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The Sustainability Study and Exploration in the Building Commercial Complex System Based on Life Cycle Assessment (LCA)–Emergy–Carbon Emission Analysis

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Abstract: This paper focuses on the sustainable exploration of building systems, which combines ecological concepts and low-carbon designs for a comprehensive sustainability assessment investigation. The study employed the Life Cycle Assessment (LCA)-Emergy and Life Cycle Assessment (LCA)-Carbon emission methods to discuss a range of topics, including the main contributing factors, sustainability index verification, sensitivity analysis, and potential improvement measures. From an ecological sustainability perspective, the results indicate that the building operation stage plays a critical role, accounting for approximately 45% of the entire emergy in the building commercial complex. The sustainable index (ESI) is 0.354, which is below the standard of 1. Moreover, the building operation stage also significantly contributes to carbon emissions, particularly in the 50th anniversary of operation. Based on these findings, the study recommends two potential strategies to improve the ecological state and low-carbon design which involve the use of renewable energy and carbon sink improvement, respectively.

Keywords: sustainability; building system; LCA-emergy; LCA-carbon emission

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Citation: Cao, J.; Zhu, Y.; Zhang, J.; Wang, H.; Zhu, H. The Sustainability Study and Exploration in the Building Commercial Complex System Based on Life Cycle Assessment (LCA)–Emergy–Carbon Emission Analysis. *Processes* **2023**, *11*, 1989. https://doi.org/10.3390/pr11071989

Academic Editors: Reihaneh Aghamolaei and Mohammad Reza Ghaani

Received: 2 June 2023
Revised: 24 June 2023
Accepted: 28 June 2023
Published: 30 June 2023

1. Introduction

With abnormal climate change becoming increasingly prevalent, the development of building systems that prioritize ecology, low energy consumption, and low carbon emissions has become a research hotspot in many countries [1–4]. In China, building carbon emissions and energy consumption account for nearly half of the country's total consumption, according to data from 2022 [5]. Despite this, the construction industry continues to grow rapidly, with China's added value reaching 8.33831 billion yuan in 2022—a 5.5 percent increase from the previous year—and Jiangsu's total output value exceeding 4 trillion yuan for the first time at 4066.05 billion yuan [6]. However, this growth is also exacerbating negative impacts on the climate and environment. To address these issues and meet China's goal of being carbon neutral by 2060, it is crucial that the building industry focuses on low-carbon retrofitting and design to mitigate the pressures of climate change [7,8].

Currently, there is a range of literature available on the topic of sustainable building systems from an ecological perspective, utilizing various methods, including ecological footprint analysis [9], ecological assessment [10], ecological security analysis [11], Eco-GIS framework [12], and ecological emergy [13]. One notable framework, which integrates both the emergy method and life cycle assessment, is the LCA-Emergy framework designed and utilized in the building system, providing a novel methodology [14]. However, life cycle assessment (LCA) involves various stages, including building material production, building construction, operation, and demolition, and requires the integration of both basic data and unit emergy values [15]. Due to the wide range of sustainable inputs involved in the building system, such as materials, machinery, and human services, different researchers have explored this concept in diverse ways [16–21].

Sustainable emergy evaluation of building material systems is a popular research direction that includes material production processes as well as labor and transportation inputs. As building materials are one of the main components of the building system, research in this direction is valuable [22–27]. The combination of Building Information Modeling (BIM) technology and building systems has brought more accurate research results to sustainable architecture, and the fully visualized results provide designers and engineers with a more intuitive sense, improving the ecological level of the entire building system [28,29]. Due to the coupling of numerous devices in building systems, including refrigeration equipment, power generation equipment, heating equipment, intelligent equipment, etc., the complexity of building system operation is caused. At the same time, the sustainability of individual equipment systems also affects the ecological level of the entire building, which is also an area of interest for many researchers [30–32]. As one of the necessary components of building systems, building envelope structures directly affect the sustainable level of the entire building system. Various walls, glass, doors, and windows that come into contact with the environment are all reasons for fluctuations in sustainable results for the entire building system [33]. Scholars have also studied energy types in building systems. Different energy inputs maintain the operation of building systems while also bringing different results. Which type of building energy is more suitable for building systems is also an important research topic [34,35]. Furthermore, different ecological assessment models have a direct impact on sustainable assessment results for building systems. Different processes for updating building systems are also reasons for these changes; therefore, scholars from various countries have explored this research field as well [36,37]. In addition to this, research on similarities and differences in sustainability among high-density buildings [38], renewable balance design for building systems [39], sustainable residential construction assessment [40], and accuracy analysis models for architectural energy value analysis [41] have also gained favor among researchers.

Indeed, low-carbon design throughout the entire life cycle of a building system is an essential means for achieving sustainable architecture [42,43]. Sustainable architecture aims to promote environmentally responsible and resource-efficient design and construction practices that minimize negative impacts on the environment and promote social well-being. Low carbon design is critical to achieving sustainable architecture as it addresses the significant environmental impact of buildings throughout their entire life cycle. By reducing greenhouse gas emissions, minimizing energy consumption, and promoting renewable energy sources, low-carbon design helps reduce the environmental footprint of buildings and promotes long-term sustainability [44–46]. Moreover, sustainable architecture also considers other aspects beyond low-carbon design, such as water efficiency, waste reduction, use of environmentally friendly materials, and enhancement of indoor environmental quality. Therefore, low-carbon design is not only a necessary means for achieving sustainable architecture but also an integral part of it [47,48].

Low carbon design throughout the entire life cycle of a building system refers to the reduction of greenhouse gas emissions from the production, construction, operation, and demolition phases of the building. It involves optimizing the choice of building materials, reducing energy consumption during operation, increasing the efficiency of renewable energy utilization, and promoting sustainable waste management [49–52].

In the production phase, low carbon design can be achieved by selecting environmentally friendly raw materials, reducing transportation distances, and improving production processes to reduce energy consumption and greenhouse gas emissions [8]. During the construction phase, efficient construction methods, high-performance insulation materials, and renewable energy sources should be considered to minimize carbon emissions. For the operational phase, low carbon design can be achieved by adopting energy-efficient technologies, using renewable energy sources, promoting energy-saving behaviors, and implementing green building certification systems. In addition, carbon sinks, such as green roofs and vertical gardens, should be incorporated into the building's design to absorb carbon dioxide and reduce carbon emissions [53]. During the demolition phase, low carbon design can be achieved through the reuse and recycling of building materials, reducing waste generation, and promoting circular economy principles. Through the implementation of low-carbon design throughout the entire life cycle of a building system, it is possible to significantly reduce greenhouse gas emissions, improve energy efficiency, and promote sustainable development in the construction industry [54].

However, currently, there is a greater focus on research related to low-carbon buildings and ecological buildings, and there are few studies that specifically explore the sustainability of building systems based on the concepts of ecological value and low-carbon methods. This has resulted in a lag in research in this area. Since ecological buildings and low-carbon buildings are defined from different perspectives as architectural types, it is essential to conduct a sustainable analysis of building systems using both ecological value and low-carbon methods.

The purpose of this study is to use the building system as a carrier to complete the positioning and analysis of the target building case through ecological emergy and carbon emissions assessment throughout the life cycle. By analyzing from an ecological perspective and a carbon emission view, the sustainability level of the building system was comprehensively judged, and the main influencing stages under the two categories were identified to verify the accuracy of the analysis results.

Through the promotion of this research, the deviation in the sustainable analysis of the building system under a single method has been filled, which is conducive to the accuracy of research results and provides a new way of thinking for architects, engineers, and government managers.

2. Material and Methods

2.1. Research Framework

Figure 1 presents the basic research framework for this paper, which consists of four subsections that guide the research direction. The research questions are displayed on the left, focusing on the ecological and carbon emission effects of the building commercial complex system. The system is analyzed using the LCA method, which is divided into five stages: material production, material transport, construction, building operation, and building demolition. To assess the ecological and carbon emission stages, a range of indicators are adopted using the LCA–Emergy–Carbon emission methodology.

2.2. Emergy Diagram of the Building System

The emergy diagram depicts the structure of the building system, consisting of four parts: renewable energy (on the left), non-renewable input (on the top), the building system (in the middle), and output (on the right). The flow of the process is from left to right and top to bottom, with inputs entering the building system and various outputs being produced. The main input and output types can be easily identified and displayed through the emergy structure diagram. Based on the emergy diagram (shown in Figure 2), the LCA-Emergy calculation model and sustainable indexes are presented in the following section.

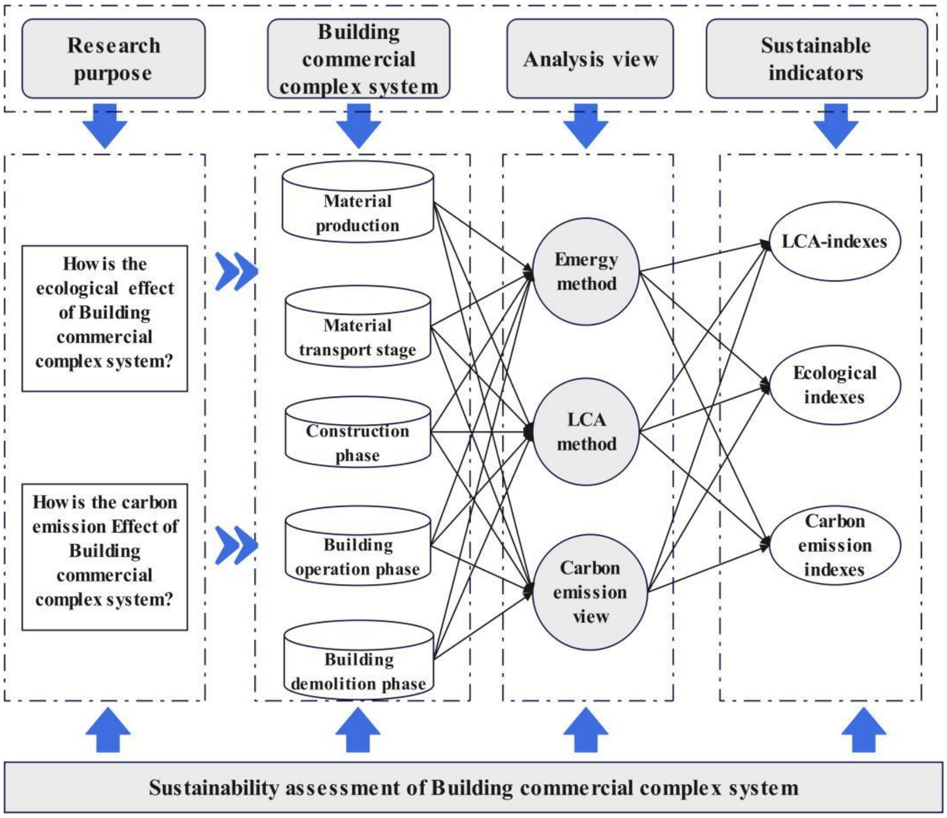

Figure 1. Research framework based on the LCA–Emergy–Carbon emission methodology.

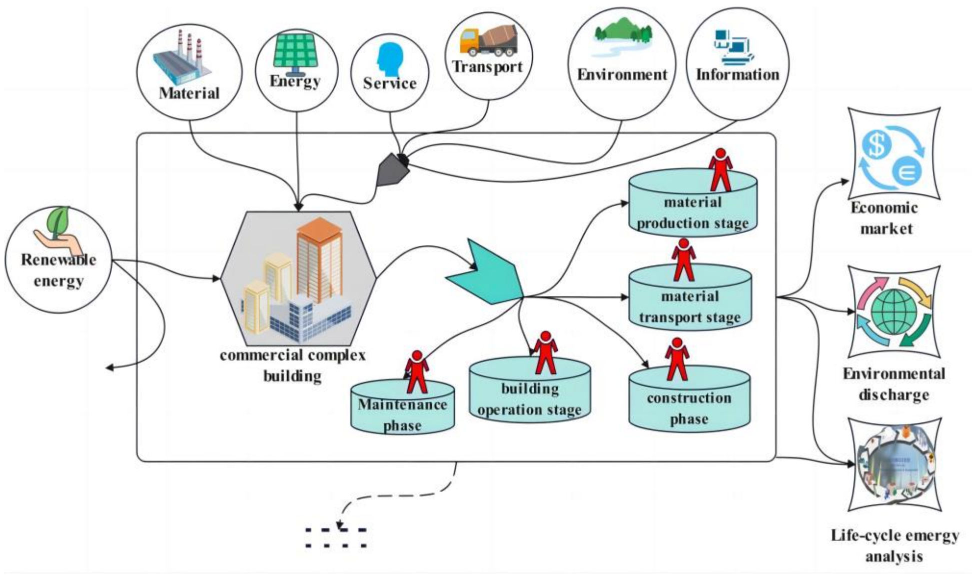

Figure 2. Emergy diagram of the building commercial complex system.

2.3. LCA-Emergy Analysis Model

In order to realize the LCA-Emergy calculation model, seven types of input need to be calculated for emergy evaluation (in Figure 3). The specific calculation models have been displayed in Table 1.

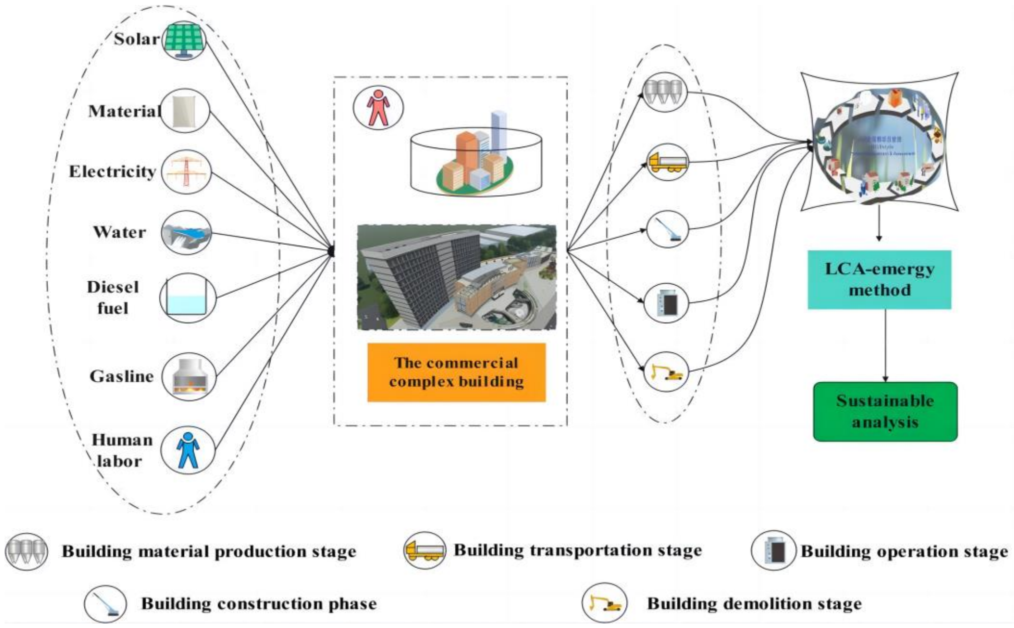

Figure 3. LCA-Emergy implementation path.

Table 1. The calculation models for LCA-emergy assessment.

Types	Equation	Explains
Solar	$E_S = A \times J \times (1-\beta) \times T_C \times T_{UEVs}$	Where E_S represents the solar emergy in the construction process; A is the site surface; J is the solar radiation amount (3.5 × 10^9 J/m^2); β is the surface albedo (0.7); T_C is the construction time; T_{UEVs} is the unit emergy value.
Material	$E_{\text{material}} = \sum_{i=1}^{n} Q_i \times T_{U1}$	Where E_{mass} is the emergy value of mass; Q_i is mass amount; T_{U1} represents the unit emergy value.
Electricity	$E_{\text{e}} = L \times T_{U\text{e}}$	Where E_{e} is the emergy of electricity in the building system. L is the electricity quantity. $T_{U\text{e}}$ is the unit emergy value of electricity.
Water	$E_{water} = V \times \rho \times G \times UEV_w$	Where E_{water} is the water emergy; V is the water volume; ρ is the water density; G is the Gibbs energy of water (4.92 J/g); UEV_w is the water transformity.
Diesel fuel	$E_{\text{diesel}} = \mu \times \chi \times UEV_d$	Where E_{diesel} is the emergy of the diesel fuel; μ is the amount of diesel oil used in the buildings system; χ is the calorific value of diesel fuel; UEV_d is the unit emergy value of diesel fuel.
Gasoline	$E_{gasoline} = \phi \times \varphi \times UEV_g$	Where $E_{gasoline}$ is the gasoline emergy; ϕ is the gasoline quantity; φ is the calorific value of gasoline; UEV_g is the unit emergy value of gasoline.
Human labor	$E_H = L_T \times N_P \times T_d \times UEV_H$	Where E_H is the emergy of human labor; L_T is the working time (8 h); N_P is the number of employed workers; T_d is the working day; UEV_H is the unit emergy value of human labor.

Note: The above formulas can be referenced from the literature [55].

2.4. Emergy Indexes

Based on the emergy diagram and LCA-Emergy implementation path, a series of sustainable indicators can be utilized for the ecological evaluation, as follows:

(1) Renewable rate (R_i) expresses the proportion of renewable energy in the overall system structure.

(2) Non-renewable rate (N_i) represents the ratio of non-renewable resources and energy sources.

(3) Emergy yield ratio (EYR) reveals the dependence of the whole building system on the outside world.

(4) Environmental loading ratio (ELR) demonstrates the ecological pressure of building commercial complex systems.

(5) Emergy sustainability indicator (ESI) can be obtained based on EYR and ELR, which illustrates the sustainability state for the building commercial complex system.

2.5. LCA-Carbon Emission Calculation Model

Based on the national standard [56], the LCA-Carbon emission implementation path and calculation models have been shown in Figure 4 and Table 2.

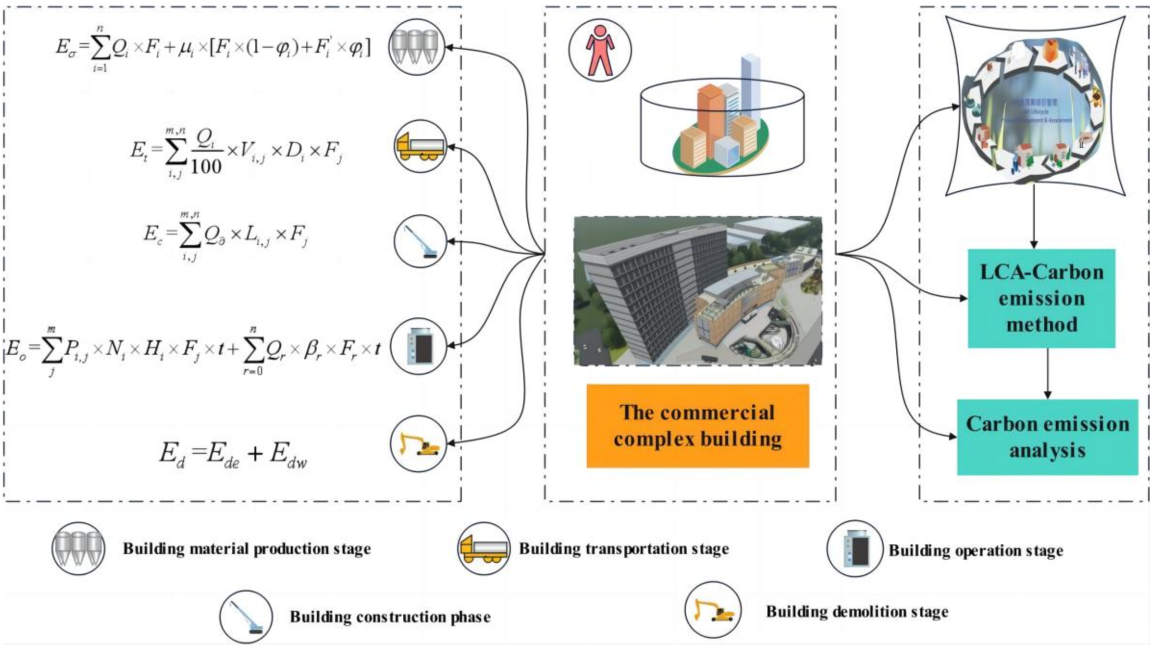

Figure 4. LCA-Carbon emission analysis implementation path.

Table 2. The calculation models for LCA-carbon emission assessment.

Types	Equation	Explains
Total carbon emission	$E_W = E_\sigma + E_t + E_c + E_o + E_d$	Where E_W is the total carbon emission in the building system; E_σ is the carbon emission in the building material production stage; E_t is the carbon emission in the construction material transport stage; E_c is the carbon emission in the construction phase; E_o is the carbon emission in the operational use and maintenance phase; E_d is the carbon emission in the abandoned and dismantled stage.
Building material production stage	$E_\sigma = \sum_{i=1}^{n} Q_i \times F_i + \mu_i \times [F_i \times (1-\varphi_i) + F_i' \times \varphi_i]$	Where E_σ is the carbon emission calculation of the building material production stage; n is the number of building materials; Q_i is the consumption of building material i; F_i is the carbon emission factor in the initial state; φ_i is the carbon emission factor in the recycling state; μ_i is the rate of attrition; F_i' is the recovery utilization rate.
Material transport stage	$E_t = \sum_{i,j}^{m,n} \frac{Q_i}{100} \times V_{i,j} \times D_i \times F_j$	Where E_t is the carbon emission calculation of the construction transport stage; n is the number of building materials; Q_i is the consumption of building material i; $V_{i,j}$ is the amount of energy used to transport materials (t/100 t·km); D_i is the transportation distance of materials or equipment (km); F_j is the carbon emission factor.
Construction stage	$E_c = \sum_{i,j}^{m,n} Q_\partial \times L_{i,j} \times F_j$	Where E_c is the carbon emission calculation of the building construction stage; n is the quantity of equipment; m is the number of energy types; Q_∂ is the Total number of machines; $L_{i,j}$ is the energy consumed by machinery; F_j is the carbon emission factor.
Operational use stage	$E_o = \sum_{j}^{m} P_{i,j} \times N_i \times H_i \times F_j \times t + \sum_{r=0}^{n} Q_r \times \beta_r \times F_r \times t$	Where E_o is the carbon emission calculation of operational use stage; m is the total types of energy; n is the material renewal quantity; t is the life of the building (year); $P_{i,j}$ is the energy expended per hour; N_i is the total number of equipment; H_i is the average operating hours of the device; F_j is the carbon emission factor of equipment; Q_r is the maintenance update consumption; β_r is the annual renewal rate; F_r is the carbon emission factor of alternate material.
Building demolition stage	$E_d = E_{de} + E_{dw}$	Where E_d is the carbon emission at the stage of building demolition; E_{de} is the carbon emission of mechanical equipment; E_{dw} is the carbon emission of waste transportation.

Note: The above formulas can be referenced from the literature [56].

3. Case Study and Data Collection

3.1. Case Introduction

A large architectural design category commercial complex has been selected for this project, consisting of six floors of commercial buildings and fifteen floors of hotel buildings (in Figure 5). The complex is located in Nanjing City, China, and covers a total building area of 40,000 square meters. The building is constructed using a reinforced concrete pattern, with partial use of assembly mode to reduce negative environmental impact. The design of the complex is based on ecological principles, with a high-rise building located in the northwest corner to provide a better view. The landscape design in front of the building includes a green space design on the west side, a sunken green square in the middle, and an embedded garden on the east side, enhancing the ecological attributes of the complex. The style of the complex is divided into two categories, with the high-rise hotel buildings mainly using gray to represent the business attribute, while the commercial podium building uses warm colors in its facade design to attract shoppers.

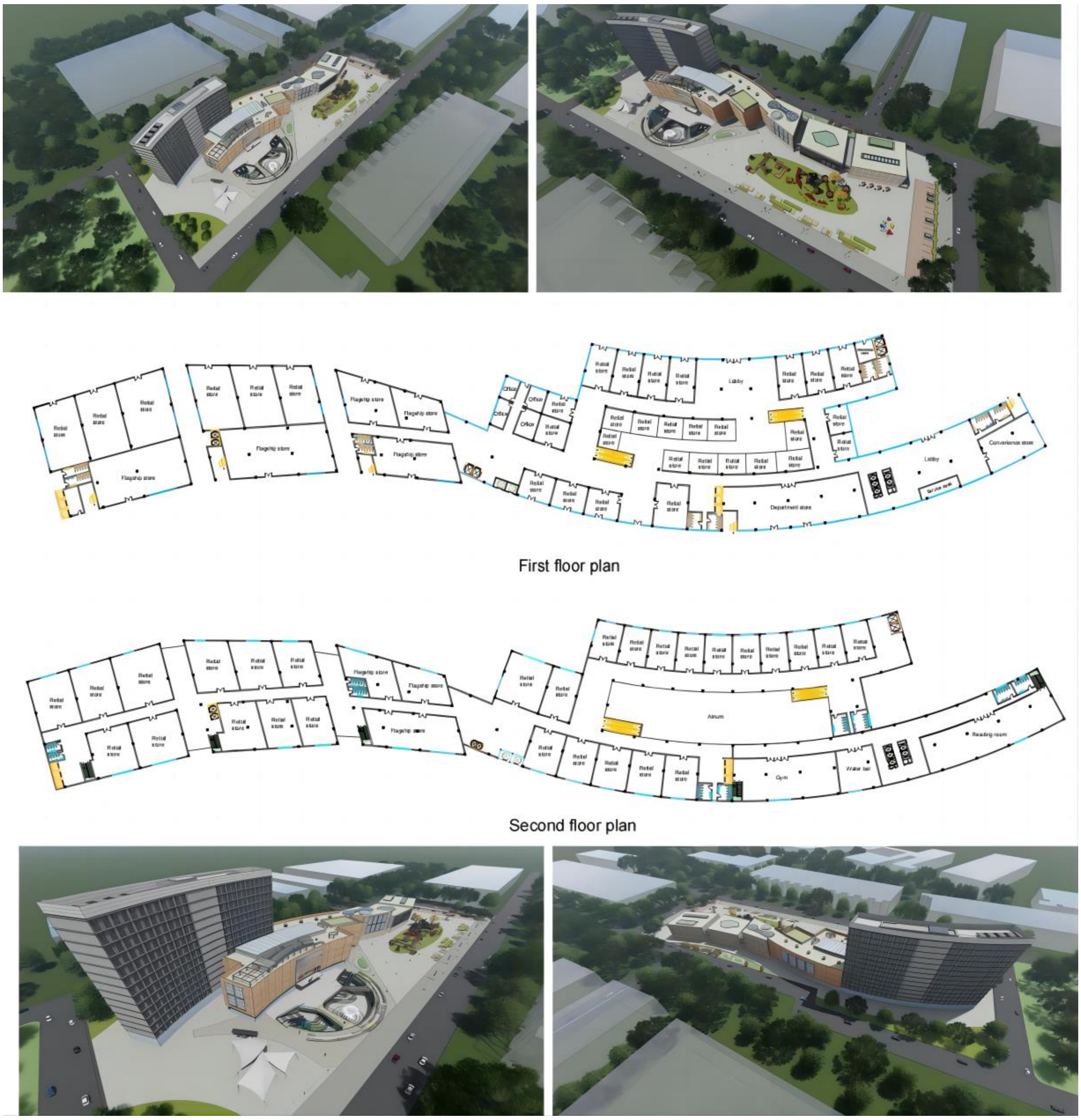

Figure 5. Building plan of the commercial complex.

As this architectural case is a new construction project, it was initially defined as a Nearly Zero Energy Building (NZEB), involving the implementation of several passive design measures throughout the entire building project. Some of these measures include:

(1) Optimizing orientation and layout: Maximizing the use of daylighting and natural ventilation by strategically positioning and designing buildings to reduce energy consumption.

(2) High-performance insulation materials: Utilizing high-quality insulation materials such as insulation materials and double-glazed windows to minimize heat transfer and energy loss.
(3) Natural lighting and lighting control: Designing windows and skylights effectively to increase natural lighting and implementing intelligent lighting systems to reduce energy consumption.
(4) Thermal bridge control: Designing to avoid or minimize thermal bridges, which prevent heat from transferring through the building structure and improve thermal performance.
(5) Natural ventilation: Designing appropriate ventilation systems to utilize natural airflow for air circulation and improvement of indoor air quality, reducing reliance on mechanical ventilation.
(6) Passive solar energy utilization: Maximizing the use of solar energy to meet the building's energy needs through the selection of suitable materials and design features such as solar collectors and photovoltaic panels.
(7) Green roofs and vertical greening: Adding vegetation layers such as green roofs and vertical green walls to provide insulation and thermal benefits, enhancing indoor comfort.
(8) Optimization of heating, cooling, and ventilation systems: Designing efficient systems like geothermal energy and air-source heat pumps to reduce energy consumption and carbon emissions.

The combination of these measures can collectively reduce energy use and environmental impact in buildings, contributing to energy efficiency and sustainable development goals.

The reason for choosing this architectural case is primarily because commercial complexes are a complex type of building that involves various types of spaces, including residential, commercial, and surrounding landscape design. It holds significant representative value for sustainable research on ecological and low-carbon methods. Additionally, this particular case has a relatively complete database that is allowed to be accessed and utilized, ensuring the typicity and accuracy of the entire study.

3.2. Data Collection

In this study, we collected basic building data, including information on the main building materials, transportation of building materials, labor involved in construction, emergy conversion rates for building inputs, and carbon emission factors related to construction. The detailed data can be found in the calculation list. We obtained all the data from the Nanjing Urban Construction Department with proper authorization.

4. Results and Discussion

The analysis point of view is elaborated from two aspects, which are LCA-Emergy and LCA-Carbon, respectively. LCA-Emergy analysis contains dominated contributors' selection, sustainable index explanations, and sensitivity analysis. LCA-Carbon emission analysis involves full life cycle carbon emission status and carbon sink improvement, etc.

4.1. LCA-Emergy Analysis

In this section, according to the national standard [57], the emergy of building commercial complexes is calculated according to the term of 50 years of comprehensive land use.

4.1.1. Primary Emergy Contributors Analysis

In Figures 6 and 7, the life cycle emergy trend is shown. The building operation stage plays a critical effect, accounting for roughly 45% of the entire emergy for the commercial building complex, followed by the building construction stage (approximately 32%), building material production stage (approximately 17%), building transport stage (approximately 5%) and building demolition stage (approximately 2%), etc.

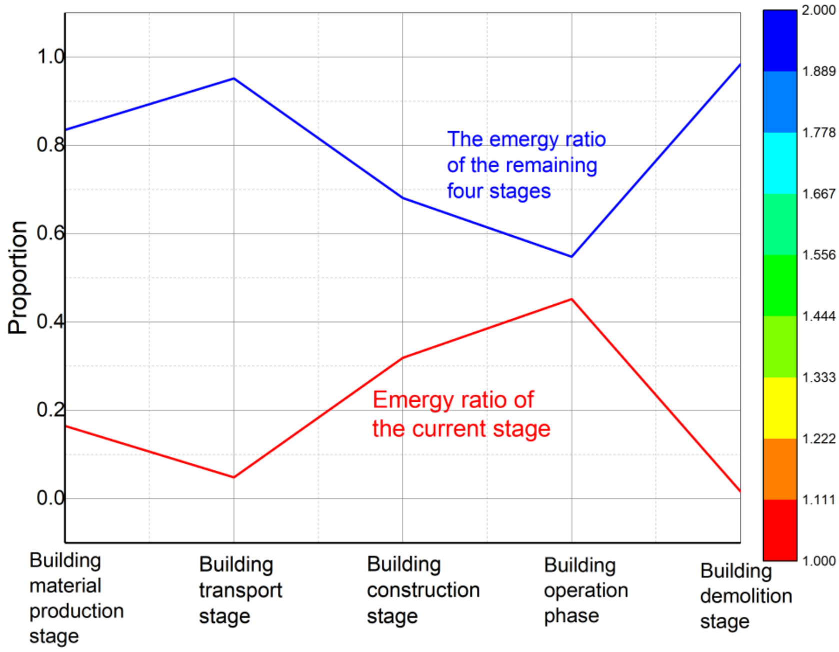

Figure 6. Emergy trend graph.

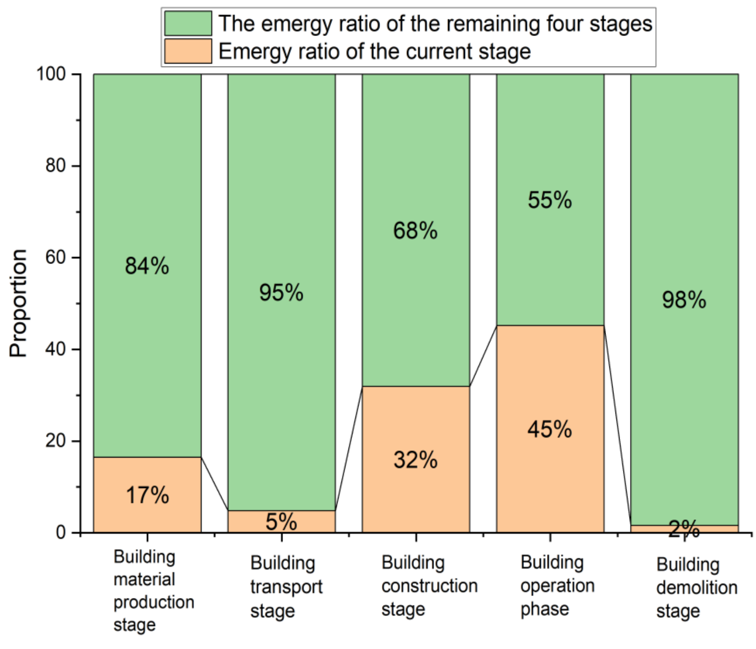

Figure 7. Emergy distribution proportion.

The building operation stage is the most important factor in determining the emergy calculation for a commercial building complex. It consists of six subsystems: Labor and Service, Water Supply and Sewage Treatment Facilities, Heating and Cooling Systems, Electricity Installations, Telecommunications Systems, and Elevator Systems. The contribution of each subsystem to the total emergy was compared, with Labor and Service accounting for 31.3%, followed by Water Supply and Sewage Treatment Facilities (roughly 23.5%), Heating and Cooling Systems (roughly 20.31%), Electricity Installations (roughly 14.6%), Telecommunications Systems (roughly 6.49%), and Elevator Systems (roughly 3.81%) in Figure 8.

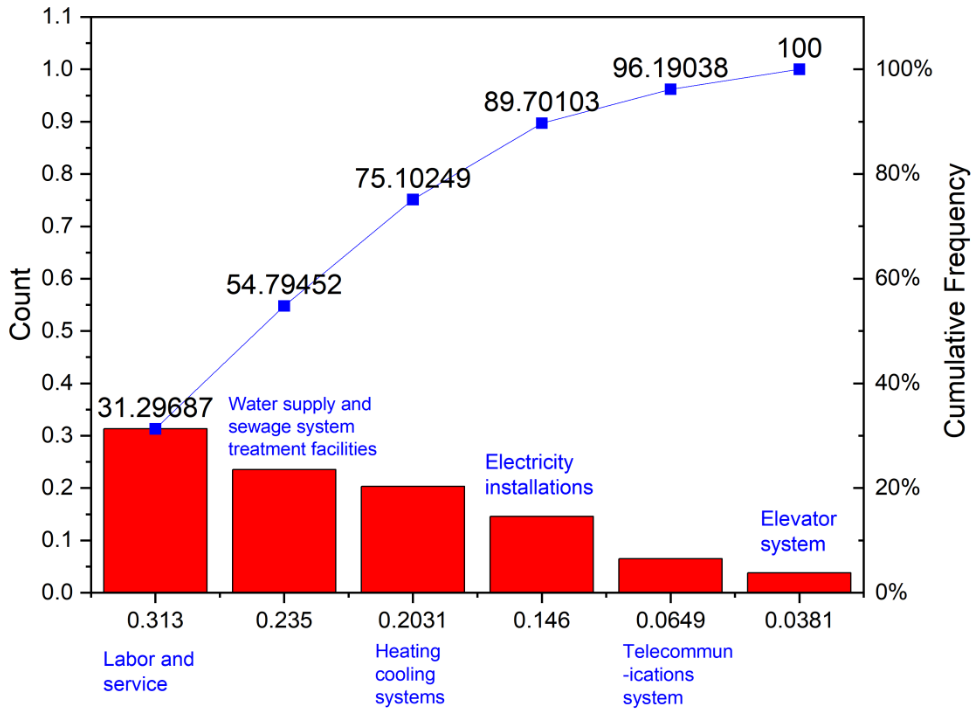

Figure 8. Emergy contribution proportion of six subsystems.

Labor and Service include all emergy inputs for various subsystems, which explains why it has the highest emergy amount. Water supply and heating/cooling subsystems are critical inputs, contributing to more than 40% of the entire emergy in the building system due to their frequent use. The remaining three subsystems have relatively minor contributions to emergy in the building commercial complex system.

In conclusion, understanding the emergy contribution of each subsystem in the building operation stage is crucial for sustainable building design and operation. This information can guide us in optimizing resource usage and reducing energy waste, leading to a healthier and more sustainable environment.

4.1.2. Sustainable Indicator Analysis

In this paper, five sustainability indicators have been selected for analysis, which are as follows:

(1) Renewable rate (R_i) expresses the proportion of renewable energy in the overall system structure.

(2) Non-renewable rate (N_i) represents the ratio of non-renewable resources and energy sources.

(3) Emergy yield ratio (EYR) reveals the dependence of the whole building system on the outside world.

(4) Environmental loading ratio (ELR) demonstrates the ecological pressure of building commercial complex systems.

(5) Emergy sustainability indicator (ESI) can be obtained based on EYR and ELR, which illustrates the sustainability state for the building commercial complex system.

Based on five emergy indexes, their influence was demonstrated. Through the calculation for the commercial building complex, its renewable rate is only 6.18%. Correspondingly, the non-renewable rate is more than 90 percent, which puts a serious burden on the sustainability of the building system. According to the Renewable rate (R_i) and Non-renewable rate (N_i), Emergy yield ratio (EYR), Environmental loading ratio (ELR), and Emergy sustainability indicator (ESI) were counted, which are 26.3, 74.2, 0.354, respectively. Taking the ESI as an example, its eligibility criteria are 1. Now the result is 0.354 (less than 1), which illustrates that the sustainability of the building system is not qualified and needs to enhance the degree of sustainability.

4.1.3. Sensitivity Analysis

To ensure the accuracy of research results, it is crucial to conduct a sensitivity analysis. In this study, an uncertainty analysis was carried out on five emergy indicators. The changes in these indicators were attributed to two factors—variations in underlying data and differences in emergy transformity. To test this, four hypotheses were formulated and assessed.

Hypothesis 1. *Float the underlying data by 5% to see how the sustainability indicators change*.

Hypothesis 2. *Change 10% of the underlying data and see the results*.

Hypothesis 3. *Ensure basic data is unchanged, emergy transformity changes by 5%*.

Hypothesis 4. *Similarly, holding the basic data constant, emergy transformity changes by 10%*.

To better illustrate the results of the four hypotheses, their trend changes are shown in Figure 9, as follows.

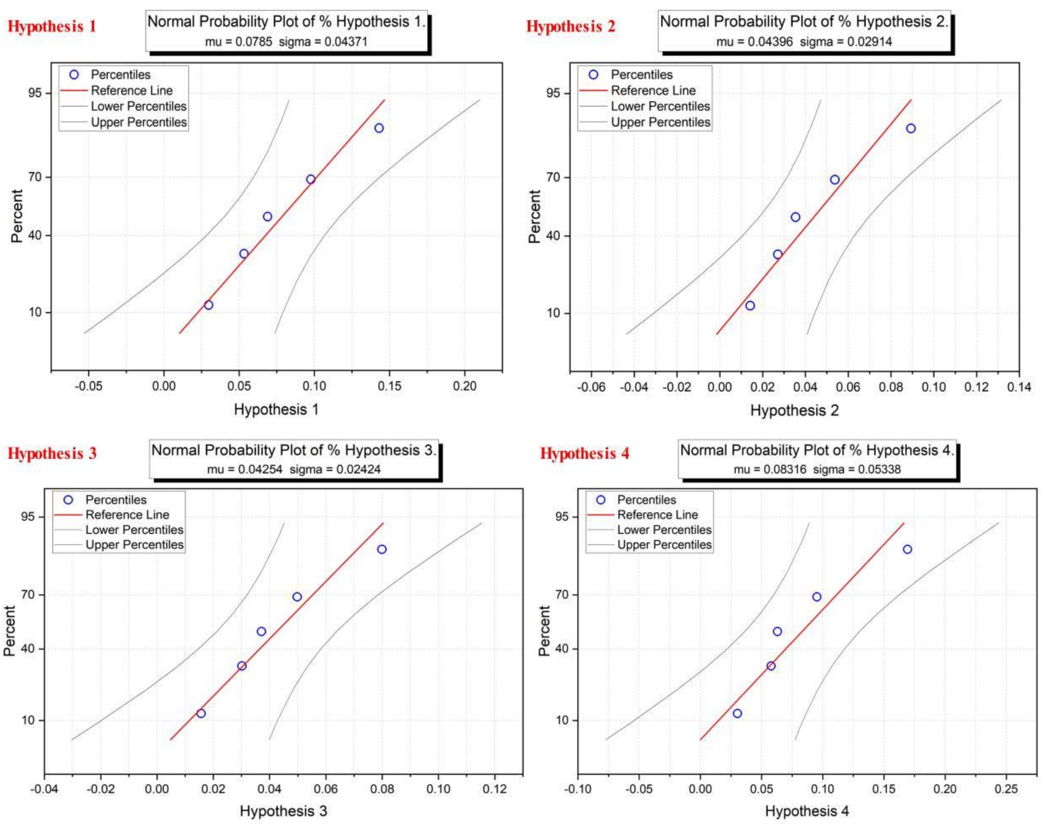

Figure 9. Sensitivity analysis trend changes of sustainable indicators.

Based on the data presented, it is evident that Hypothesis 1 is more stable than Hypothesis 2. Similarly, when considering emergy transformity, it can be concluded that Hypothesis 3 is superior to Hypothesis 4 in terms of sensitivity stability.

4.2. LCA-Carbon Emission Analysis

In addition to LCA-Emergy analysis, it is important to consider the full-cycle carbon perspective. Section 4.2 explores three subsections, namely the carbon emissions associated with building material production and transport stages, building construction stage, building operation stage, and building demolition stage. The life cycle carbon emission status and sensitivity analysis of the LCA-Carbon view is also presented.

4.2.1. The Carbon Emission of the Building Material Production and Transport Stages

This section consists of two aspects, which are the building material production stage material transport stage. The primary material list has been displayed in Table 3, including main material items (18 types) and the amount of diesel fuel used to transport materials.

Table 3. The carbon emission in the material production and transport stages.

Item	Data	Unit	Carbon Emission Factors	Carbon Emission	Unit
Steel	6.31×10^3	t	2.67 tCO_2/t	16,847.7	tCO_2
Cement	5.23×10^4	t	0.07 tCO_2/t	3661	tCO_2
Gravel	4.57×10^2	t	16 $kgCO_2/kg$	7312	tCO_2
Brick	8.92×10^3	t	0.24 $kgCO_2/kg$	2140.8	tCO_2
Lime	9.52×10^3	t	0.44 tCO_2/t	4188.8	tCO_2
Sand	7.59×10^5	t	2.51 $kgCO_2/t$	1905.09	tCO_2
Water	4.22×10^6	m^3	0.82 $kgCO_2/m^3$	3460.4	tCO_2
Iron	7.74×10^3	t	2.05 tCO_2/t	15,867	tCO_2
Wood	5.31×10^5	t	0.31 $kgCO_2/kg$	16,461	tCO_2
Glass	7.63×10^3	t	1.4 $kgCO_2/kg$	10,682	tCO_2
Polyester	6.42×10^1	t	72.65 tCO_2/t	4664.13	tCO_2
Adhesive	5.19×10^1	t	1.1 $kgCO_2/kg$	57.09	tCO_2
Bituminous	6.83×10^1	t	0.04 $kgCO_2/kg$	2.732	tCO_2
Aluminum	7.89×10^1	t	15.8 tCO_2/t	1246.62	tCO_2
Ceramic tile	5.28×10^1	t	0.74 tCO_2/t	39.072	tCO_2
Polystyrene	4.82×10^1	t	3.78 $kgCO_2/kg$	182.196	tCO_2
Fly ash	5.69×10^2	t	0.18 tCO_2/t	102.42	tCO_2
PVC	1.37×10^1	t	4.79 $kgCO_2/kg$	65.623	tCO_2
Diesel fuel	7.84×10^1	t	3.797 tCO_2/t	297.6848	tCO_2

Table 3, Figures 10 and 11 present the carbon emission amounts, indicating that steel, wood, and iron are the top three inputs for carbon emissions, accounting for 19%, 18%, and 18% of the total carbon emission amount, respectively. This is because these industries are highly polluting, resulting in significantly more carbon emissions than other inputs (as shown in Figure 10). Additionally, glass (12%), gravel (8%), polyester (5%), lime (5%), cement (4%), water (4%), brick (2%), sand (2%), and aluminum (1%) are the input items with higher carbon emissions.

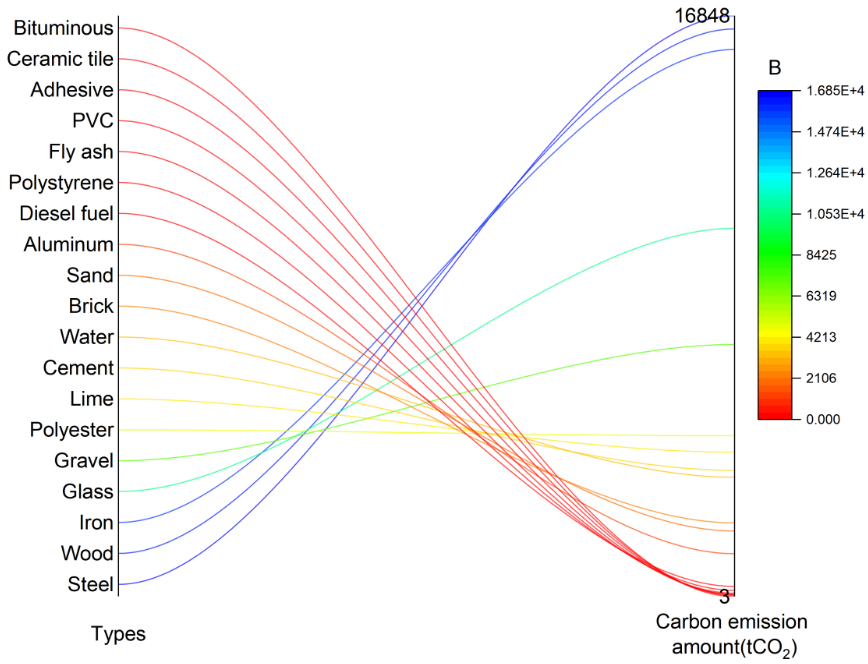

Figure 10. Carbon emission comparison before improvement.

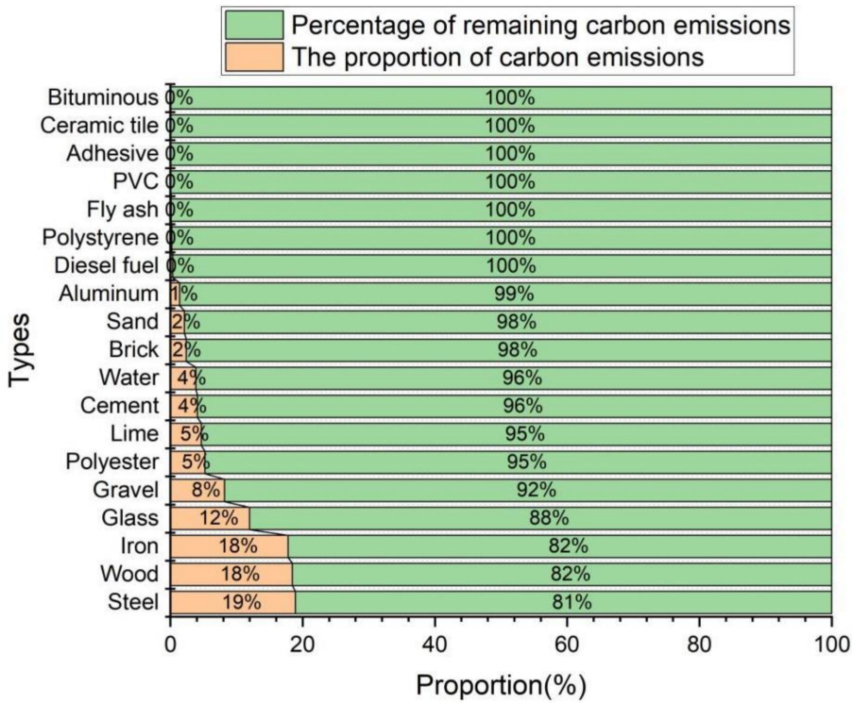

Figure 11. Quantitative carbon emission comparison.

To confirm and analyze their sensitivity, six hypotheses have been proposed: a 5%, 8%, and 10% reduction and increase in carbon emissions, respectively. The violin diagram (in Figure 12) is used to analyze data structure changes, data density, data contour, etc.

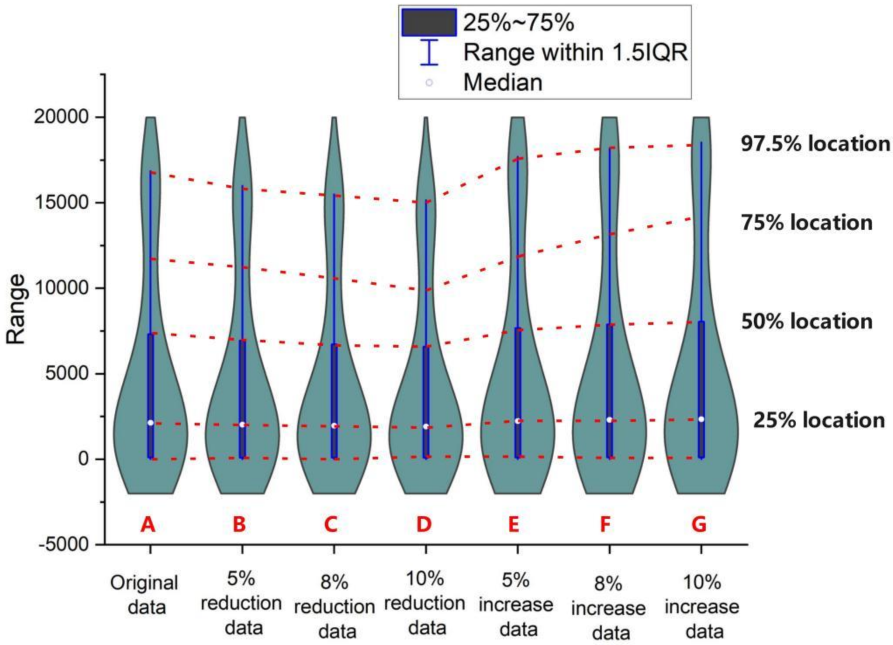

Figure 12. Violin structure analysis diagram.

Figure 12 depicts the changes in data structure before and after implementing the six proposed hypotheses using the violin plot. Each change resulted in a different data structure form. Generally, reducing the data narrows the overall data structure (5%, 8%, and 10%), whereas increasing it widens the shape of the data structure (as indicated by the 97.5% to 100% location). When compared with the original data model, about 25% of the data showed little change at the 25% location. Changes become noticeable at the 50% position of the data structure, first down and then up. At the same time, the density of the data structure increases from left to right in Figure 12. Between the 75% to 97.5% positions, the change is more and more prominent.

When considering only the reduction of data structures (B, C, D), the structural morphology is similar. A similar pattern of change can also be seen when increasing the data variation (E, F, G). However, compared to the original data patterns (A), all of them show significant changes in Table 3, indicating the high sensitivity of data and the need to verify its accuracy repeatedly.

4.2.2. The Carbon Emission of Building Construction Stage

For the construction stage, carbon emissions involve multiple subsystems, including Subsystem transport, water supply, and sewage treatment facilities, heating and cooling systems, electricity installations, telecommunications system, elevator systems, etc.

Table 4, Figures 13 and 14 compare the carbon emissions of the six subsystems. It is evident that water supply and sewage treatment facilities are the primary contributors (36,124 tCO_2), accounting for 46% of the entire carbon emission of the six subsystems. The other five subsystems have significantly lower carbon emissions, with electricity installations being the second-largest contributor (approximately 24%), followed by subsystem transport (11% roughly), telecommunications systems (8% roughly), heating and cooling systems (6% roughly), and elevator systems (6% roughly).

Table 4. The carbon emission in the building construction stage.

Item	Data	Unit	Carbon Emission Factors	Carbon Emission	Unit
Subsystem Transport					
Diesel fuel	7.50×10^2	t	3.797 tCO_2/t	2847.75	tCO_2
Machinery diesel	1.05×10^3	t	3.797 tCO_2/t	3986.85	tCO_2
Transport diesel	4.31×10^2	t	3.797 tCO_2/t	1636.51	tCO_2
Water supply and sewage treatment facilities					
Steel	7.60×10^6	Kg	2.67 tCO_2/t	20,283.99	tCO_2
PVC	1.38×10^4	Kg	4.79 $kgCO_2/kg$	66.24	tCO_2
Polystyrene	6.43×10^3	Kg	3.78 $kgCO_2/kg$	21.67	tCO_2
Brass	4.93×10^3	Kg	3.73 tCO_2/t	18.40	tCO_2
Polypropylene	9.43×10^3	Kg	5.98 tCO_2/t	56.40	tCO_2
Glass fiber	7.55×10^3	Kg	1.4 $kgCO_2/kg$	10.57	tCO_2
Iron	5.64×10^4	Kg	2.05 tCO_2/t	115.69	tCO_2
Ceramic	7.62×10^5	Kg	0.74 tCO_2/t	563.88	tCO_2
Glass	9.11×10^6	Kg	1.4 $kgCO_2/kg$	12,754	tCO_2
Cement	3.99×10^6	Kg	0.07 tCO_2/t	279.3	tCO_2
Water	6.38×10^4	m^3	0.82 $kgCO_2/m^3$	52.316	tCO_2
Gravel	6.69×10^4	Kg	16 $kgCO_2/kg$	1070.4	tCO_2
Diesel fuel	7.61×10^2	t	3.797 tCO_2/t	831.54	tCO_2
Heating and cooling systems					
Steel	7.12×10^5	Kg	2.67 tCO_2/t	1901.04	tCO_2
Polypropylene	6.76×10^3	Kg	5.98 tCO_2/t	40.41882	tCO_2
Aluminum	7.31×10^3	Kg	15.8 tCO_2/t	115.498	tCO_2
Glass wool	1.04×10^4	Kg	1.4 $kgCO_2/kg$	14.5894	tCO_2
Brass	9.81×10^3	Kg	3.73 tCO_2/t	36.59876	tCO_2
Copper	9.12×10^3	Kg	3.73 tCO_2/t	34.02879	tCO_2
Diesel fuel	6.51×10^2	t	3.797 tCO_2/t	2471.847	tCO_2
Electricity installations					
Copper	1.77×10^4	Kg	3.73 tCO_2/t	49.982	tCO_2
Aluminum sheet	6.37×10^4	Kg	15.8 tCO_2/t	761.56	tCO_2
Galvanized steel	7.56×10^4	Kg	15.8 tCO_2/t	903.76	tCO_2
Steel	1.19×10^6	Kg	15.8 tCO_2/t	14,283.2	tCO_2
Rubber	9.24×10^4	Kg	2.4 tCO_2/t	167.76	tCO_2
Polyester	1.03×10^4	Kg	72.65 tCO_2/t	568.458	tCO_2
Iron	7.19×10^4	Kg	2.05 tCO_2/t	111.52	tCO_2
Ceramics	8.96×10^4	Kg	0.74 tCO_2/t	50.172	tCO_2
Plastic	1.31×10^5	Kg	7.83 $kgCO_2/kg$	778.302	tCO_2
Glass	5.05×10^4	Kg	1.4 $kgCO_2/kg$	53.48	tCO_2
Diesel fuel	2.23×10^2	t	3.797 tCO_2/t	847.97	tCO_2
Telecommunications system					
Copper	7.44×10^4	Kg	3.73 tCO_2/t	277.50	tCO_2
PVC	8.81×10^4	Kg	4.79 $kgCO_2/kg$	422.20	tCO_2

Table 4. *Cont.*

Item	Data	Unit	Carbon Emission Factors	Carbon Emission	Unit
Aluminum sheet	1.05×10^5	Kg	15.8 tCO_2/t	1666.15	tCO_2
Plastic	3.08×10^4	Kg	7.83 $kgCO_2$/kg	241.09	tCO_2
Brass	5.99×10^4	Kg	3.73 tCO_2/t	223.29	tCO_2
Aluminum	8.91×10^4	Kg	15.8 tCO_2/t	1407.25	tCO_2
Glass	1.17×10^5	Kg	1.4 $kgCO_2$/kg	164.28	tCO_2
Steel	8.97×10^4	Kg	15.8 tCO_2/t	1417.69	tCO_2
Diesel fuel	2.51×10^0	t	3.797 tCO_2/t	721.43	tCO_2
			Elevator system		
Steel	2.79×10^5	Kg	15.8 tCO_2/t	4405.47	tCO_2
Rubber	7.03×10^3	Kg	2.4 tCO_2/t	16.87	tCO_2
Iron	1.18×10^4	Kg	2.05 tCO_2/t	24.19	tCO_2
Glass	1.20×10^4	Kg	1.4 $kgCO_2$/kg	16.76	tCO_2
Diesel fuel	2.52×10^1	t	3.797 tCO_2/t	95.84	tCO_2

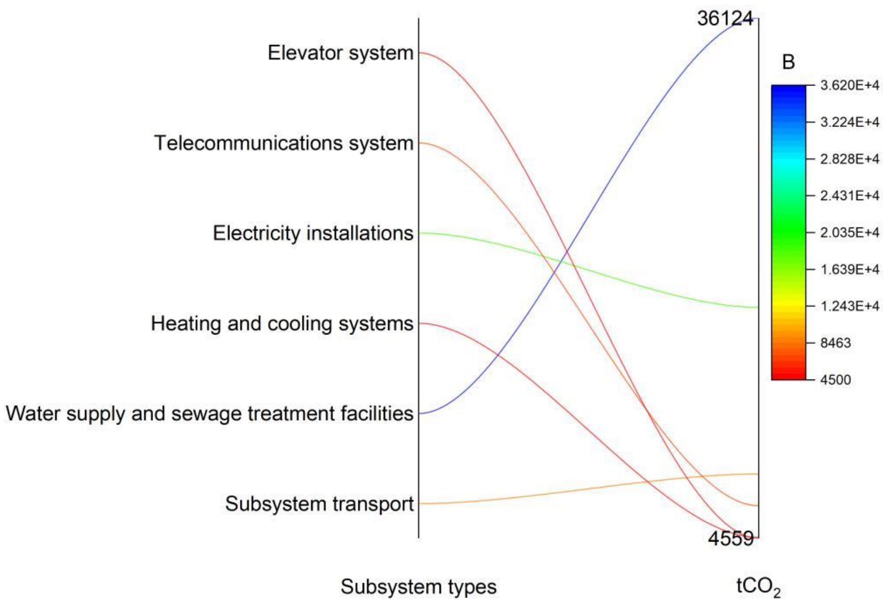

Figure 13. Carbon emission comparison of six subsystems.

Comparing the six subsystems, the large amount of water usage and sewage treatment required results in significantly more carbon emissions than any other project (the other five subsystems). Additionally, the use of power systems is also a common input, responsible for about 24% of the carbon emissions in Figure 14. The other four carbon emissions play minor roles.

Figure 15 displays the carbon emission distribution of the six subsystems, and it confirms the primary input elements. For instance, in the case of subsystem transport (in Figure 15(1)), machinery diesel has the most significant carbon emissions, followed by Diesel fuel and Transport diesel. Similar analysis can be obtained from other sub-graphs (in Figure 15(2–6)).

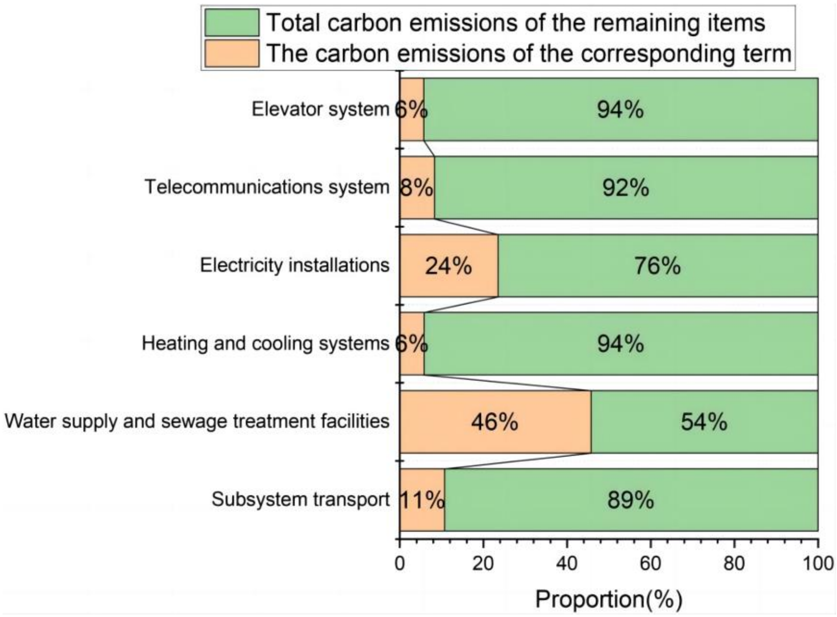

Figure 14. Carbon emission proportion of six subsystems.

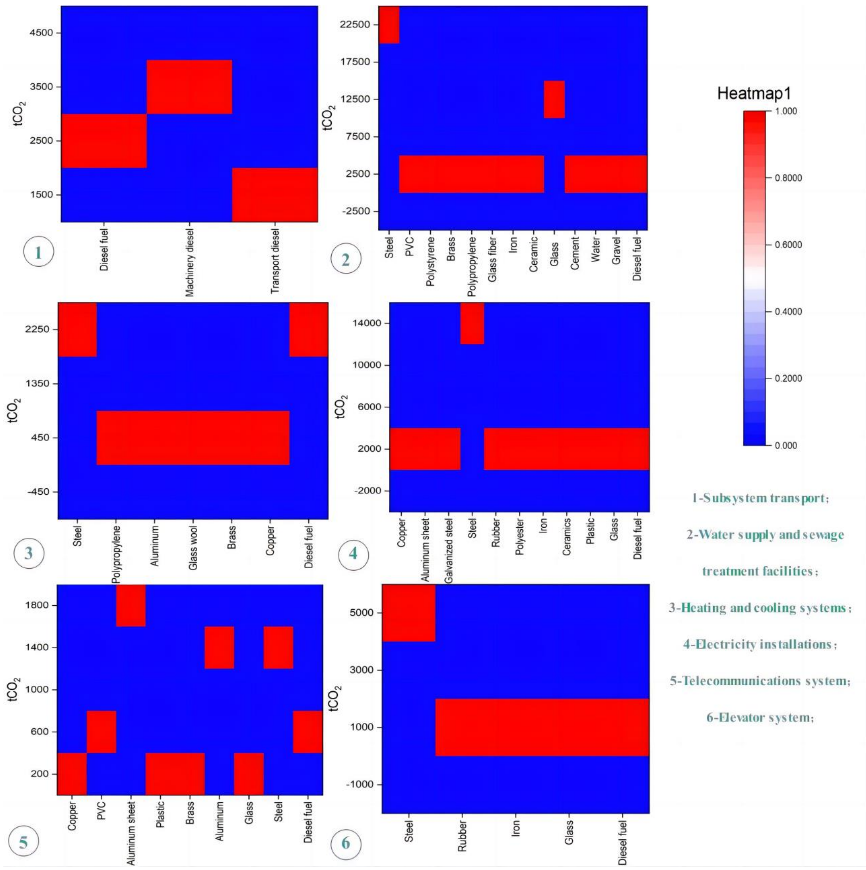

Figure 15. Detailed carbon emission distribution in six subsystems.

4.2.3. The Carbon Emission in the Building Operation Stage

According to the standards for the use of public buildings in China [55], the fiftieth anniversary building life cycle is considered and calculated. It was found that the carbon emission from electricity usage accounts for approximately 76.2% of the total carbon emission in the building operation phase, significantly more than the carbon emission from heat (approximately 22.8%). Moreover, water has the least amount of carbon emissions throughout the entire life cycle of the building. However, it is important to note that the water used here is for the sewage treatment plant. Therefore, considering the significant differences in the efficiency of different sewage treatment plants, it is necessary to carry out separate calculations for specific projects (in Table 5 and Figure 16).

Table 5. The carbon emission in the building operation stage.

Item	Data	Unit	Carbon Emission Factors	Carbon Emission	Unit
Electricity	7.41×10^9	kWh	0.7025 $kgCO_2/kWh$	5.21×10^6	tCO_2
Heat	7.79×10^8	J	0.002 tCO_2/J	1.56×10^6	tCO_2
Water	8.25×10^6	m^3	0.82 $kgCO_2/m^3$	6.77×10^3	tCO_2

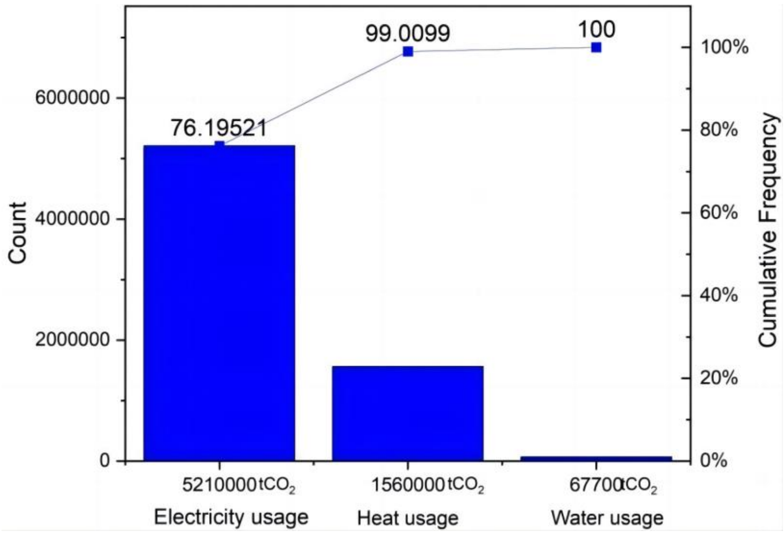

Figure 16. The carbon emission in the building operation stage.

4.2.4. The Carbon Emission in the Building Demolition Stage

Table 6 and Figure 17 present the carbon emissions of the demolition phase, revealing that glass emits 1638 tons of carbon dioxide, accounting for about 28% of the total carbon emission (in Figure 18). Iron follows closely behind with 1498.6 tCO_2, followed by concrete, aluminum (1023.8 tCO_2), PVC (152.8 tCO_2), bricks (158.6 tCO_2), and diesel fuel (29.73 tCO_2), respectively.

Table 6. The carbon emission of the building demolition stage.

Item	Data	Unit	Carbon Emission Factors	Carbon Emission	Unit
Glass	1.17×10^6	Kg	1.4 $kgCO_2/kg$	1638	tCO_2
Iron	7.31×10^5	Kg	2.05 tCO_2/t	1498.6	tCO_2
PVC	3.19×10^4	Kg	4.79 $kgCO_2/kg$	152.8	tCO_2
Aluminum	6.48×10^4	Kg	15.8 tCO_2/t	1023.8	tCO_2
Bricks	6.61×10^5	Kg	0.24 $kgCO_2/kg$	158.6	tCO_2
Concrete	9.95×10^6	Kg	0.13 $kgCO_2/kg$	1293.5	tCO_2
Diesel fuel	7.83×10^3	Kg	3.797 tCO_2/t	29.73	tCO_2

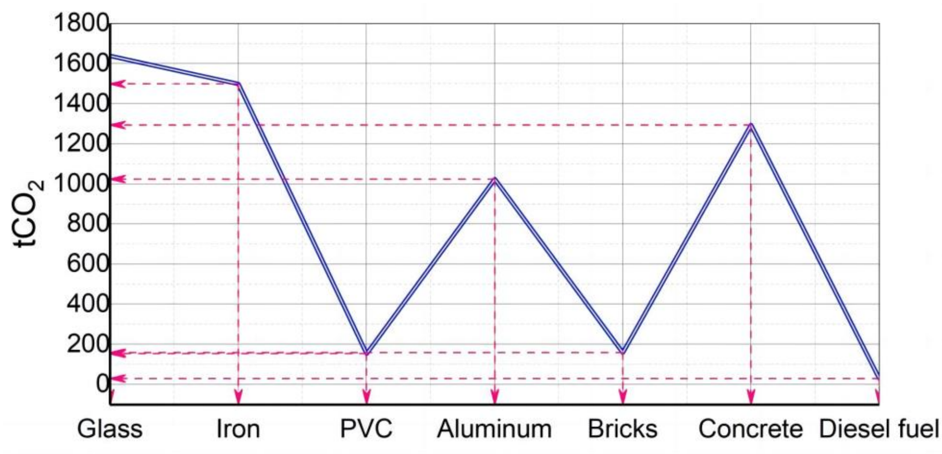

Figure 17. The carbon emission in the building demolition stage.

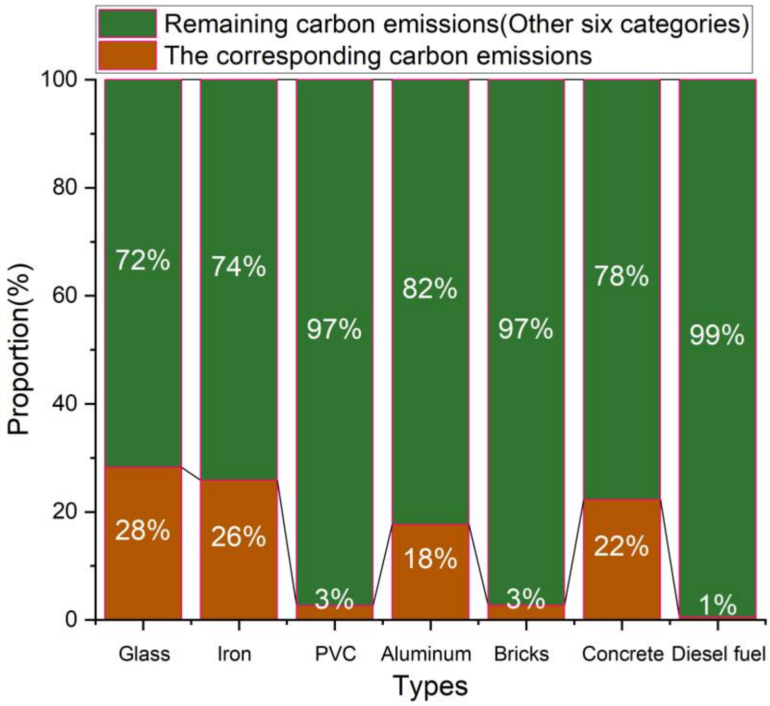

Figure 18. The proportion of various inputs.

In this stage, four types of materials will be recycled for reuse to enhance the utilization efficiency of materials. Glass (iron, aluminum) can be remelted and recast into new products for building systems. Concrete will be broken down and used as raw materials to regenerate building products, reducing carbon emissions, and improving the sustainability of the building system.

4.2.5. Life Cycle Carbon Emission Status

Table 7 displays the carbon emissions of the five stages in the building system, revealing that the carbon emission amount in the building operation stage accounts for the majority, approximately 97.4% of the entire carbon dioxide proportion (as shown in Figures 19 and 20). This highlights that the operational phase of the building system emits a significant amount of carbon dioxide within the 50-year cycle range, requiring special attention to reduce system carbon emissions and improve the sustainability of the entire building system.

Table 7. The carbon emission calculation of the LCA-Carbon method.

Stages	Abbreviation	Carbon Emission	Unit
Building material production stage	B1	8.92×10^4	tCO_2
Building material transport stage	B2	8.47×10^3	tCO_2
Building construction stage	B3	7.89×10^4	tCO_2
Building operation stage	B4	6.77×10^6	tCO_2
Building demolition stage	B5	5.79×10^3	tCO_2

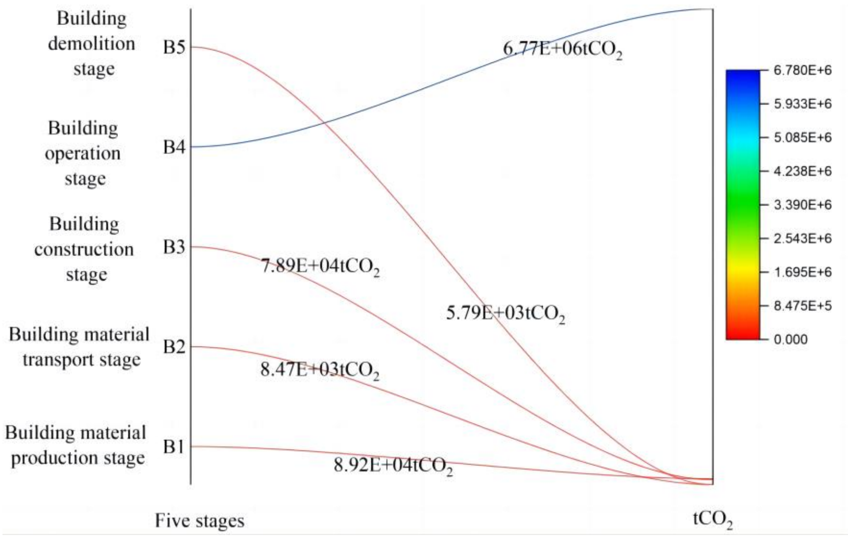

Figure 19. Full life cycle carbon emission analysis of building system.

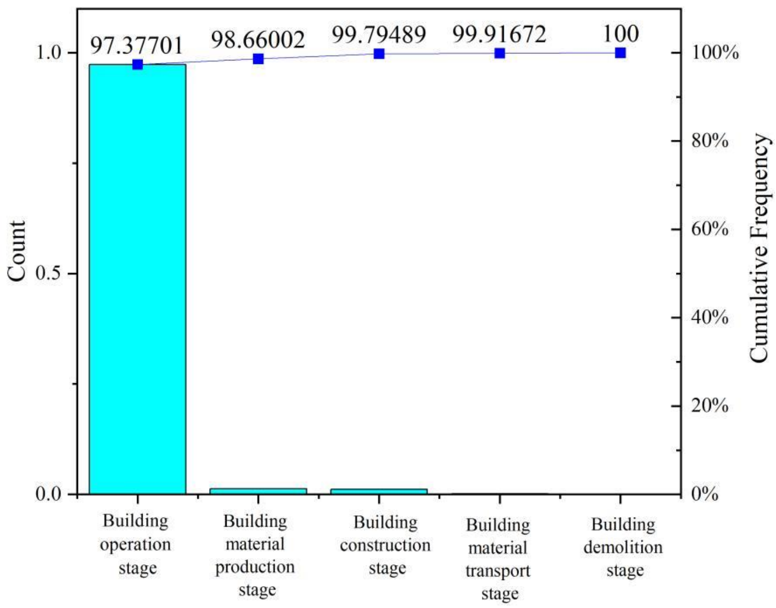

Figure 20. The proportion of each stage.

4.3. Entropy Analysis of Building System

Entropy, as an expression of the state in the system, can demonstrate how chaotic the building system is and indicate sustainable changes in the building system. For example, in a closed building system, the result is increasingly chaotic and inefficient. Therefore, to improve the efficiency of a building system, it is necessary to exchange material flow, energy flow, and information flow.

In this study, several inputs were considered to assess their effectiveness in creating a sustainable system. Although the building system may function normally based on a series of inputs, it doesn't guarantee the orderliness of the building system. For instance, according to the Emergy Sustainability Indicator (ESI), the building is in an unsustainable state (confusion state), which is less than the standard value. In line with the analysis in this section, improvement strategies for building systems need to be provided to enhance their sustainability.

5. Improvement Measures and Strategies

According to the analysis in Section 4.3, two optimized measures were provided, involving renewable energy use and carbon sink improvement, respectively.

5.1. Renewable Energy Use

From the perspective of life cycle assessment (LCA)-Emergy analysis, the input of renewable energy helps improve the sustainability of the building system [58,59]. Therefore, in this study, solar energy was selected and applied to the building case to explore the quantitative analysis of renewable energy on the sustainability of the building system. To better demonstrate the effects of renewable energy, four strategies were considered and calculated by substituting total emergy in the building system with 3% (Scheme 1), 5% (Scheme 2), 8% (Scheme 3), and 10% (Scheme 4) renewable energy inputs, respectively.

Figure 21 displays the sustainable change effect of solar energy. In Scheme 1, when only a 3% increase in renewable energy is applied, compared to the original state, Emergy yield ratio (EYR) increases, the Environmental loading ratio (ELR) decreases, and Emergy sustainability indicator (ESI) improves. With the increase in the proportion of solar energy utilization in the building system (as shown in Figure 22), the increased Emergy yield ratio (EYR) contrasts with the decreased Environmental loading ratio (ELR), resulting in improved ecological sustainability for the building system. These results illustrate that the increased utilization of solar energy has a significant positive effect on the sustainability of the building system.

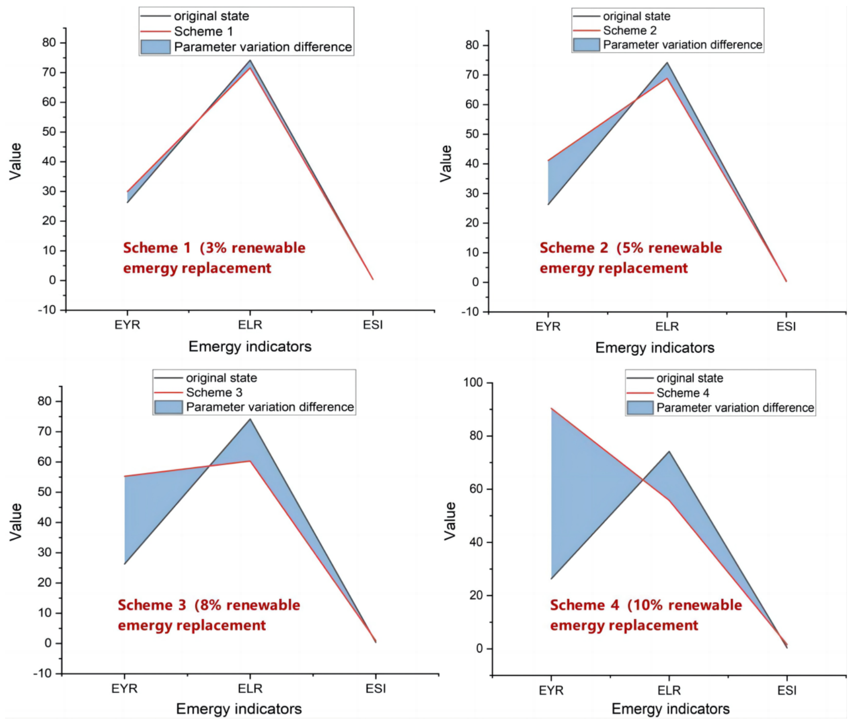

Figure 21. The relationship between solar energy substitution and sustainability.

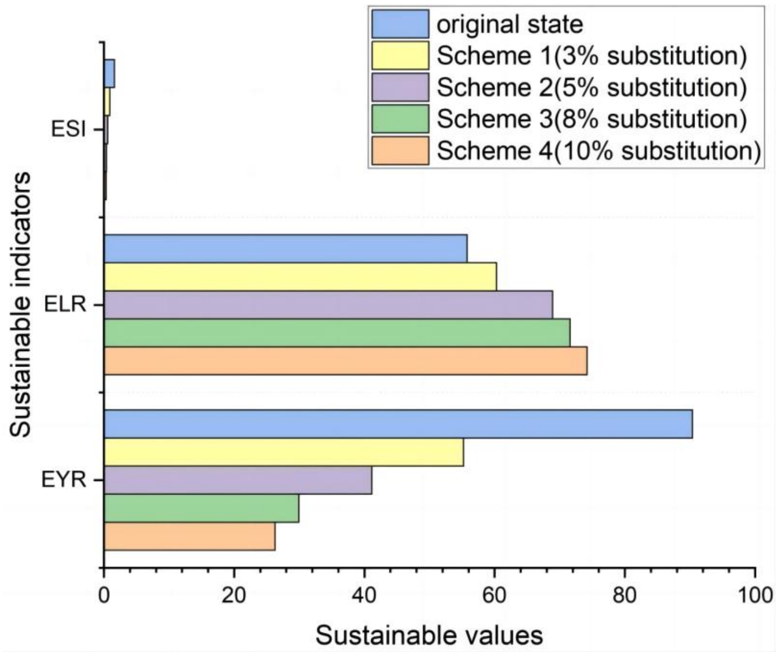

Figure 22. Variation variance trend.

5.2. Carbon Sink Improvement

Carbon sequestration refers to the process of removing and storing carbon dioxide (CO_2) from the atmosphere through natural or artificial means. Here are some common methods of carbon absorption: (1) Plant Absorption: Plants absorb carbon dioxide from the atmosphere through photosynthesis and store it in their tissues. This includes forests, grasslands, and other vegetation types. (2) Forest Management: Increasing carbon storage in forests can be achieved through activities such as protecting existing forests, reforestation, or afforestation. (3) Soil Carbon Storage: Improving soil quality and preserving organic matter can increase carbon storage in the soil. This involves adopting appropriate agricultural practices, vegetation cover, and organic waste composting. (4) Ocean Carbon Sink: Marine phytoplankton absorbs carbon dioxide through photosynthesis and stores it in marine organisms. Additionally, the ocean absorbs carbon dioxide through dissolution and sedimentation processes. (5) Carbon Capture and Storage (CCS) Technology: This is an artificial method that involves capturing carbon dioxide from combustion processes and storing it underground or in other locations. This can be achieved using techniques like absorption, membrane separation, and chemical reactions. These carbon sequestration methods aim to reduce the concentration of carbon dioxide in the atmosphere and have a positive impact on global climate change. However, it is important to integrate these principles and implement effective management measures to maximize carbon storage effectiveness.

The application of carbon sinks in building systems has an important positive significance for carbon reduction. In Section 5.2, two types of carbon sinks are considered and evaluated, including the carbon absorption of soil and concrete materials and landscape plant, respectively.

➢ The two carbon absorption models are calculated as follows:

(1) Life zone method computational model (soil absorption)

Relationship between density and depth of soil organic carbon:

$$B_D = b_0 + b_{1D} + b_2 \lg C_f \quad (1)$$

where B_D is soil weight; $b1$, $b2$, $b3$ is the constant of soil weight and carbon density under different vegetation types; D is the depth from the surface to the center of the soil layer; C_f is the Organic carbon mass fraction.

The average carbon density of layers per unit area:

$$C = C_f + B_D(1 - \delta_{2mm})V \quad (2)$$

(2) Molecular-level carbonization theory estimation model (concrete materials absorption)

$$d = \sqrt{\frac{2D_{CO_2}[CO_2]^0}{[Ca(OH)_2]^0 + 3[CSH]^0 + 3[C_3S]^0 + 2[C_2S]^0}} \cdot \sqrt{t} \quad (3)$$

Among them, $[Ca(OH)_2]^0[CSH]^0[C_3S]^0[C_2S]^0$ there are respectively the initial concentration of each carbide-able substance; D_{CO_2} is the Effective diffusion coefficient of carbon dioxide in concrete; $[CO_2]^0$ is the concentration of carbon dioxide on the concrete surface.

➢ The two kinds of carbon absorption effects are verified as follows:

According to the building operation cycle of 50 years, the carbon dioxide absorption of the building area and concrete material are displayed in Figure 23.

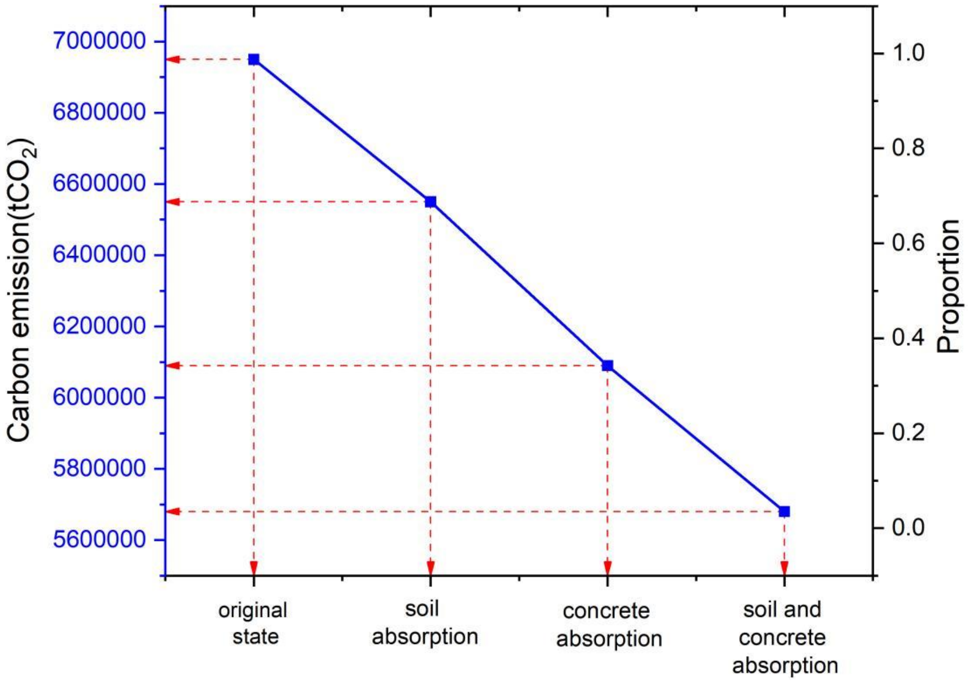

Figure 23. The change in carbon emissions by conducting carbon sinks measure.

Figure 23 illustrates the effect trends of carbon sink measures. Fifty years of CO_2 sequestration of soil and building materials significantly reduces the carbon emissions of the entire building system. Building materials have better carbon dioxide absorption than soil. A 12.4% reduction in CO_2 absorbed through building materials is compared to the total building carbon emission, whereas the corresponding effect of soil absorption is only 5.76%. Both contribute more than 18.3% to building carbon emissions, making it necessary to consider carbon sink design in the building system.

However, since there are different calculation models for soil carbon dioxide storage and concrete carbon dioxide storage, there may be differences in the calculation results that need to be further verified.

Some researchers have conducted in-depth studies on carbon sequestration, particularly analyzing the carbon absorption effects of building materials and soil [60–62]. The results indicate that both types of substances have the ability to absorb carbon dioxide. However, the carbon absorption capacity varies depending on the type of material, soil composition, and scale, and it needs to be individually validated.

6. Conclusions

This study focuses on the ecologically low carbon sustainability of a commercial building complex. Using the LCA–Emergy–Carbon emission methodology, questions were explored and discussed from the perspective of ecology and carbon emissions. The research framework, evaluated indicators, calculation equations, LCA-Emergy analysis, LCA-Carbon emission discussion, and improvement measures were all considered.

The main research results are as follows:

(1) The results highlight that the building operation stage plays a critical role, accounting for roughly 45% of the entire emergy in the building complex. Additionally, the carbon emission amount in the building operation stage accounts for the majority, approximately 97.4% of the entire carbon dioxide proportion. These two analyses indicate that the ecology and carbon emission of the building operation phase needs to be focused on.

(2) According to the Renewable rate (R_i) and Non-renewable rate (N_i), Emergy yield ratio (EYR), Environmental loading ratio (ELR), and Emergy sustainability indicator (ESI) were counted, which are 26.3, 74.2, 0.354, respectively. Taking the ESI as an example, its eligibility criteria are 1. Now the result is 0.354 (less than 1), illustrating that the sustainability of the building system is not qualified and needs to enhance sustainability degree.

(3) The carbon emission amount in the building operation stage accounts for the majority, approximately 97.4% of the entire carbon dioxide proportion. This highlights that the operational phase of the building system emits a significant amount of carbon dioxide within the 50-year cycle range, requiring special attention to reduce system carbon emissions and improve the sustainability of the entire building system.

(4) Two optimized measures were provided, involving renewable energy use and carbon sink improvement, respectively. Simultaneously, both types of effects have also been validated.

In future research, this paper plans to conduct an in-depth discussion on the operation mode, element analysis, and sensitive design of the building system.

Author Contributions: Conceptualization, J.Z., J.C.; investigation, J.C., Y.Z., H.W. and H.Z.; formal analysis, J.Z., Y.Z.; methodology, J.Z., J.C., H.W.; resources, J.C., J.Z., H.Z.; writing—review and editing, J.Z., J.C., Y.Z. All authors have read and agreed to the published version of the manuscript.

Funding: The work described in this paper was supported by the National Natural Science Foundation of China (No. 52208009): Research on Tissue Recognition and Interactive Optimization of Place Unit in High-density Urban Form Based on "Meta Modeling"; National Natural Science Foundation of China (No. 52278010): Research on the Mixed-Use Mode and Internal Mechanism of Intensive-Oriented Old City Residential Blocks: Typomorphological Lineage Analysis. Major research projects on philosophy and social sciences of Jiangsu universities in 2023 (No. 2023SJZD131).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: This study did not report any data.

Conflicts of Interest: The authors declare no conflict of interest.

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