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Research on Residential Interior Design and Energy Saving Optimization with Sustainable Low-carbon Development

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Abstract. The escalating crisis of global warming, driven by the emission of greenhouse gases, poses a formidable challenge for humanity as a whole. Notably, the construction industry contributes significantly to the global greenhouse gas inventory. Consequently, prioritizing low-carbon construction assumes paramount importance in mitigating the pervasive impact of the greenhouse effect on a global scale. Such an endeavor stands as a crucial safeguard for ensuring the sustainable development of human civilization. Therefore, from the perspective of low-carbon building design optimization research is an important part of low-carbon building. From the perspective of architectural design, this paper summarizes that low-carbon building design should pay attention to following aspects: reasonable use of natural lighting and natural ventilation, reduce the carbon emission value of building use stage; Taking the transformation project of the former engineering Institute of Southeast University as an example, this paper probes into the effect of design optimization on reducing carbon emissions, and quantitatively studies the relationship between the design optimization of lighting, ventilation and envelope structure materials and the reduction of building carbon emissions. The Angle selection of roof skylight is studied from the Angle of day-lighting optimization, the size and position of facade opening and the strategy of natural ventilation path are studied from the Angle of ventilation optimization. The indoor ventilation further reduces the refrigeration energy consumption, which is 22.1% less than before the renovation, and the roof reduces the heat gain by 22%-32%.e.

Key words. Low Carbon Perspective, Building Design Optimization, Ex-Industrial Courtyard Renovation Programme.

1. Introduction

Since the 1990s, while creating a comfortable and warm living environment, architectural designers have also integrated the concept of low-carbon life into their design works [1], [2]. Since ancient times, interior design has led the aesthetic consumption of The Times, but in the face of the contemporary "low carbon emission reduction" strategic plan, "consumption" and "low carbon" have become contradictory individuals [3], how to integrate them into one, to achieve the perfect transformation of "high profile consumption" and "high and low carbon" has become the focus and hot spot of designers. Faced with the severe situation of today's ecosystem, people begin to reflect on the environmental and ecological damage caused by modern science and technology culture [4], [5]. Designers also pay attention to the return of social responsibility on the basis of aesthetics, resulting in the concept of low-carbon architectural design, which is systematic and comprehensive. It should take full account of the sustainability of the site, efficient use of resources (water, electricity, gas), recycling of materials, air quality assurance, novel and unique design, user needs and so on. To create a friendly, harmonious and sustainable built environment between man and nature.

The process of building construction, use, transformation and dismantling consumes non-renewable resources, but also produces a large amount of CO2, harmful gases and construction waste, resulting in rapid resource depletion and environmental degradation [6], [7]. Therefore, it is urgent to reduce the resource and environmental load of the construction industry and the public buildings with the highest carbon emission intensity. With the progress of social economy and the development of scientific and technological level, the requirements of architectural space experience and indoor comfort will continue to improve. How to adopt the correct optimization strategy to reduce building energy consumption and carbon emission in the building design stage is a very worthy topic.

Current architectural design practices are often heavily reliant on traditional qualitative and fuzzy experience-based judgments, with only a limited number of numerical simulation analyses conducted, typically after the design scheme has already been largely formulated. This approach essentially constitutes a passive "testing" of the design, lacking an active integration into the architectural design process, thereby exhibiting a notable degree of passivity and lag [8], [9]. The consequence of this phenomenon is that architects lack a full understanding of low-carbon strategies in the scheme design, resulting in high energy consumption and high carbon emissions in buildings.

In the world, the carbon emission value of buildings is usually calculated through the consumption of building materials and energy consumption statistics, and this calculation formula is more accurate [10]. Because the calculation needs to calculate the types and quantities of building materials used, it is necessary to complete the design in many aspects such as civil construction, water and electricity, heating and ventilation, and interior design. Therefore, carbon emission assessment is mostly located in the design stage of construction drawings or as a late supplement of energy-saving and low-carbon technologies and becomes the final verification procedure of the entire design process. Therefore, this carbon emission calculation method is of little help to the architectural design stage and cannot provide a timely judgment basis for the scheme comparison and selection in the design process [11].

2. Low Carbon Buildings

Although the total area of public buildings is less, but the unit area consumption of energy and carbon emissions are huge, public buildings per square meter emissions of CO264.61kg, much higher than residential buildings, 2.22 times of urban residential buildings, 3.81 times of rural residential, is the national average emission intensity of 2.09 times [12], [13]. The energy consumption per square meter of public buildings is 30.09, which is 2.13 times of the national average. Among them, the formula for calculating energy consumption per square meter of buildings is shown in (1) and (2):

$$\nabla_{W_G} L_{adv}^{f} = ge \cdot \frac{\partial\big(x + G(x)\big)}{\partial G(x)} \cdot \frac{\partial G(x)}{\partial W_G} \tag{1}$$

Among them, w_G represents the energy consumption coefficient of the interior design, L_{adv} represents the thermal conductivity of the material, and *ge* represents the natural lighting efficiency.

$$\Delta_t^H = \frac{(\beta\theta + 2\beta - \varphi^2)\delta_t}{2\beta\theta + 2\beta - \varphi^2} \tag{2}$$

Where H represents the artificial illumination power density, β represents the indoor temperature set point, and t represents the time.

Due to the huge volume and large flow of people, buildings have high energy consumption intensity such as air conditioning, ventilation, lighting and elevators, that is, buildings have high energy consumption density [14]. The calculation formula of environmental carbon emission is shown in (3):

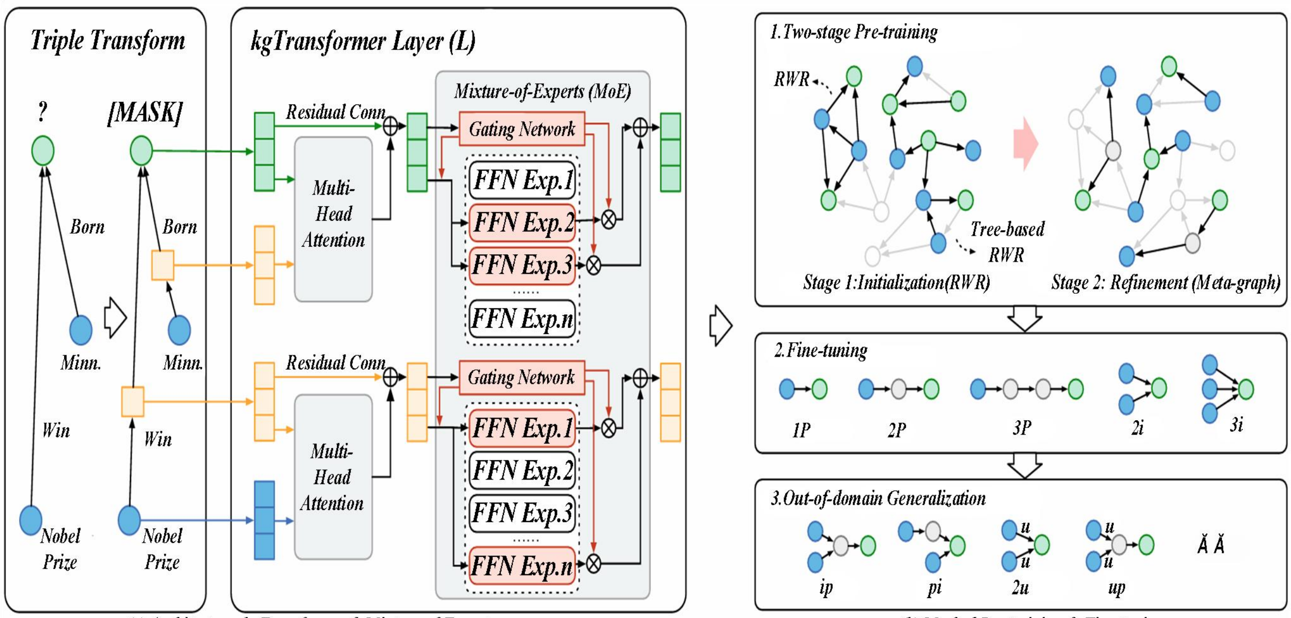
$$W_G = W_G - \eta\left(\frac{\partial L_{adv}^{f}}{\partial W_G} + \alpha\frac{\partial L_{GAN}}{\partial W_G} + \beta\frac{\partial L_{hinge}}{\partial W_G}\right) \tag{3}$$

Where, W_G indicates the thickness of the insulation material, and L_{GAN} indicates the ventilation efficiency.The current architectural design process is predominantly guided by traditional qualitative and somewhat vague experience-based judgments, with numerical simulation analysis only occurring infrequently, typically after the design scheme has been largely finalized. This approach tends to lag behind and lacks active integration into the design process. In essence, it is a passive "test" of the design, rather than an active combination with the architectural design process, which reflects a certain passivity and lag [15].

The consequence of this phenomenon is that architects lack a full understanding of low-carbon strategy in the scheme design, which leads to high energy consumption and high carbon emissions in buildings. The formula for calculating energy consumption efficiency is shown in (4).

$$W_D = W_D - \eta\left(\frac{\partial L_{GAN}}{\partial W_D}\right) \tag{4}$$

Where W_D represents energy recovery efficiency and η represents efficiency.



(a) Architecture: kgTransformer & Mixture-of-Experts

(b) Masked Pre-training & Fine-tuning

Fig. 1. A Schematic Diagram of the Integrated Design Process

Figure 1 shows a schematic diagram of the integrated design process. In the world, the carbon emission value of buildings is usually calculated through the consumption of building materials and energy consumption statistics [16], [17]. This calculation method results are more accurate. Because the calculation needs to calculate the type and quantity of building materials used, it is necessary to complete the design in many aspects such as civil construction, hydropower, HVAC, interior design, etc. Therefore, the carbon emission assessment is mostly located in the construction drawing design stage or as the late supplement of energy-saving and low-carbon technology and becomes the final checking calculation procedure of the whole design process. Therefore, this method of carbon emission calculation is of little help to the architectural design stage and cannot provide a timely judgment basis for the scheme comparison and selection in the design process.

3. Low Carbon Building Content and Calculation Methods

The whole life cycle of a building is to treat a building as a system from its generation to its demise, and its carbon emissions refer to the total [18]. The whole life cycle of a building has different division and calculation range. This paper adopts the division and calculation method of each life stage of a building in "Building Carbon Emission Calculation Standard". Figure 2 shows optimization design of combustion performance and fire resistance of building components. The whole life cycle of a building is divided into the production and transportation stage of building materials, the use stage and the construction and demolition stage. The carbon emissions in the whole life cycle are the sum of the carbon emissions in the three stages.

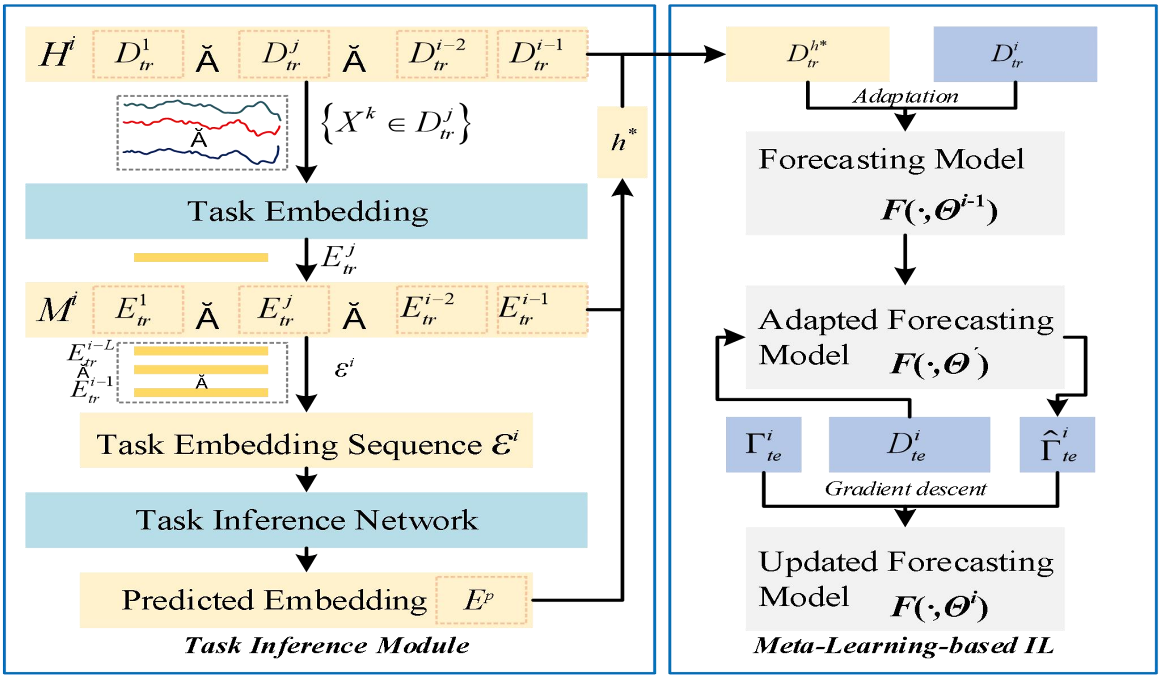


Fig. 2. Optimization Design of Combustion Performance and Fire Resistance of Building Components

A. Stages of Production and Transport of Building Materials

Each link of building materials and components from raw material mining, processing and manufacturing to transportation to the construction site will produce greenhouse gas emissions, which is the embodied carbon emissions of building materials. Carbon emissions in this stage [19], [20]. The carbon emissions generated in this stage (unit kgCO2eq./m2) is the sum of carbon emissions in the production process and transportation process of building materials and the ratio of building area. The carbon emissions of building materials production process are calculated according to the following formula (5):

$$C_{SC} = \sum_{i=1}^{n} M_i \times F_i \tag{5}$$

Among them, C_{SC} represents the proportion of low-carbon materials used, M_i means the renewable energy utilization rate, and F_i represents the indoor environment comfort index.

In the given formula, the building materials encompass both the primary structure and the envelope structure of the building. It is stipulated that the total mass of the primary building materials should constitute no less than 95% of the total weight of all building materials used. Furthermore, the weight ratio of any material accounting for less than 0.1% can safely be disregarded. The building filling structure is ignored because of its complex and diverse materials, and the proportion of carbon emissions in the total building materials is not large [21]. The material consumption in the process of building renovation and maintenance is also calculated at this stage. Carbon emissions during transportation are calculated according to formula (6):

$$C_{YS} = \sum_{i=1}^{n} M_i \times D_i \times T_i \tag{6}$$

Among them, C_{YS} represents energy efficiency ratio, Mi is in it, D_i means low carbon material factor, and T_i is in natural light utilization.

B. Building Use Phase

The time of the building use stage is determined according to the design document or calculated in 50 years. The carbon emission in this stage mainly refers to the indirect carbon emission. Carbon emissions reduced by the renewable energy system during the use of the building.

The total carbon emissions per unit of floor area during the use phase of the building are calculated according to the following formula (7):

$$C_{SY} = \frac{(c_h + c_c + c_w + c_l + c_{re}) \times 50}{A} \quad (7)$$

C_{SY} represents the thermal and humidity environment regulation coefficient, c_h represents the energy recovery and reuse coefficient, and c_c represents the indoor air quality index.

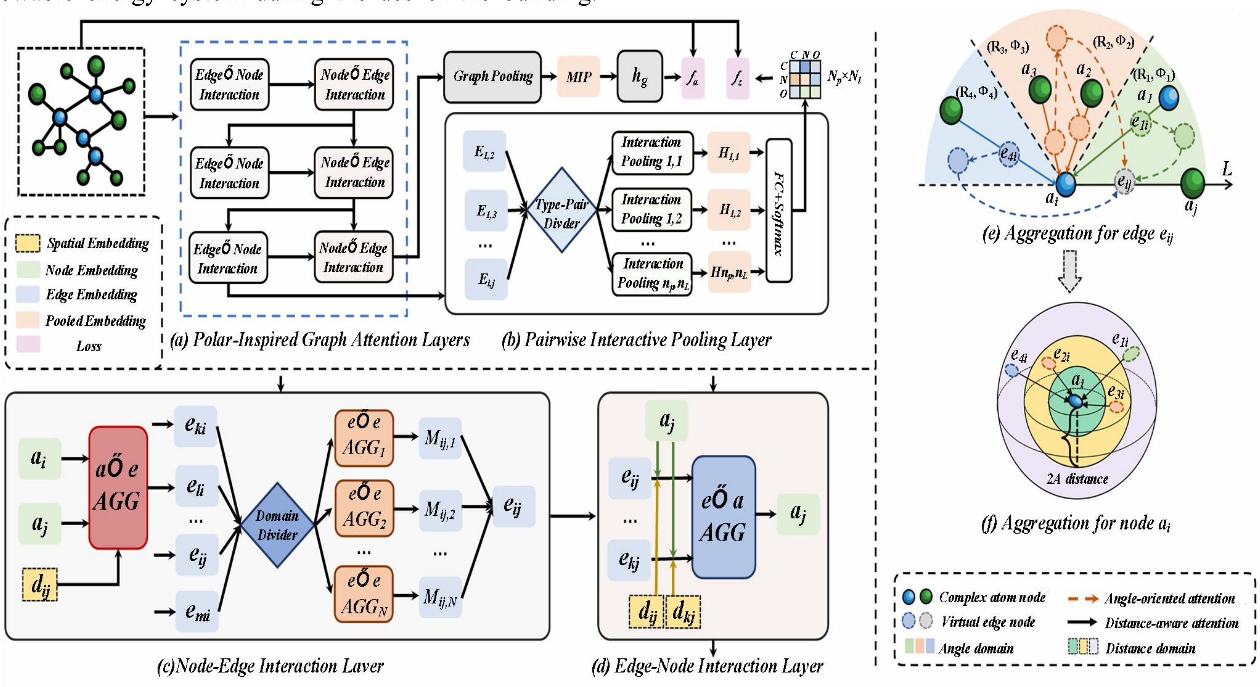


Fig. 4. Flow Chart of Residential Energy Optimization

Figure 4 shows flow chart of residential energy optimization. Different from other calculation methods, the carbon emission of office appliances and the carbon reduction of greening are not calculated in the building use stage, because the correlation between the carbon emission of electrical appliances and the building design is low, the carbon reduction effect of greening is weak [22], [23]. The changes caused by building maintenance and transformation on the energy consumption of the building use stage are difficult to predict, so they are not considered in the calculation of the use stage, and the material consumption caused by building transformation is calculated in the production and transportation of building materials [24]. The carbon emissions of this process are calculated according to the following formula (8):

$$C_{JZ} = \sum_{i=1}^{n} E_i \times F_i \quad (8)$$

C_{JZ} represents the indoor heat and humidity load coefficient, E_i represents the sustainable design index, and F_i represents the lighting energy efficiency ratio.

4. Case Studies

A. Overview of Project

The former Engineering Institute is located in Sipai Lou Campus of Southeast University. It was formerly a two-story teaching building named "New Classroom" built in 1929. The Department of Architectural Engineering of Central University, the predecessor of the School of Architecture of Southeast University, was also founded here.

The structure stands at a height of 22.4 meters, measuring 45.9 meters in length from east to west and 62.9 meters from north to south, encompassing a comprehensive construction area of 10,700 square meters. The atrium extends 31.5 meters in the east-west direction and 21.6 meters in the north-south direction. Surrounded by a two-story corridor spanning from north to south, the building comprises six floors, with a five-story western corridor and a two-story eastern corridor. On the ground level, a 6.6-meter-wide passageway seamlessly integrates with the campus, providing a smooth transition between the two spaces.

In the following ten years, with the growth of the scale of the School of Architecture, there was still a shortage of teaching space. As a first-class architecture school in China, the School of Architecture of Southeast University has the most limited space compared with other similar institutions, which is reflected in the extreme lack of design teaching discussion space and the extreme lack of drawing evaluation and display space.

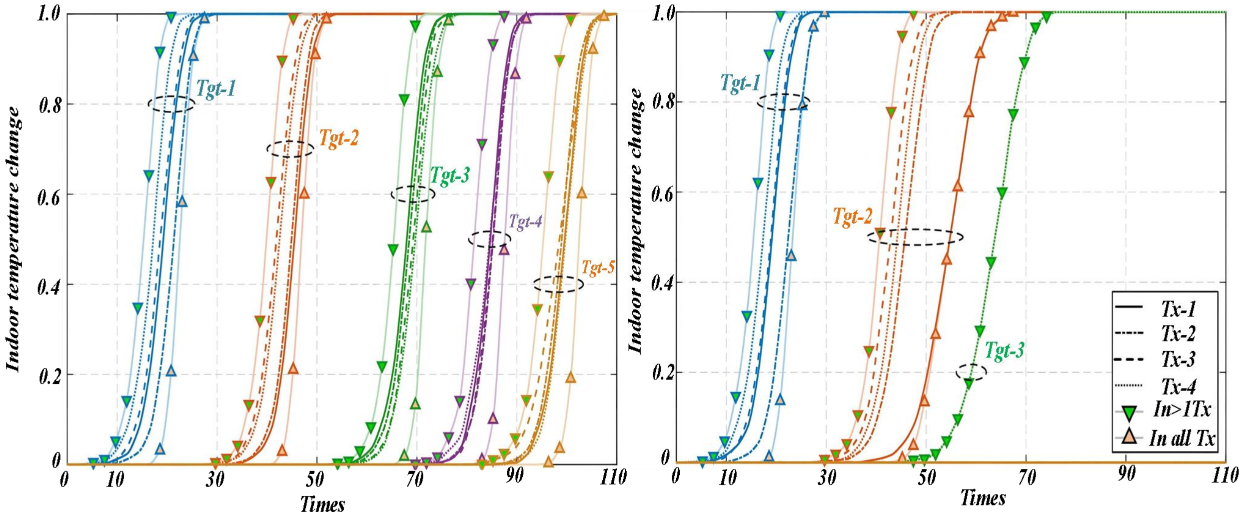


Fig. 5. Indoor Temperature Changes Over Time

Figure 5 shows indoor temperature changes over time. The former engineering institute of the transformation plan needs to make the best use of natural ventilation and natural lighting through reasonable shape, efficient space organization and structural design [25]. On the premise of improving the original building environment and minimizing the negative impact, through the performance simulation and comparison of different schemes, the indoor wind, light and thermal environment comfort of large space is optimized, the dependence on HVAC is reduced, the carbon emission in the use stage is reduced, and the carbon emission in the whole life cycle is reduced by combining the optimization of the envelope structure materials and construction methods.

B. Analysis of Original Built Environment

1) Analysis of Light Environment

The analysis of lighting coefficients is carried out for a typical plane of the former engineering college. The simulation adopts the CIE full cloudy day model, and the parameters are: outdoor illuminance value of 5000lux, 5mm thick transparent glass of external windows, visible light transmission ratio of 0.837, reflection coefficient of white paint on the internal walls and ceilings of 0.8, and reflection coefficient of grey floor of 0.42. The simulation obtains the typical planar lighting coefficient of the former College of Technology, and the main function of the building is the students' studio, which is stipulated that the lighting coefficient shall not be lower than 3 by the Light Design Standard for Buildings [26], [27]. Despite its remarkable results in optimizing residential interior design to reduce energy consumption and carbon emissions, we must also recognize the limitations that may exist in specific climate conditions. For example, in extreme climate conditions (such as cold or hot areas), certain energy-saving design measures may not be fully effective, or additional auxiliary systems are required to ensure comfort in the indoor environment. In addition, building codes and standards in different regions may also impose restrictions on the implementation of design optimization.

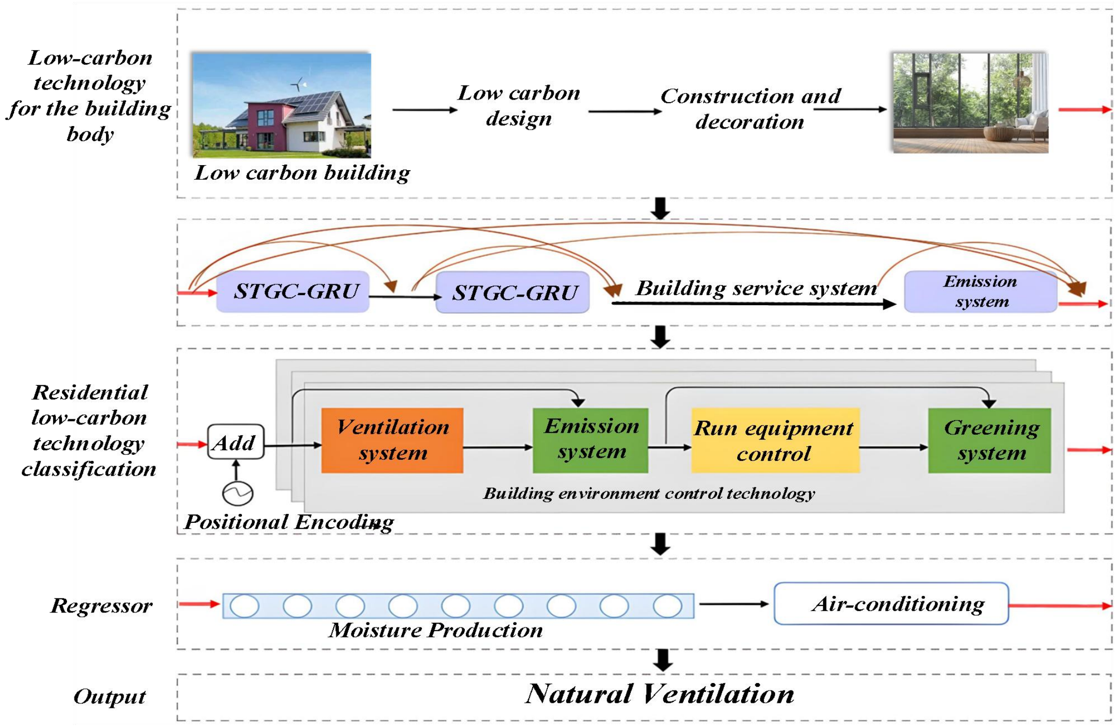


Fig. 6. Research Flow Chart of Residential Interior Design and Energy Saving Optimization

Figure 6 shows research flow chart of residential interior design and energy saving optimization. The main function of the building is students' studio, and the Lighting Design Standard for Buildings stipulates that the lighting coefficient shall not be lower than 3, and at the same time, Nanjing belongs to the light climate zone IV, and the minimum value of the lighting coefficient needs to be multiplied by the value of K 1.1, so the value of meeting the standard is 3.3. The analysis of the light environment is calculated according to the following formula (9):

$$\mathcal{L}_{CE} = -\frac{1}{K}\sum_{k=1}^{K} y_k \log(\hat{y}_k) \tag{9}$$

Where, $\mathscr{L}_{CE}$ represents the indoor heat and humidity load, K indicates the natural light utilization rate, and y_k represents the low-carbon material factor

2) Wind Environment Analysis

The building module in Phoenics2009 is used as the simulation tool. According to the meteorological data of Ecotec Analysis. The optimal ventilation condition with all Windows open is simulated. The student studios on the 2nd floor and 5th floor of the former engineering Institute were selected as typical planes, and the wind environment of the main used Spaces was analyzed, and the indoor plane wind environment, indoor section wind environment and outdoor courtyard wind environment were obtained.

The design optimization measures of this study are mainly based on the climatic conditions and data of the current study. However, we believe that these measures also have some applicability under other climate types. For example, design strategies to increase natural ventilation and lighting are effective in most climatic conditions. However, upon specific implementation, it may need to be fine-tuned to local climate characteristics to ensure its optimal results. Therefore, future studies could further explore the efficacy and potential of these optimization measures under different climate types.

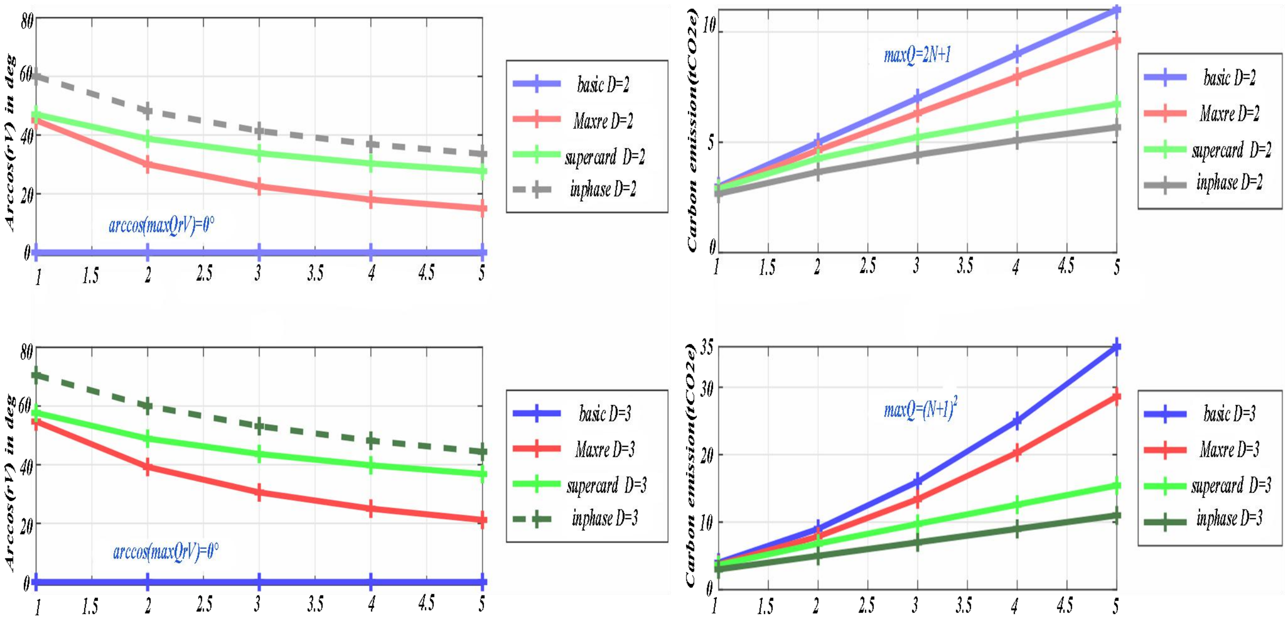


Fig. 7. Changes in the Energy Consumption or Carbon Emissions of the Residential Interior Design

Figure 7 shows changes in the energy consumption or carbon emissions of the residential interior design. In the case of not opening the door, there is basically no wind in the classroom, the wind speed is less than 0.25m/s; The central corridor has good ventilation due to the inlet air from the eastern window, and the wind speed is 0.75m/s~1.25m/s. The second floor of the North building of the former industrial Institute is divided into small studios, and the internal ventilation is similar to that of the South building. There is basically no wind when the door is not opened; The large studio on the 5th floor of the north building without separation forms a ventilation path through the north and south, and the ventilation is the best. In the vicinity of the eastern window, the wind speed exhibits a heightened velocity, averaging at 0.33 m/s. Contrastingly, the mean wind speed within working area of the south building is recorded at 0.19 m/s, while the corresponding figure for the northern building stands at 0.24 m/s. The wind environment analysis is calculated by formula (10):

$$\mathcal{L}_{KD} = -\frac{1}{K}\sum_{k=1}^{K} \hat{y}_k^t \log(\hat{y}_k^s) \tag{10}$$

Where, $\mathcal{L}_{KD}$ represents the indoor air quality optimization coefficient, K represents the sustainable design evaluation index, and yk represents the lighting system energy efficiency index.

3) Thermal Environment Analysis

In this paper, Openstudio, an energy simulation software with EnergyPlus as its core, is used to simulate the thermal environment of the building and the value of energy consumption per unit area, and the model is established according to various parameters. In this paper, we use the EnergyPlus kernel energy simulation software Openstudio to simulate the thermal environment of the building and the energy consumption per unit area, and build a model based on various parameters, to simulate the indoor temperature of the studio throughout the year in winter, when the minimum fresh air volume is met, and the minimum ventilation frequency is maintained, and the maximum ventilation frequency is used to naturally ventilate the building during the transitional seasons and in summer.

It can be seen that from December to mid-January, due to the low ventilation of the studio in winter, the working room is about 10°C higher than outdoor, daytime temperature is 10°C - 15°C, which needs to be supplemented by turning on the air-conditioning; from March to April and some dates in October to November, the temperature is low compared with the comfort temperature, and the frequency of window opening should be controlled between the minimum and maximum number of air exchanges, so as to make the indoor temperature reach the comfort requirement; in May, June, September Most of the time periods and some dates in April and mid-October when natural ventilation is strongest, the temperature still exceeds the comfort temperature. The way to reduce energy consumption with the greatest potential is to strengthen natural ventilation in summer and part of the transitional seasons, so as to reduce reliance on air-conditioning and refrigeration. The thermal environment analysis is calculated according to the following formula (11):

$$\mathcal{L}_{FM} = \frac{1}{|\Omega|} f_i^t - f_i^s \tag{11}$$

Where $\mathcal{L}_{FM}$ represents the natural light utilization coefficient, Ω represents the heat and humidity regulation energy consumption coefficient.

C. Optimisation of Original Built Environment

1) Optimisation of Photothermal Balance

The roof with its structure is the most expressive part of a large space, and at the same time as the span of proportion of the roof in the building envelope increases [28], [29]. The form of the roof has a direct impact on the atmosphere of the space, and light roofing plays the most important role in effectively using natural light to reduce the energy consumption of lighting and create a transparent, light and bright indoor space. Lighting Hot summer and cold winter areas in the translucent roof to improve the indoor temperature in winter at the same time will cause overheating in summer, from the current completed projects, a large number of buildings in the atrium of the thermal environment is not ideal and energy consumption is very large, mainly due to the high angle of the sun in the summer, for the horizontal translucent skylight of the intensity of heat radiation than close to the vertical surface of the translucent window is much larger, making the solar radiation heat gain is too large. This makes the solar radiation heat gain too large. Therefore, the area of the light-transmitting part of the roof and the angle of the light-transmitting part of the roof need to be carefully designed in order to achieve a balance between the reduction of the annual energy consumption value and the comfort of lighting. The design of the roof shape should take into account the lighting and ventilation enhancement, for different months and different times of the day, the design of the roof form can be adjusted [30]. The roof form should be designed to be adjustable for different months and different times of the day.

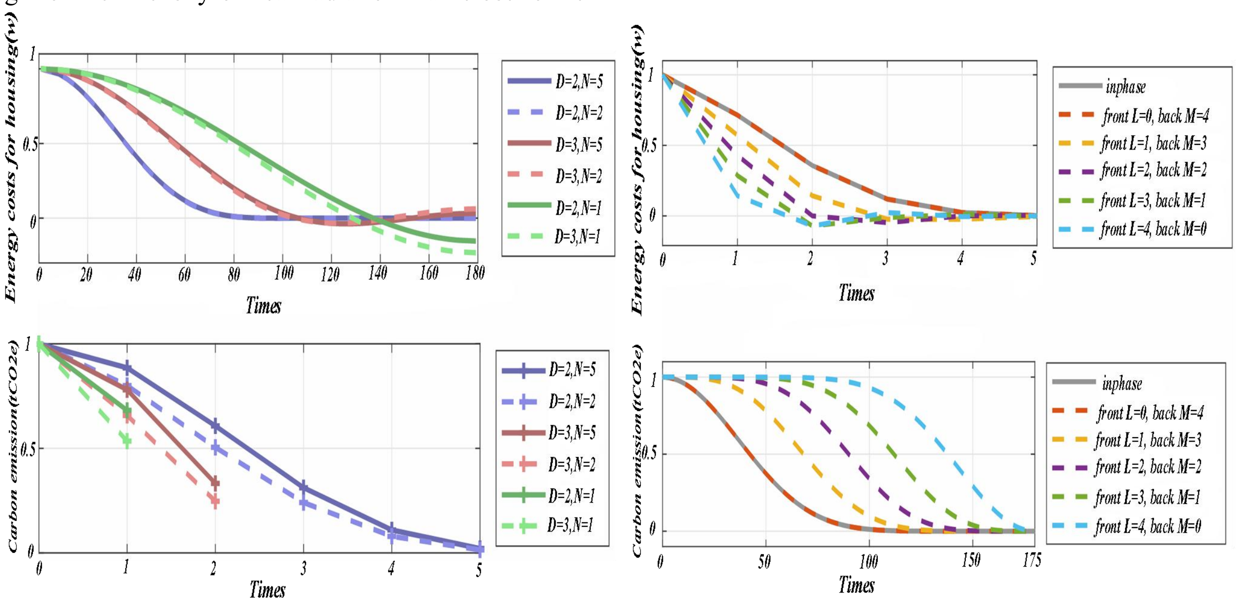


Fig. 8. Plot of Residential Carbon Emissions and Energy Costs Over Time

Figure 8 shows plot of residential carbon emissions and energy costs over time. On the premise of meeting the requirements of indoor lighting, the skylight design is further optimized: the horizontal skylight is changed to a north-facing skylight. Under the condition of controlling the horizontal projected area of skylight unchanged, study the influence of skylight angle on heat gain and illumination of large space, and strike a balance between controlling space heat gain and ensuring indoor illumination. In the structure and modelling allows the range of the skylight vertical direction and the horizontal plane angle 300, 45% 60 ^ case, as well as the horizontal direction of the south-east deflection 5 work 10 ~ 15 hukou 20 knock spoon case was studied, a comprehensive comparison of different angles to meet the 3001 ^ illuminance of the large space under the length of the time and the heat to determine the reasonable value of the angle of the skylight deflection range. According to the following formula (12):

$$\gamma = \beta^2\theta^2 + (2\beta - \varphi^2)(4\beta\theta + 2\beta - \varphi^2) \qquad (12)$$

Where γ represents the energy saving efficiency coefficient, β represents the low carbon material use coefficient, and φ represents the low carbon material use coefficient.

In the case of the horizontal projection area of the skylight remains unchanged, with the vertical angle of the skylight from 30 ^ to 60 with the increasing, the skylight heat gain and the number of hours to meet the illuminance are reduced. In the vertical tilt angle of 60 called spoon case, the horizontal tilt angle has little effect on illuminance, the skylight heat gain has a greater impact, different tilt angle compared to no tilt case can reduce the heat gain of 22% - 32%. With the increase of the horizontal deflection angle, the heat gain first decreases and then increases, and reaches the minimum value in the deflection of 10 kow inches, the reason is that the south-east deflection angle blocks the skylight from receiving the solar radiation from the west. Under comprehensive consideration, the skylight angle is selected as 60° from the horizontal in the vertical direction and 10° from the south-east in the horizontal direction.

Enhanced indoor ventilation further reduced cooling energy consumption by 18.1 per cent compared to the reference building and 22.1 per cent compared to the pre-retrofit period. The formula for calculating carbon emissions per square meter per year during the former IIT use phase is shown in (13).

$$\hat{p}_s = \left(1 - \frac{\tau}{M}\right)^{N-1} \qquad (13)$$

Where, P_s represents the sustainable design index, M represents the indoor air quality index, and N represents the indoor environment composite index.

2) *Wind Environment Optimisation*

In response to simulation in previous stage, the natural ventilation path was further optimised by designing a wind puller and adjustable air outlets at the top, and setting up four courtyards in the lower part of the atrium which are connected to the outdoor environment as air intake ducts, so as to bring in fresh and cold air from the lower part of the large space by means of both natural and mechanical ventilation to displace the hot and unfresh air. The air is replaced by hot, unfresh air through natural and mechanical ventilation.

The increase of the east side air duct can effectively guide the natural wind to enter from the bottom of the large space, which obviously improves the wind speed in the personnel activity area at the bottom, and the wind velocity is higher than 0.5m/s in the majority of the area, and the proportion of wind blowing into the area from the south building is further reduced, which indicates that the freshness of the air in the personnel activity area has also been improved.

To clarify the positioning of this study in the current research trends, we compare the results of this study with existing case studies or benchmarks. For example, we can compare the energy-saving design strategies adopted in other similar studies and the energy-saving effects achieved in order to evaluate the innovation and contribution of this study. In addition, we can refer to international building energy efficiency standards and guidelines to see whether the design optimization measures of this study comply with industry best practices.

The organisation of natural ventilation pathways has an important contribution, and the average wind speed in the large space reaches 0.56m/s. The energy consumption for refrigeration was further reduced compared to the previous phase, by 26.7 per cent compared to the reference building and by 30.2 per cent compared to the pre-retrofit period. The formula for calculating carbon emissions per square meter per year in the former IIT use phase is shown in (14).

$$\mathbb{P}(R, w|R, 0) = \frac{p}{W}, \forall w \in [0, W-1] \tag{14}$$

Where R represents the sustainable design index, w represents the lighting energy efficiency ratio, and p represents the indoor heat and humidity load.

4. Conclusion

This paper examines the low-carbon optimisation of buildings from the perspective of building design and explores the role of design optimisation in reducing carbon emissions. Through the rational use of natural lighting and natural ventilation, the value of carbon emissions in the use phase of the building is reduced. The main work and findings of this paper are as follows: passive design strategies for buildings can reduce the carbon emission values during the use phase of the building. Using passive solar heating and natural ventilation in summer with the transition season of high temperature, the combined passive conditioning strategy can increase the annual comfort hours from 6% to 42%. With the combined use of lighting and ventilation optimisation strategies, the carbon emission value per unit area of the building is significantly reduced compared with that before the renovation, and the carbon emission value per unit area is reduced by a total of 18.96% compared with the reference building, of which the optimisation of the roof light-heat balance is reduced by 8.24%, which accounts for 43.46% of the total reduction ratio, and the optimisation of the ventilation is reduced by 9.84%, which accounts for 51.90% of the total reduction ratio. In this project, the optimisation of lighting and ventilation design plays an important role in reducing the carbon emission value of large space

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