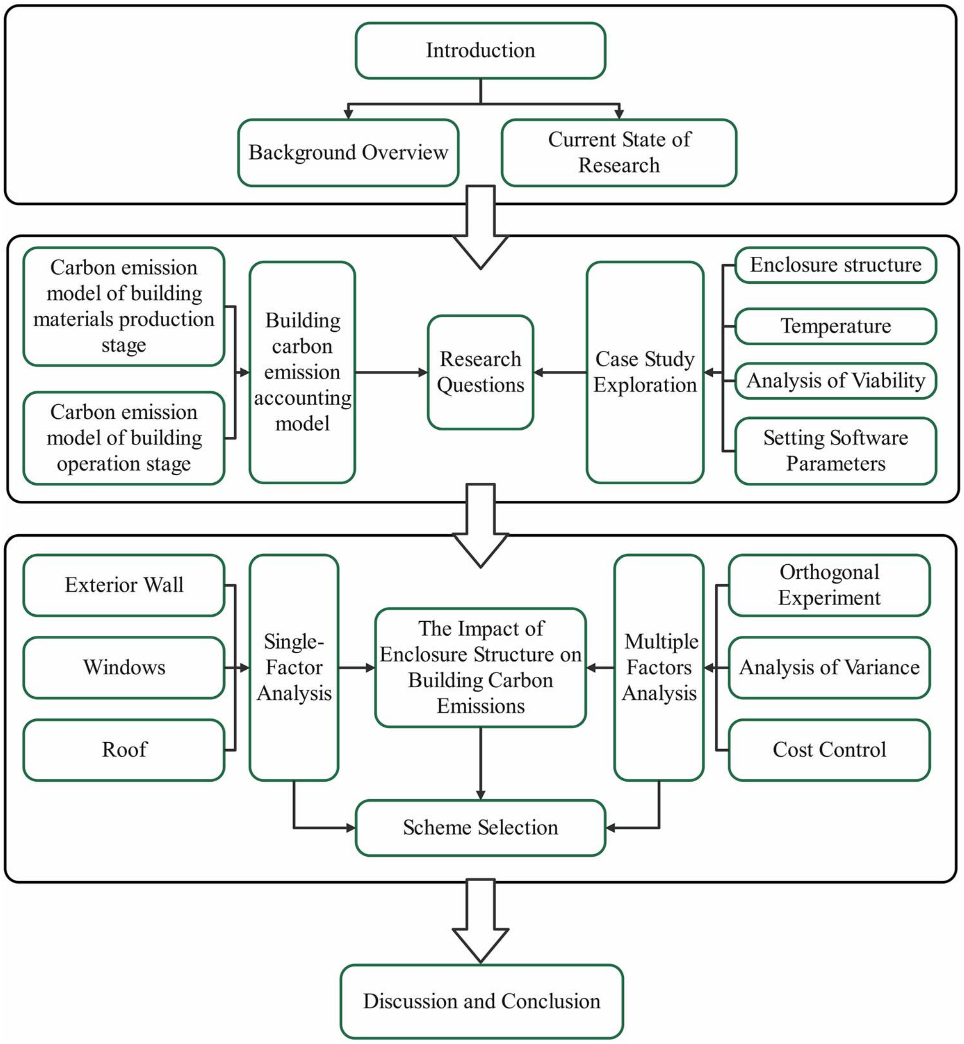

Figure 1. *Technology roadmap.*

Table 1. *Construction method and thermal parameters of building envelope structure.*

Type of enclosure structure	Construction method	Heat-transfer coefficient (W/(m ^{2}·K))
Exterior wall	20 mm cement mortar + 200 mm coal gangue hollow block + 40 mm rubber powder polystyrene particle insulation slurry + alkali resistant fiberglass mesh cloth, polymer crack-resistant cement mortar protection + decorative layer	0.84
Roof	1:2 cement mortar protective layer + one layer of styrene butadiene styrene (SBS) roll waterproof layer + 20 mm cement mortar leveling layer + 1:8 cement expanded perlite 2% slope + 40 mm extruded polystyrene board insulation layer + cast-in-place reinforced concrete structural layer	0.62
Ground	Fine aggregate concrete or floor tiles + 25 mm cement mortar leveling and bonding layer + 80 mm reinforced concrete + 100 mm crushed stone, pebble concrete + plain soil compaction	0.49
Window	Insulated aluminum alloy white insulating glass (6 + 9A + 6)	3.30

3.3 Carbon emission of building envelope

Relevant data were sorted out and analyzed to calculate the carbon emissions of the building material production stage and operation stage of the building; the specific values are shown in Table 3.

3.4 Simulation software

This paper uses DesignBuilder software to simulate and qualitatively analyze carbon emissions of case buildings, which is accurate and useful for the simulation of building energy

Table 2. *Comparison of thermal parameters of building envelope structures—unit: heat transfer coefficient (W/(m²·K)).*

Enclosure structure	Technical standards for near-zero-energy-consumption buildings	General specification for building energy conservation and renewable energy utilization	Case architecture
Roof	0.15∼0.35	≤0.40	0.62
Exterior wall	0.15∼0.40	≤0.80	0.84
Window	≤2.2	≤3.00	3.30

Table 3. *Carbon emissions during the production and operation stages of building materials.*

Category	Carbon emissions in building material production stage) (unit: tCO_2e)	Carbon emission per unit building area during construction operation (unit: $kgCO_2/m^2$)	Annual carbon emissions during construction operation (unit: tCO_2e)
Value	362.42	1397.74	651.01

The carbon emissions in the production stage of building materials in the table refer to the carbon emissions generated by building external wall insulation materials, roof insulation materials and external window materials in the production stage.

consumption [47]. The software application is divided into three steps. The first step is the parameter setting and simulation of the measured environment of the case building. The error values of the measured data and the simulated data are compared to verify the parameter setting to ensure the reliability of the simulation. The second step is the single factor simulation of the outer envelope structure, comparing the exterior wall, exterior window and roof with different heat transfer coefficients, and qualitatively analyzing the influence of different factors on the carbon emission of the building. The third step is to optimize and integrate all single factors through an orthogonal test method, and simulate and analyze the influence of the multi-factor scheme on building carbon emissions, so as to determine the carbon reduction transformation scheme suitable for the building envelope structure.

3.5 Parameter settings

Hefei, located in the middle of Anhui Province, is an area with typical hot summer and cold winter climate. The meteorological data on Hefei in the Chinese standard meteorological database CSWD in DesignBuilder were used [48]. Compared with other types of buildings, the teaching building has obvious characteristics in use, that is, during the coldest and hottest winter and summer vacations throughout the year, the electrical equipment in the teaching building is closed or in a low running state. Combined with this feature, the heating season is set as November 15th to March 15th every year, of which February 1st to March 1st is the winter vacation period; June 1st to September 15th is the cooling season, of which July 1st to September 1st is the summer vacation period. The main spaces of the building, such as classrooms and faculty offices, are equipped for heating and cooling, while the rest of the space is left uninstalled. According to the relevant specifications and design data set, the classroom density is set to 2 m²/person. During weekends and winter and summer vacations, the classroom in the case building is deserted. The indoor temperature of the case building is set at 18°C in the winter heating period and 26°C in the summer cooling period. The parameters of each room are shown in Table 4. The air conditioner is a multi-coupled air conditioner unit with an energy efficiency ratio of 2.9 for cooling and 2.4 for heating.

3.6 Field measurement and verification

The case building was tested on 31 July 2023, and the architectural model is shown in Figure 2. According to the indoor and outdoor characteristics of the building, such as the building orientation, number of building floors, envelope structure, spatial function and patio space, seven measuring points are selected and arranged in representative parts, as shown in Figure 3. Among them, measuring point 1 is the foyer on the first floor of the case building, and the other measuring points are arranged on the second floor of the building. The height of the measuring point is 1.2–1.5 m, the test time is from 9:00 to 16:00, the test content is the indoor air temperature of the building and the data acquisition interval of the thermometer is 10 min. The test results are shown in Figure 4. In the software simulation, the indoor and outdoor temperatures of the building were simulated through the above parameter settings, and the simulated temperatures in Figure 5 were obtained. The analysis of the test results showed that the indoor temperature gradually increased with a range of 24°C, among which measuring points 2, 4 and 5 were classrooms and were the main-use spaces. The temperature changes were in the range of 32.5–33°C, 32.5–33.5°C and 32–33°C, respectively, with a range of 1–1.5°C, which is far from the comfortable temperature of the human body. This indicates that the thermal insulation effect of the building is not good. Measuring point 3 is a corridor, and its temperature range is about 3°C. The temperature range of the other measuring points is also about 1–3°C. Using DesignBuilder software to simulate the temperature of the case building without active heating and cooling, it is found that the simulated temperature is correlated with the test temperature, indicating that the simulation of the building with DesignBuilder software is effective and the parameters in the software are set reasonably.

4 INFLUENCE OF SINGLE FACTOR ON BUILDING CARBON EMISSION

Through the field test, it can be understood that the carbon emissions of the building envelope are mainly concentrated in the exterior wall and roof, so it is necessary to conduct targeted research on the type and thickness of its insulation materials, as

Table 4. *Room personnel parameters.*

Room type	Room set temperature in summer (°C)	Room set temperature in winter (°C)	Personnel density (m ²/person)	Illumination power density (W/m ²)	Equipment power density (W/m ²)
Classroom	26	18	2	9	5
Office	26	20	6	9	6
Toilet	28	16	–	6	–
Staircase	–	–	–	5	–
Corridor	–	–	–	5	5

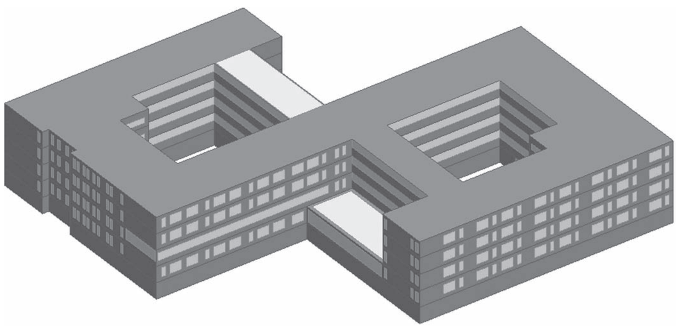

Figure 2. *Case building model diagram.*

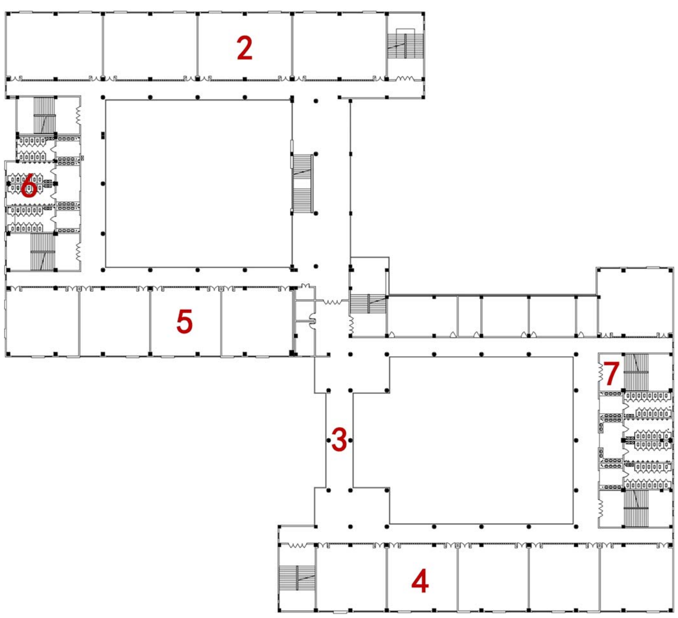

Figure 3. *Plane distribution of measuring points in the case building.*

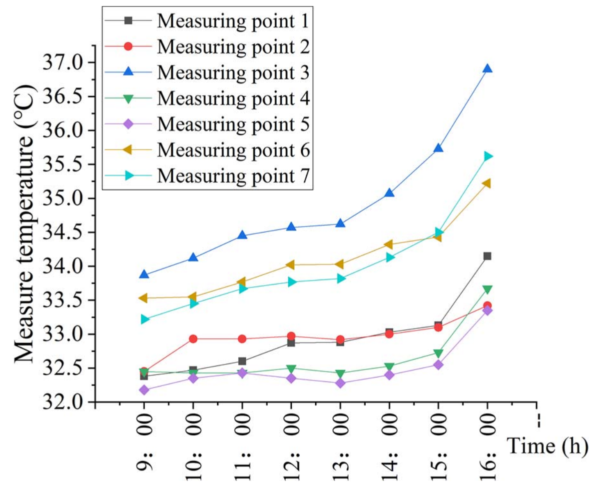

Figure 4. *Measuring temperature of building measuring point.*

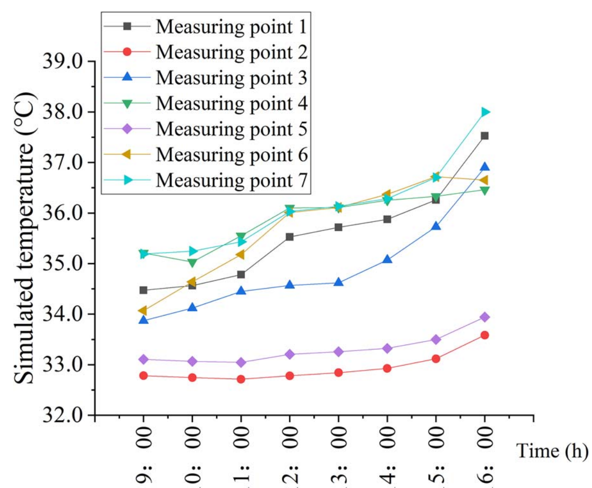

Figure 5. *Simulated temperature of building measuring point.*

well as the materials of doors and windows, the ratio of building windows to walls and the shading measures of buildings. Due to the external characteristics of the teaching building, it is necessary to retain the facade image of the building as much as possible during the renovation process. Therefore, under the premise of saving costs and improving the carbon reduction effect, this paper mainly conducted a single-factor carbon emission simulation study on the external walls, roofs and windows of the building.

Table 5. *Heat transfer coefficients of external walls with different insulation layer materials at different thicknesses—unit: heat transfer coefficient (W/(m²·K)).*

Thickness of insulation layer	Heat transfer coefficient					Thickness of insulation layer	Heat transfer coefficient
	Expanded polystyrene board	Extruded polystyrene board	Graphite polystyrene board	Polyurethane board	Rockwool board		Vacuum insulation board
10 mm	1.315	1.207	1.220	1.072	1.449	5 mm	0.876
20 mm	0.996	0.876	0.891	0.741	1.158	10 mm	0.566
30 mm	0.801	0.688	0.702	0.566	0.964	15 mm	0.418
40 mm	0.670	0.566	0.579	0.458	0.826	20 mm	0.332
50 mm	0.576	0.481	0.492	0.385	0.722	25 mm	0.275
60 mm	0.505	0.418	0.428	0.332	0.642	30 mm	0.234
70 mm	0.450	0.370	0.379	0.291	0.577	35 mm	0.204
80 mm	0.405	0.332	0.340	0.260	0.525	40 mm	0.181
90 mm	0.369	0.300	0.308	0.234	0.481	45 mm	0.163
100 mm	0.338	0.275	0.282	0.214	0.444	50 mm	0.148

4.1 Exterior Wall

Based on the external wall parameters of the national 'Near Zero Energy Building Technical Standard' (GB/T51350-2019) and 'General Code for Building Energy Conservation and Renewable Energy Utilization' (GB55015-2021), materials such as expanded polystyrene board, extruded polystyrene board, graphite polystyrene board, vacuum insulation board, polyurethane board and rockwool board were selected for testing and research. The external wall heat transfer coefficients of different insulation materials under different thicknesses were compared with those of external walls of the case buildings. The selected thickness range suitable for each insulation material is shown in Table 5.

The heat transfer coefficient of the original external wall of the known case building is 0.84. Comparing the heat transfer coefficient of different insulation materials in Table 5, the external wall insulation materials with a heat transfer coefficient less than 0.84 are selected. Therefore, the thickness of vacuum insulation board is 5–50 mm, and the thicknesses of expanded polystyrene board, extruded polystyrene board and graphite polystyrene board are 30–100 mm. The thickness of the polyurethane board is 20–100 mm, and the thickness of the rockwool board is 40–100 mm. The selected results are substituted into Equations (1) and (2) to calculate the carbon emissions of various materials in the production stage and buildings in the operation stage under different thicknesses. The results are shown in Figures 6 and 7.

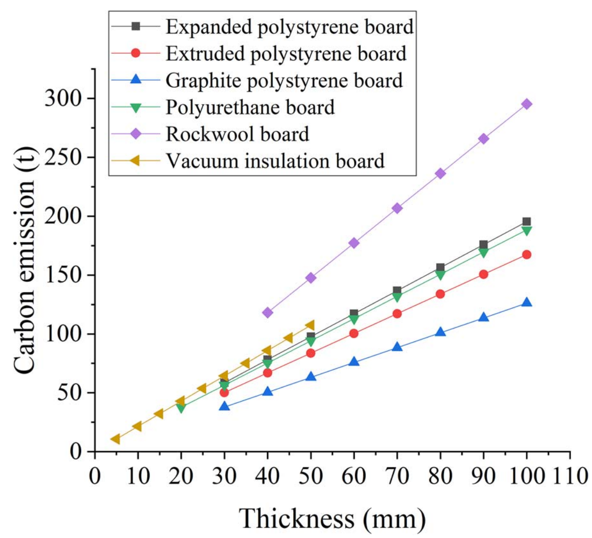

Figure 6. *Carbon emissions of various material production stages at different thicknesses.*

Figure 6 shows that the carbon emissions of thermal insulation materials in the production stage are positively correlated with the thickness of the thermal insulation layer, among which, when the material thickness is the same, the carbon emissions of graphite polystyrene board are the least, and the carbon emissions of rockwool board are the highest, which is due to the different density of different materials leading to different amounts of materials required in the production stage. As shown in Figure 7, the carbon emissions in the building operation stage decrease with the increase in the thickness of building materials. When the thickness is the same, the selection of rockwool board as the insulation material for the building exterior wall will produce the highest carbon emissions in the building operation stage, while the selection of vacuum insulation board will produce the least carbon emissions in the building operation stage. When the thickness of vacuum insulation board is 25 mm, the carbon reduction effect of the building is relatively smooth, and the energy-saving effect is gradually limited. Expanded polystyrene board, extruded polystyrene board, graphite polystyrene board and polyurethane board began to flatten out after 50-mm thickness. Considering the carbon emissions of building materials in the production stage and operation stage, this paper takes 25-mm-thick vacuum insulation board; 50-mm-thick expanded polystyrene board, extruded polystyrene board, graphite polystyrene board and polyurethane board; and 60-mm-thick rockwool board as the external wall reconstruction scheme of the case building.

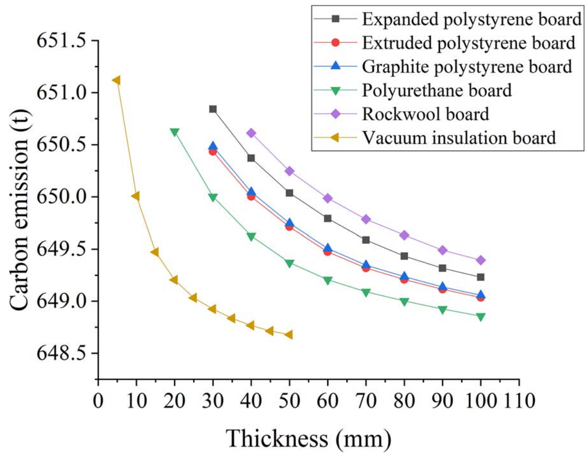

Figure 7. *Building carbon emissions at different material operation stages under different thicknesses.*

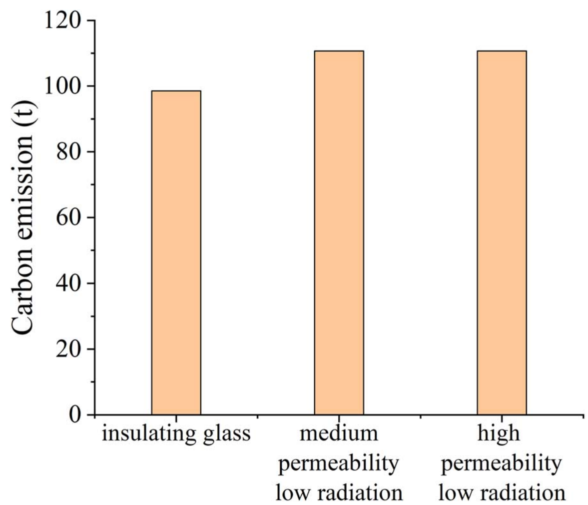

Figure 8. *Carbon emissions of different types of glass materials at the production stage.*

4.2 Windows

The insulating glass with a 6-mm + 9 Air + 6-mm window used in the case building has a heat transfer coefficient of 3.3, which makes the indoor temperature of the building susceptible to the outdoor temperature and has an important impact on the carbon emissions in the building operation stage. In order to improve the energy saving rate and carbon reduction effect of buildings in the building material production stage and operation stage, 6-mm + 12 Air + 6-mm insulating glass, 6-mm + 12 Air + 6-mm medium-permeability low-radiation glass and 6-mm + 12 Air +6-mm high-permeability low-radiation glass are selected. The carbon emissions of different types of exterior windows in the production stage were compared, and their impact on the carbon emissions in the building operation stage was analyzed. The specific results are shown in Figures 8 and 9.

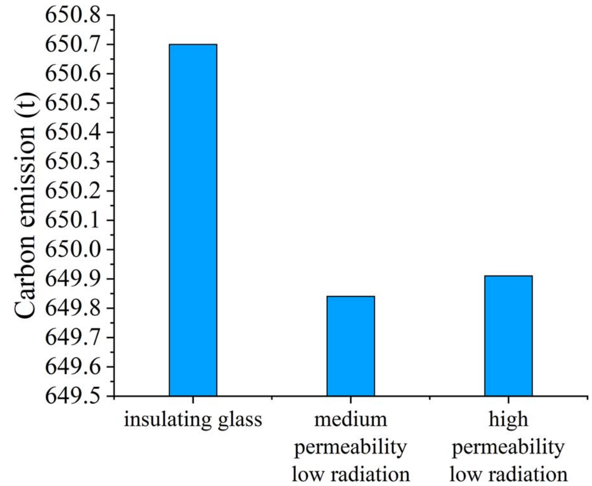

Figure 9. *Influence of different glass materials on carbon emissions in building operation stage.*

As can be seen from Figures 8 and 9, the carbon emissions of the three kinds of glass, 6 mm + 12 Air +6 mm, in the production stage of building materials are staggered and different from the carbon emissions in the building operation stage, which requires comprehensive research. In this paper, three kinds of glass, 6 mm + 12 Air +6 mm, are taken as the external window transformation scheme of the case building.

4.3 Roof

The roof of the case building is an unoccupied roof. Based on the standards, polyurethane board, graphite polystyrene board and extruded polystyrene board are selected as the research objects of building roof insulation materials by comparing the heat transfer coefficients of different materials. The roof heat transfer coefficient of different insulation layer materials at different thicknesses is compared with that of the case building, and the thickness range suitable for each insulation material is selected; see Table 6 for details. Among them, the thickness range of extruded polystyrene board is 50–100 mm, the thickness range of graphite polystyrene board is 50–100 mm and the thickness range of polyurethane board is 40–100 mm. The carbon emissions of various materials in the production stage and their impact on the carbon emissions of buildings in the operation stage under different thicknesses are analyzed, and the results are shown in Figures 10 and 11.

According to Figures 10 and 11, in the production stage of building materials, the carbon emissions of three kinds of building materials increase with the increase in material thickness, indicating that the carbon emissions of building materials are positively correlated with material thickness. During the operational phase of the building, the carbon emissions generated by the building decrease as the thickness of the material increases. When the material thickness is the same, the polyurethane board produces the least carbon emissions in the operation stage, followed by the extruded polystyrene board,

Table 6. *Roof heat transfer coefficients of different insulation materials under different thicknesses—unit: heat transfer coefficient (W/(m²·K)).*

Thickness of insulation layer	Heat transfer coefficient		
	Extruded polystyrene board	Polyurethane board	Graphite polystyrene board
10 mm	–	1.452	1.712
20 mm	–	0.965	1.210
30 mm	–	0.723	0.936
40 mm	–	0.578	0.763
50 mm	0.525	0.481	0.644
60 mm	0.451	0.412	0.557
70 mm	0.395	0.361	0.491
80 mm	0.352	0.321	0.438
90 mm	0.317	0.288	0.396
100 mm	0.288	0.262	0.362

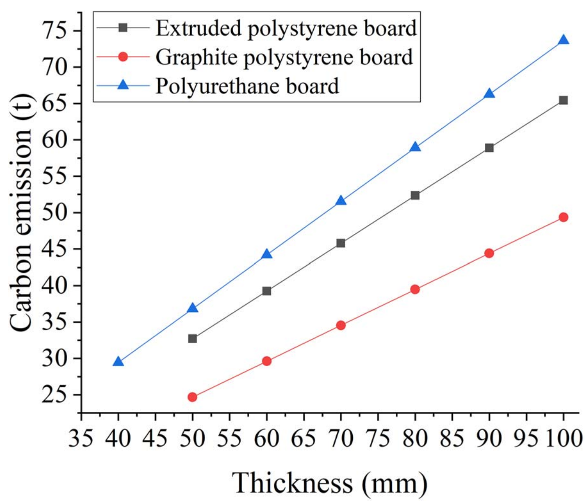

Figure 10. *Carbon emissions of various material production stages at different thicknesses.*

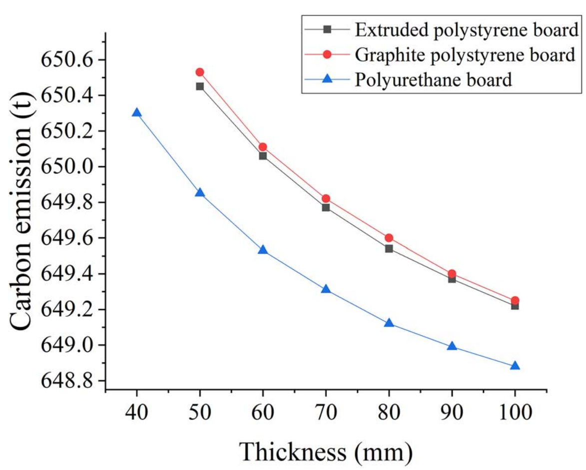

Figure 11. *Carbon emissions of various materials at different thicknesses.*

and the graphite polystyrene board produces the most carbon emissions. When the thickness reaches 60–70 mm, the carbon reduction effect of polyurethane board begins to moderate, and when the thickness reaches 70–80 mm, the carbon reduction effect of graphite polystyrene board and extruded polystyrene board begins to moderate. Considering the carbon emissions of the three materials in the production stage and operation stage, this paper takes 60-mm-thick polyurethane board and 70-mm-thick graphite polystyrene board and extrusion-polystyrene board as the roofing renovation scheme of the case building.

5 INFLUENCE OF MULTIPLE FACTORS ON BUILDING CARBON EMISSIONS

5.1 Orthogonal experimental design

The effects of single factors on carbon emissions in the production and operational phases of building materials have been discussed above. In the analysis of the carbon emission impact of various materials in the production stage and operation stage, cost factors should also be considered. If a comprehensive test is carried out, the workload of simulation calculation is large and the data processing is cumbersome, so this paper adopts the orthogonal test method with efficient and concise characteristics [49]. The core idea of the orthogonal test method is to select representative samples from comprehensive test combinations according to certain rules for testing, which is an efficient test design method [49]. The orthogonal test includes three factors: (A) the type and thickness of exterior insulation material, (B) the type and thickness of roof insulation material and (C) the type of exterior window. There are six levels of factor A, three levels of factor B and three levels of factor C.

SPSS is a group of professional and general statistical software packages, and it is also a combined software package with functions including data management, statistical analysis, statistical plotting and statistical reporting [50]. In this paper, SPSS was used to obtain orthogonal test tables, and the obtained results were

Table 7. *Multi-factor orthogonal combination of envelope structure and its results.*

Program	Combination mode	Carbon emissions in building material production stage (unit: tCO_2e)	Carbon emissions per unit building area during construction operation (unit: $kgCO_2/m^2$)	Cost (unit: CNY 10000)
1	A1:B1:C1	196.45	1390.43	208.92
2	A1:B1:C3	208.56	1389.57	216.14
3	A1:B2:C2	198.92	1390.05	229.05
4	A1:B2:C3	198.492	1390.00	232.66
5	A1:B3:C1	198.06	1390.81	206.00
6	A1:B3:C2	210.17	1389.96	209.61
7	A2:B1:C1	240.45	1392.15	80.91
8	A2:B1:C3	252.56	1390.88	85.22
9	A2:B2:C2	242.92	1391.39	101.05
10	A2:B2:C3	242.92	1391.39	104.66
11	A2:B3:C1	242.06	1392.59	78.00
12	A2:B3:C2	254.17	1391.42	81.61
13	A3:B1:C1	226.43	1391.58	69.23
14	A3:B1:C3	238.54	1390.40	76.45
15	A3:B2:C2	228.90	1390.96	89.36
16	A3:B2:C3	228.90	1390.88	92.97
17	A3:B3:C1	228.04	1392.00	66.31
18	A3:B3:C2	240.15	1390.87	69.92
19	A4:B1:C2	217.98	1390.54	122.56
20	A4:B2:C1	196.22	1392.18	135.47
21	A4:B3:C3	219.59	1390.83	123.25
22	A5:B1:C2	249.05	1390.03	80.30
23	A5:B2:C1	227.29	1391.51	93.22
24	A5:B3:C3	250.66	1390.34	81.00
25	A6:B1:C2	332.06	1390.92	69.12
26	A6:B2:C1	310.31	1392.63	82.06
27	A6:B3:C3	333.68	1391.24	69.82

simulated by DesignBuilder to analyze the impact of each scheme on carbon emissions in the production stage and construction operation stage of building materials, and the cost of each scheme was also calculated, as shown in Table 7. A1–A6 indicate 25-mm vacuum insulation board, 50-mm expanded polystyrene board, 50-mm extruded polystyrene board, 50-mm graphite polystyrene board, 50-mm polyurethane board and 60-mm rockwool board; B1–B3 represent 60-mm polyurethane board, 70-mm graphite polystyrene board and 70-mm extruded polystyrene board; C1–C3 indicate 6-mm + 12 Air + 6-mm insulating glass, 6-mm + 12 Air + 6-mm medium-permeability low-radiation glass and 6-mm + 12 Air + 6-mm high-permeability low-radiation glass.

5.2 Significance analysis of influencing factors

The results obtained by orthogonal experiment can generally be further screened by two methods: range analysis and variance analysis [49]. Due to the large subjectivity of range analysis and the inability to estimate the size of error in error analysis, it is difficult to provide more accurate results [51]. Analysis of variance (ANOVA) is used to study the influence of categorical variables and sequential variables (factors) on numerical variables (observational variables) to determine whether there is a relationship between them and the strength of the relationship. The basic principle is to start with the variance of observed variables, decompose the changes in all observed values and compare the systematic errors and random errors of observed variables caused by factors, so as to infer whether there are significant differences between samples. If there is a significant difference, this indicates that the influence of factors on the overall population is significant [52]. SPSS software was used to conduct ANOVA, and decisions were made according to the value of test statistic F. The larger the value of F, the stronger the significance of the influencing factor on the dependent variable [52]. Using the orthogonal test results in Table 7, ANOVA was performed using SPSS, and the contents of Tables 8–10 were obtained from the results.

According to Tables 8–10, the significance of influencing carbon emissions in the production stage of building materials is as follows: exterior wall > window > roof. The significance of carbon emissions per unit building area in the construction operation stage is as follows: window > exterior wall > roof. The importance of influencing the cost is as follows: exterior wall > roof > window.

Based on the above three indicators, when the carbon emission in the production stage of building materials is taken as the test standard, A4:B2:C1 is selected as the optimal combination; A1:B1:C3 is the best combination when carbon emission per unit

Table 8. *Results of variance analysis of carbon emissions in building material production stage simulated by multi-factor combination.*

Influencing factor	Class III sum of squares	Degree of freedom	Mean square	*F*	Significance
Exterior wall	33 526.042	5	6705.208	1 183 727 186	0.000
Roof	666.617	2	333.308	58 841 762.62	0.000
Window	880.316	2	440.158	77 704 844.27	0.000

Table 9. *Analysis of variance of carbon emissions per unit building area during the operation stage of a multi factor combination simulation building.*

Influencing factor	Class III sum of squares	Degree of freedom	Mean square	*F*	Significance
Exterior wall	8.559	5	1.712	205.195	0.000
Roof	1.248	2	0.624	74.803	0.000
Window	7.495	2	3.747	449.195	0.000

Table 10. *Analysis of variance results of multi-factor combination simulation cost.*

Influencing factor	Class III sum of squares	Degree of freedom	Mean square	*F*	Significance
Exterior wall	83 386.669	5	16 677.334	48 733.012	0.000
Roof	2005.926	2	1002.963	2930.769	0.000
Window	214.053	2	107.026	312.743	0.000

Table 11. *Details of three optimization schemes.*

Program	Carbon emissions in building material production stage (unit: tCO_2e)	Carbon emissions per unit building area during construction operation (unit: $kgCO_2/m^2$)	Annual carbon emissions during construction and operation phase (unit: tCO_2e)	Cost (unit: CNY 10 000)
A4:B2:C1	196.22	1392.18	648.42	135.47
A1:B1:C3	208.56	1389.57	647.21	216.14
A6:B1:C2	332.06	1390.92	647.83	69.12

building area in the construction operation stage is taken as the test standard; and when the cost is taken as the test standard, A6:B1:C2 is the optimal combination, as shown in Table 11.

By comparing the results in the table with the data in Table 3, it can be seen that the carbon emissions of the three optimization schemes in the production stage of building materials are successively reduced by 166.2, 153.86 and 30.36 t compared with the case buildings. In the annual building operation stage, the carbon emission is reduced by 2.59, 3.8 and 3.18 t successively compared with the case building.

5.3 Cost control

When green reconstruction of existing buildings is carried out, the renovation cost is often an important influencing factor [53]. From the perspective of cost control, according to the results in Table 7, the renovation cost of the case building is divided into three sections: less than CNY 1 million, CNY 1–2 million and more than CNY 2 million. Based on the carbon emissions in the operation stage of the building and the carbon emissions in the production stage of building materials, the transformation plan suitable for the case building can be selected, as shown in Table 12. Under the cost-oriented background, a total of seven renovation schemes were selected, among which the annual carbon emissions of the building operation stage were reduced by 2.96–3.62 t compared with the case building, and the carbon emissions of the building material production stage were reduced by 30.36–165.97 t compared with the case building.

When the transformation cost is less than CNY 1 million, the transformation cost of Scheme 1 is CNY 8000 less than that of Scheme 2. The carbon emissions of the two schemes are basically the same in the operation stage, but in the production stage of building materials, the carbon emissions of Scheme 1 are 91.91 t more than that of Scheme 2. Therefore, within this range, taking this into consideration, we believe that Scheme 2 is better.

When the renovation cost is CNY 1 million to 2 million, the renovation cost of Scheme 3 is CNY 215 100 less than that of

Table 12. *Optimization plan details.*

Category	Combination mode	Scheme number	Cost (unit: CNY 10 000)	Carbon emissions per unit building area during construction operation (unit: $kgCO_2/m^2$)	Annual carbon emissions during construction and operation phase (unit: tCO_2e)	Carbon emissions in building material production stage (unit: tCO_2e)
Under 1 million	A6:B1:C2	1	69.12	1390.92	647.83	332.06
	A3:B3:C2	2	69.92	1390.87	647.81	240.15
1–2 million	A2:B2:C2	3	101.05	1391.39	648.05	242.92
	A4:B1:C2	4	122.56	1390.54	647.66	217.98
Over 2 million	A1:B1:C1	5	208.92	1390.43	647.61	196.45
	A1:B3:C1	6	206.00	1390.81	647.78	198.06
	A1:B3:C2	7	209.61	1389.96	647.39	210.17

Scheme 4. In the construction operation stage, the carbon emissions of Scheme 3 are 0.39 t more than those of Scheme 4. In the building material production stage, the carbon emissions of Scheme 3 are 24.94 t more than those of Scheme 4. Considering the carbon emissions of the operation stage and building material production stage, Scheme 3 is feasible within this cost range.

When the renovation cost is more than CNY 2 million, Scheme 7 has the highest renovation cost. Although Scheme 7 has lower carbon emissions in the construction operation stage, Scheme 7 has the highest carbon emissions in the building material production stage. After comprehensive consideration, Scheme 7 can be excluded first. In the comparison between Plan 5 and Plan 6, the cost of Plan 5 is higher than that of Plan 6. In the construction operation stage, the carbon emission of Plan 5 is slightly lower than that of Plan 6, while in the building material production stage, the carbon emission of Plan 5 is slightly higher than that of Plan 6. On the whole, we think that Plan 6 is superior.

Due to their complexity and particularity, in the operation stage, little attention is paid to the investment recovery and economic benefits for public buildings, which is largely different from residential buildings, for which there is a need to consider renovation costs and economic returns [51]. Therefore, in the final choice of the plan, it is necessary to comprehensively consider many aspects.

6 DISCUSSION

This study conducts a detailed analysis of the envelope structure of a case building, revealing its key role in building carbon emissions and offering new ideas and methods for achieving low-carbon energy efficiency in buildings. The results show significant differences in the thermal transfer coefficient of the building's envelope structure compared to current standards, highlighting the necessity and practical significance of simulating its retrofit.

(1) *Thermal transfer coefficient of the building envelope structure.* The study indicates that enhancing the thermal insulation performance of the building envelope is vital for reducing the overall carbon emissions of buildings. This finding resonates with the research of Zhipan, Yue J and Zu'an L [54–56], who also emphasized the importance of improving building insulation to reduce energy consumption and carbon emissions. Additionally, this study goes further than existing research by exploring the specific impacts of different types and thicknesses of insulation materials on carbon emissions, thereby enriching the research in this area.

(2) *Carbon emissions in the building material production stage.* The study further reveals a significant impact of the building's exterior walls on carbon emissions and retrofit costs during the material production stage. This underscores the importance of selecting appropriate exterior wall insulation materials, aligning with the research of Xin, Muhammad and Daria [57–59], which highlights the significant role of material selection in a building's overall carbon emissions.

(3) *Carbon emissions in the building operation stage.* Moreover, the study finds that building windows significantly affect carbon emissions during the operational stage, emphasizing the importance of optimizing window materials to reduce these emissions. This aligns with the findings of Chunzhen *et al.* [60], who also pointed out the significant impact of window type and performance on energy consumption.

(4) *Cost–benefit analysis.* The study explores finding the optimal balance between retrofit costs and carbon emissions, proposing various optimization scenarios based on different retrofit cost thresholds. This not only provides guidance for practical engineering but also offers a new perspective for future research.

While this study has made important discoveries, there is still room for further research. Future studies could explore a wider range of insulation materials and window types to comprehensively evaluate their impact on building carbon emissions. Additionally, considering factors such as the lifespan and maintenance costs of buildings could lead to a more comprehensive cost–benefit analysis.

Through the optimization of the building envelope structure design, this research provides new insights and exploration for achieving low-carbon energy efficiency in buildings. The findings not only emphasize the importance of simulating the retrofit of the case study building's envelope structure but also reveal the specific impacts of different insulation materials and window types on carbon emissions and costs, offering valuable reference for the sustainable development of the construction industry.

7 CONCLUSIONS

This paper calculates and studies the carbon emissions of building envelope structure, calculates the carbon emissions of building operation and building material production stage, comprehensively analyzes the influence of various factors on building carbon emissions and conducts follow-up studies. The following conclusions are drawn:

(1) According to the analysis of the field investigation and measured results of the case building, it can be seen that the heat transfer coefficient of the outer envelope of the case building is quite different from the requirements under the current norms, so the simulation and transformation of the outer envelope of the case building has certain practical significance.
(2) The building exterior wall has a significant impact on carbon emissions and renovation cost control in the production stage of building materials, and changing the type and thickness of insulation materials in the exterior wall is of great significance in this respect. The external window of a building has a strong significant effect on the carbon emission in the operation stage. Therefore, optimizing the material type of the external window is of great significance to the carbon emissions in the operation stage of a building.
(3) When the renovation cost is less than CNY 1 million, it should be preferred to use 50-mm extruded polystyrene board for the exterior wall, 70-mm extruded polystyrene board for the roof and medium-penetration low-radiation glass for the exterior window. When the renovation cost is CNY 1 million to 2 million, external walls made from 50-mm expanded polystyrene board, rooves made from 70-mm graphite polystyrene board and low-radiation glass windows are more advantageous. When the renovation cost is more than CNY 2 million, it is better to use 25-mm vacuum insulation board for the exterior wall, 60-mm polyurethane board for the roof and insulating glass for the exterior window. This paper provides a new idea and perspective for building to realize low-carbon energy saving through the study of the optimal design of an envelope structure.

This study not only furnishes practical guidance and strategies for mitigating carbon emissions in the construction sector but also provides a theoretical foundation and reference for the green transformation and low-carbon design of buildings. The research findings hold significant implications for propelling the construction industry toward achieving the dual carbon goals.

Future research endeavors could further explore a diverse array of insulation materials and window types to comprehensively assess their impact on building carbon emissions. Additionally, upcoming studies may delve into investigating the influence of different climate regions and building types on carbon emissions, as well as the adaptability of building retrofit strategies in diverse socio-economic contexts.

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Author Contributions

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