

Article

Sustainable Process Study on Emergy and Carbon Emission Analysis of Building System Based on Neural Network Algorithm

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Abstract: Sustainable building systems can effectively reduce environmental pressures and mitigate the deterioration of the global climate. The sustainability of complex building systems is influenced by various factors. This article quantitatively analyzes building systems from an ecological emergy and carbon emissions perspective, and considers typical feedback structures' impact. A neural network algorithm is employed for sustainability prediction analysis. The results demonstrate that both from an emergy and carbon emissions perspective, the operational phase of the building and the production phase of building materials are the main contributors (accounting for over 90%). Among the three types of feedback subsystems, the cross-feedback structure has a more significant impact and yields the best corrective effect. For example, the correction proportion of the building's emergy sustainability parameter reaches 11.3%, while it is 15.8% for carbon emissions. The neural network model predicts a decreasing trend in the energy sustainability of buildings and increasing carbon emissions over time. To improve the sustainability of building systems, measures such as ecological landscape design and carbon sequestration in building materials are considered, which can enhance the sustainability of buildings to a certain extent.



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Keywords: sustainable process; emergy and carbon emission; neural network algorithm; building system

1. Introduction

Facing increasingly deteriorating environmental changes, building systems, as a component of the global system, can contribute to alleviating environmental pressures and improving global ecological levels when their sustainability is enhanced [1,2]. As an open system, building systems require inputs of material flows, energy flows, information flows, and other resources to sustain their operational functioning. Therefore, the ecological sustainability of building systems is a dynamic process that needs to be assessed based on specific conditions [3,4]. From a carbon emissions perspective, it accounts for more than one-third of the global carbon emissions, highlighting the need to consider the sustainability of building systems [5,6].

In this study, the emergy analysis method is used to quantitatively analyze building systems, which is a perspective from ecological economics. It has been widely applied in various fields such as urban areas, agriculture, industry, materials manufacturing, ecology, and economics [7–13]. However, the research on the intersection of building systems and emergy analysis started relatively late, and scholars from different countries have pursued different research directions. Some researchers have coupled Building Information Modeling (BIM) technology with emergy analysis [14]. Others explore the sustainability of

buildings from the perspective of clean energy [15]. The ecological sustainability of building materials can also be assessed quantitatively through emergy calculations [16]. From an ecological perspective, redefining the scope of green buildings is also a research interest of many scholars [17]. Additionally, some researchers use emergy analysis as an assistant design tool for architects to enhance the sustainability performance of building systems [18]. Furthermore, there is a growing trend in exploring the integration of emergy research with whole life cycle theory, involving the analysis of ecological emergy sustainability of entire building systems, renewal design strategies, the impacts of building materials throughout their life cycles, and the operational effects of buildings [19–21].

With the global climate warming, carbon dioxide emissions reduction is essential. As an important component of the global system, building systems are a focal point of research from a carbon emissions perspective. Through a review of relevant literature, the research can be broadly categorized into four directions: (1) Low-carbon building design: This direction focuses on integrating low carbon as a design approach with architectural projects to achieve the low carbonization of building systems [22–27]. (2) Low-carbon assessment: This direction involves analyzing the sustainability state of the entire building system and includes calculations of carbon emissions throughout the life cycle of the building system. (3) Low-carbon management: For example, this includes designing carbon emission models for public buildings [28], integrating carbon emissions methods into supply chain management as a part of building system design [29], and the allocation of carbon emission quotas, which is an important task at the government level [30]. (4) Coupling of low-carbon methods with other approaches: Examples include exploring the combination of Building Information Modeling (BIM) and carbon emission calculations [31], integrating life cycle theory with low-carbon design [32], designing low-carbon buildings from an energy-saving perspective [33], and studying the application of carbon capture and storage technologies in building systems [34]. Additionally, there are studies focusing on low-carbon modules for specific types of buildings [35–37].

With the development of artificial intelligence computing, artificial neural network (ANN) as a new method is gradually being applied to many domains, which are also increasing applications in building systems [38]. This process involves computing errors and then adjusting the weights layer by layer in the opposite direction of the network to reduce errors and improve the network's predictive capabilities [39].

The subject of this research article is complex building systems, with the aim of seeking ecological and low-carbon methods for quantitatively evaluating building systems and providing support for achieving sustainable building systems. Additionally, by calculating the ecological emergy and carbon emissions throughout the entire life cycle of the building system, an accurate sustainable analysis of the building system is completed. Through the use of neural networks to predict and analyze the sustainability status of the building system, a comprehensive assessment of the sustainability of the entire building system is achieved. As one of the core elements influencing global climate, this study is beneficial for promoting global sustainability development.

2. Material and Methods

2.1. Research Framework

In order to ensure a clear delineation of the research boundaries for the building system, Figure 1 research framework diagram was designed and applied. The entire framework diagram is divided into four parts: on the left side are the inputs of renewable energy, including solar energy, rainwater energy, wind energy, and geothermal energy; on the top side are the inputs of non-renewable resources and energy, as well as artificial services, involving eight types. In the middle is the building system, where the renewable and non-renewable inputs to the building system are quantitatively analyzed in terms of emergy value and carbon emissions. This is followed by the verification of the sustainability performance of the building system through machine learning algorithms, and finally

proposing improvement measures. On the right side are the impacts of the building system on the market and environment.

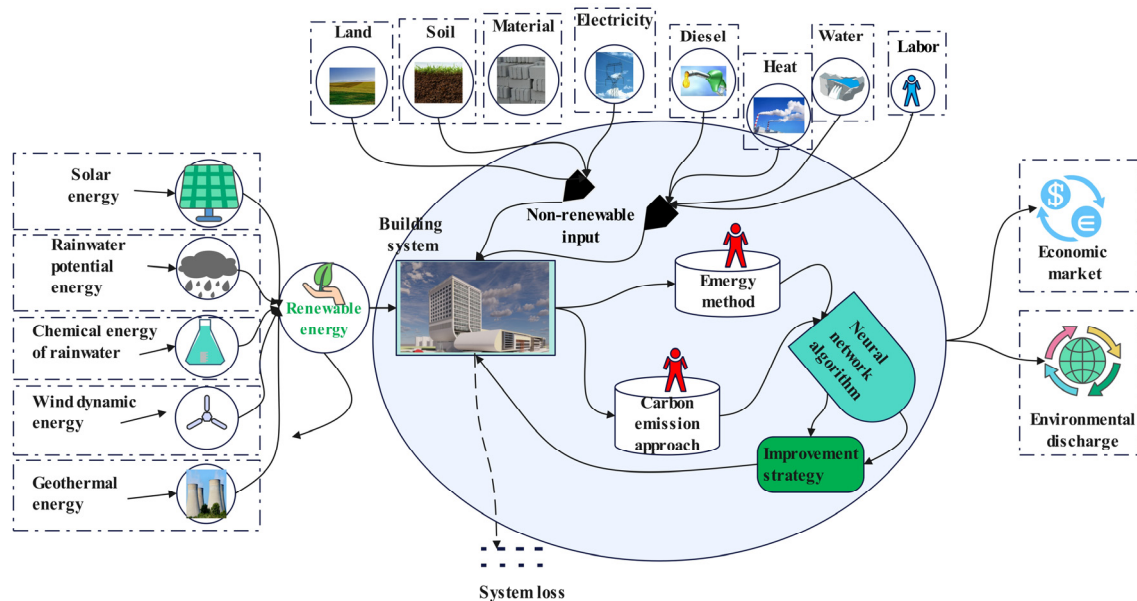


Figure 1. Research framework.

2.2. LCA-Emergy Method

2.2.1. LCA Approach

LCA (Life Cycle Assessment) is a method used to evaluate the potential environmental and resource impacts of a product, service, or process throughout its entire life cycle. It is a systematic approach that considers the entire life cycle from raw material extraction to waste disposal and comprehensively assesses its interactions with the environment.

The basic steps of the LCA (Life Cycle Assessment) method include the following:

Goal and scope definition: Clearly define the purpose of the study and determine the boundaries, time frame, and functional units for analysis. The functional unit defines the functional characteristics of the assessed system, such as producing a certain quantity of product or providing a certain quantity of service.

Life cycle inventory: Identify and describe the various life cycle stages of the assessed system, including raw material acquisition, production, transportation, use, and waste management.

Data collection: Collect data relevant to each life cycle stage, such as energy consumption, material usage, emissions, etc. Data can be obtained from on-site measurements, literature reports, statistical data, and professional databases, among others.

Impact assessment: Based on the collected data, assess the potential environmental and resource impacts of the assessed system.

The LCA method can help organizations and decision makers understand the environmental performance of products or services throughout their life cycles and provide recommendations on how to reduce environmental impacts. It is widely applied in various fields such as sustainable development, environmental management, product design, and policy making. Through the application of the LCA method, efficient resource utilization and environmental sustainability can be achieved.

2.2.2. Emergy Concept

Emergy theory is a theoretical framework used to describe and evaluate energy conversion and utilization efficiency. It is primarily based on thermodynamics and the principles of energy flow. By analyzing the input, output, and transformation processes of matter

and energy in a system, as well as their interactions with the environment, the energy performance of the system can be quantified and evaluated [40].

The core concepts of emergy theory include the following:

Emergy: Emergy refers to the form and state of matter or energy in a system. According to emergy theory, emergy can be divided into two types: actual emergy and potential emergy. Actual emergy refers to energy that can be directly used, such as electrical energy, thermal energy, etc. Potential emergy refers to energy that exists during conversion or processing processes, such as chemical energy, potential energy, etc.

Emergy conversion: Emergy conversion refers to the process of energy transitioning from one form or state to another. This includes energy transmission, conversion, and storage. The efficiency of emergy conversion depends on the losses and waste during emergy conversion processes.

Emergy assessment: Emergy assessment involves the quantitative evaluation of emergy conversion and utilization efficiency in a system. By analyzing the relationship between input and output energy and the losses during energy conversion processes, emergy assessment can reveal the energy performance and benefits of the system and provide improvement recommendations.

Emergy theory has wide applications in multiple fields, particularly in energy management and sustainable development. It can be used to assess energy efficiency in systems such as buildings, industries, and transportation, optimize energy utilization, and reduce energy waste and carbon emissions. Additionally, emergy theory can also be applied in research and guidance for energy policy making, energy technology innovation, and energy economic analysis.

In summary, emergy theory provides a theoretical framework and methodology for describing and evaluating energy conversion and utilization efficiency. Through the application of emergy theory, a better understanding and optimization of energy systems can be achieved, promoting sustainable energy development.

2.2.3. Emergy Equations

The different input indicators for emergy include Emergy Yield Ratio (EYR), Emergy Load Ratio (ELR), and Emergy Sustainability Index (ESI). In order to better demonstrate the differences between the three indicators, Figure 2 was designed and presented.

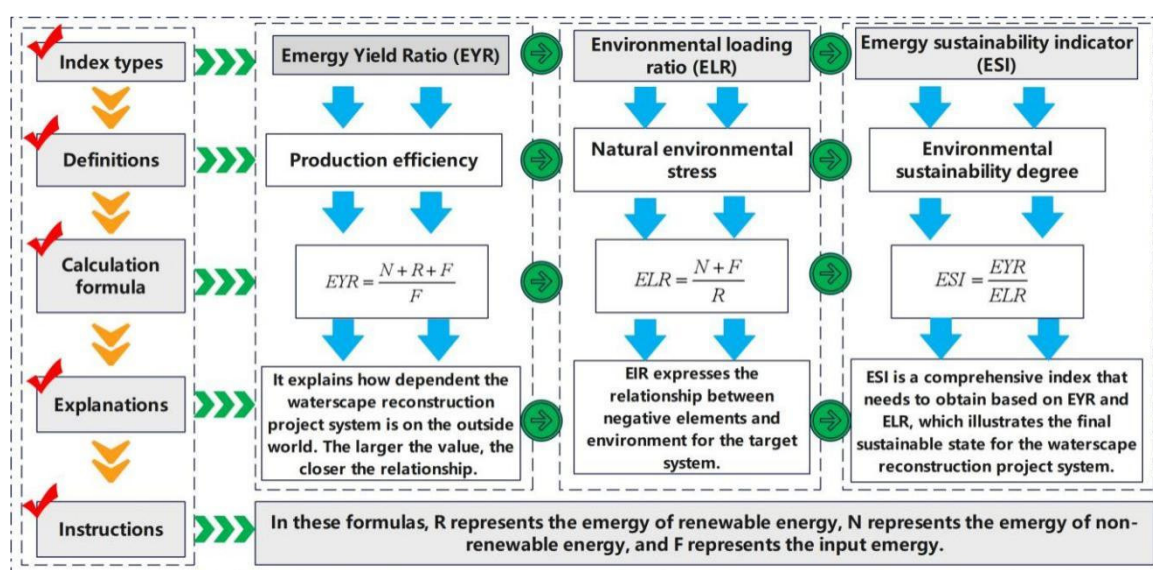


Figure 2. Key emergy indicator infographic.

Figure 2 is an infographic of key energy indicators including EYR, ELR, and ESI. These indicators assess and analyze building systems from the perspectives of societal input to the building system, environmental burden pressure, and sustainability parameters.

2.3. Carbon Emission Calculation Method

“Carbon footprinting” refers to the use of measurement and calculation methods to assess the amount of carbon emissions generated by specific activities or processes [41]. Specifically, carbon footprinting involves the following steps:

- **Boundary setting:** Determine the scope of the system or process to be assessed for carbon emissions. This may include the entire organization, specific buildings, product life cycles, etc.
 - **Data collection:** Collect relevant data within the set boundaries, including energy consumption, material usage, transportation, waste management, etc.
 - **Carbon emission factors:** Select appropriate carbon emission factors to convert the collected data into carbon emissions. Carbon emission factors represent the amount of carbon emissions per unit of activity or substance, such as the carbon content of fuels, emission coefficients of energy sources, etc.
 - **Calculation of carbon emissions:** Using the collected data and carbon emission factors, calculate the carbon emissions of specific activities or processes. This typically involves multiplication calculations to convert energy consumption and related activities into carbon emissions.
 - **Analysis and reporting:** Analyze and interpret the calculated results, and prepare a carbon emissions report. The report may include information such as total carbon emissions, key emission sources, carbon emission trends, etc., to aid organizations or individuals in developing emission reduction strategies and management measures.
1. Calculation of material carbon emissions building materials, as one of the main elements contributing to carbon emissions, can be calculated using the following formula:

$$\sum M_i = \sum R_i \times (1 + \partial) \times \xi \quad (1)$$

$\sum M_i$ represents the carbon emissions of building materials (kgCO₂)

R_i is the quantity of building materials (in kg)

∂ shows the material loss ratio (%)

ξ display the carbon emission factor of the corresponding building material (in kgCO₂/kg).

2. Calculation of electricity carbon emissions electricity, as one of the main sources of power in building systems, can be calculated using the following formula:

$$\sum W_i = \sum \frac{C_i}{\chi_1} \times \phi_1 \times \gamma_1 \quad (2)$$

$\sum W_i$ is the carbon emission factor of the corresponding substance;

C_i is the input amount of the corresponding substance;

χ_1 is the conversion rate of the substance;

ϕ_1 is the conversion rate of the corresponding electricity energy;

γ_1 is the electricity carbon emission factor for different regions. (The case is located in Jiangsu, with a value of 1.01.)

3. Calculation of Energy-related Carbon Emissions

$$\sum V_i = \sum \frac{K_i}{\rho_1} \times \phi_2 \times \gamma_2 \quad (3)$$

$\sum V_i$ is the carbon emission of different fossil fuels;

K_i is the basic data of fossil fuels;

ρ_1 is the conversion rate to standard coal;
 ϕ_2 is the conversion rate of the corresponding fossil fuel;
 γ_2 is the carbon emission factor of standard coal.

4. Calculation of Carbon Emissions from Labor Services

The carbon emissions from labor services need to be calculated for the entire life cycle of a building system. The specific calculation formula is as follows:

$$\sum D_i = \sum \frac{L_i \times j_i}{\theta_1} \times \mu_i \times \varepsilon_i \quad (4)$$

$\sum D_i$ is the carbon emissions from labor services;

L_i is the input data for labor services;

j_i is the exchange rate between RMB and USD;

θ_1 is the conversion rate of labor services;

μ_i is the conversion rate based on USD;

ε_i is the labor service factor for different regions.

Typical Feedback Subsystem Model

Figure 3 shows three types of typical feedback models: open-loop system model (E), closed-loop system model (F), and cross-feedback system model (G). The difference lies in that the open-loop system does not involve a self-regulating mechanism, while the closed-loop system ensures the operation of the entire building system while having self-regulation capabilities within its subsystems to effectively correct sustainable performance errors. The cross-feedback system not only considers the self-regulation capabilities of the system itself but also takes into account the interrelated influences between systems, further improving the accuracy of the overall building system assessment. On the left side of Figure 3 are the transfer functions corresponding to the three types of feedback systems.

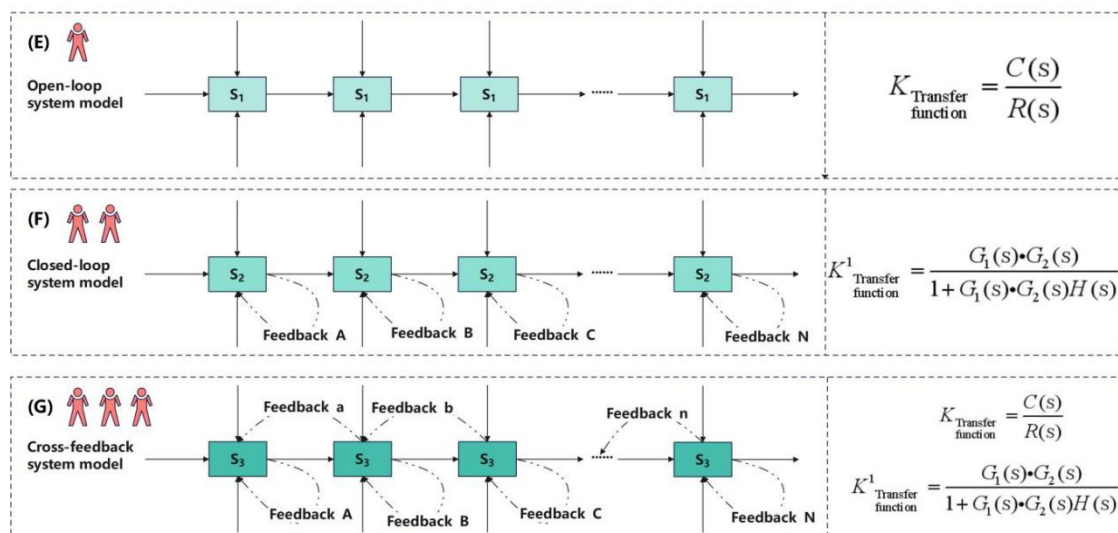


Figure 3. Three types of typical feedback system models.

2.4. Neural Network Method

A neural network prediction model is a type of machine learning model based on neural networks, used to predict unknown data. The model learns the relationship between inputs and outputs and can make predictions on new input data, generating corresponding output results. Neural network prediction models have strong fitting and generalization abilities, making them suitable for various types of prediction problems such as regression and classification.

Figure 4 shows the neural network prediction model diagram. The input layer consists of four types: material flow, energy flow, information flow, and factors influencing feedback. The output layer includes energy prediction analysis and carbon emission prediction analysis. Through the neural network model, it is possible to predict the future energy indicators and carbon emissions trends of the entire building system, which contributes to sustainable design of the building system.

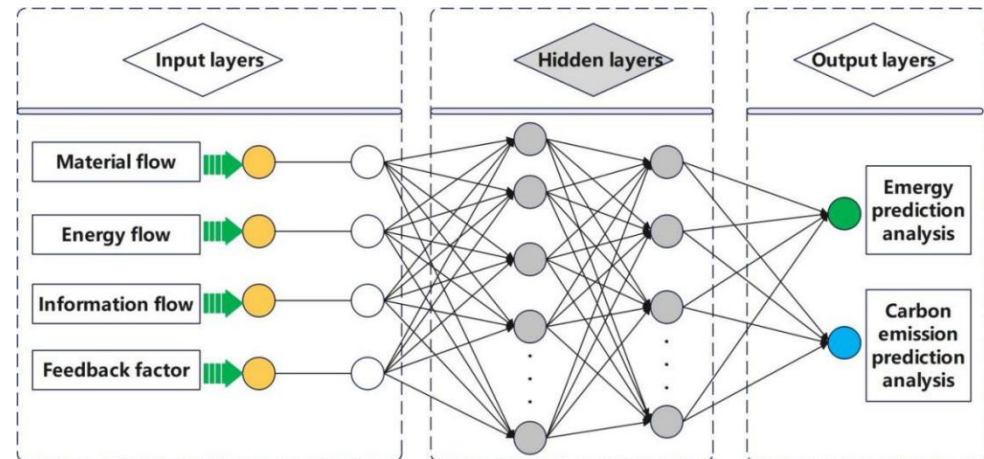


Figure 4. Neural network prediction model diagram.

3. Case Situation

3.1. Basic Introduction

The case study for this research is a commercial complex building cluster with a lifespan of 50 years. Located in Hangzhou City, the total floor area of the building is 80,000 square meters. It is a large regional center building complex that combines commercial and office functions, primarily serving surrounding industrial parks. The building complex includes functional buildings with functions such as commercial offices, accommodations, entertainment, and shopping.

To align with the national goal of carbon neutrality, the entire building complex adopts green and low-carbon design strategies, including industrialized construction methods, smart building systems, ecologically sustainable landscape design, rainwater reuse systems, sponge city design strategies, and various other measures (Figure 5). These measures effectively achieve the low-carbon design of the building system.

3.2. Data Collection

In this study, the basic data is collected and processed according to three categories: information flow data, energy flow data, and material flow data (Figure 6). Due to the large amount of data involved, it needs to be screened and processed. Qualified data are used for calculations to determine energy and carbon emissions. For data that do not meet the criteria, revalidation is required.

In addition to the basic data, Energy conversion rate data are necessary for energy calculations to ensure accurate values for the calculations. When estimating carbon emissions in the building system, carbon emission factors need to be selected, which is sourced from the Intergovernmental Panel on Climate Change (IPCC), including three types of carbon emission factors: fossil energy carbon emission factor, electric power carbon emission factor, and building material carbon emission factor. As an authoritative international institution, IPCC has conducted extensive research on carbon emission factors.

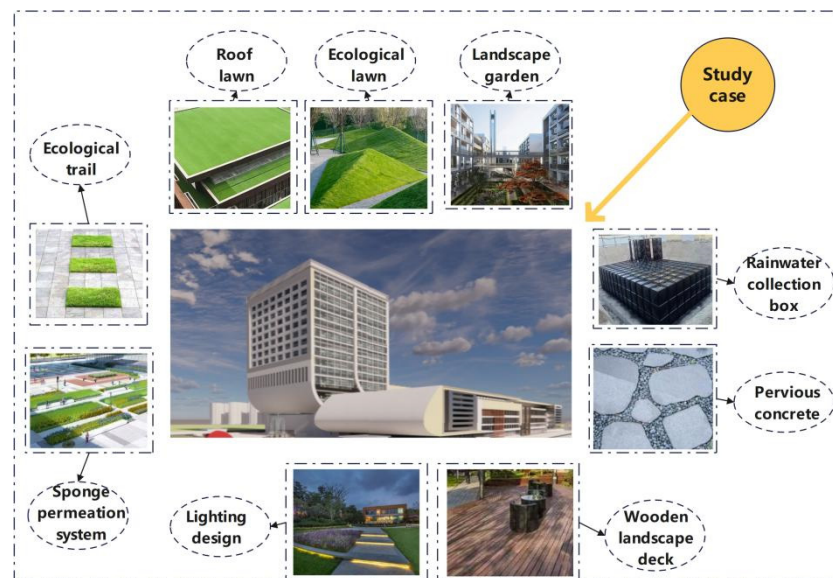


Figure 5. Research case and its low-carbon measures.

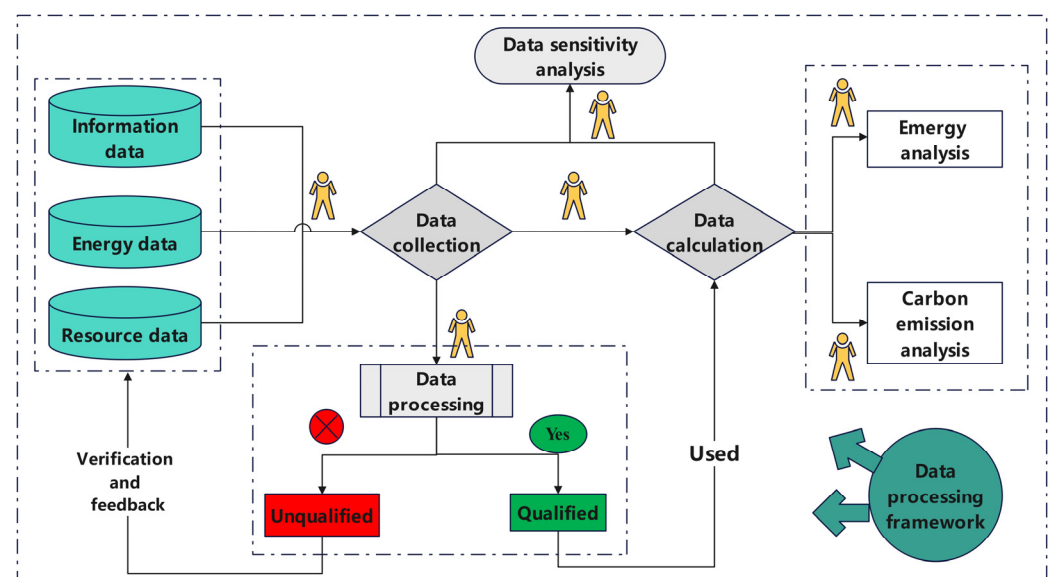


Figure 6. Basic data processing path design.

4. Results and Discussion

4.1. Emergy Analysis

This section focuses on studying the emergy distribution in the building system, the changes in sustainability indicators, the verification of three types of feedback structures' effectiveness, and sensitivity analysis of the results.

4.1.1. Dominated Contributor

By calculating the emergy in five stages of the building system, it is possible to effectively obtain the emergy for each stage. Figure 7 reveals the trend of emergy changes in these five stages. It is evident from Figure 7 that the operational stage of the building accounts for the largest proportion of emergy, followed by the building material production stage. These two stages represent approximately 90% of the total emergy in the entire building system.

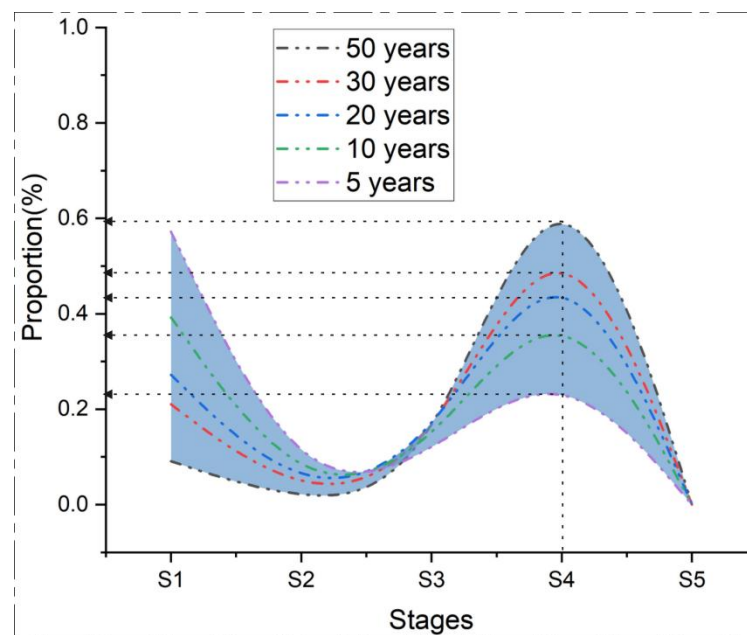


Figure 7. Energy proportion in five stages. (S1—building material production stage; S2—Building material transport phase; S3—building construction stage; S4—building operation stage; S5—building demolition stage).

Analyzing the 20-year operation cycle of the building, the operational stage accounts for 62.5% and 27.2% of the energy. At the 30-year mark, the proportions are 70.8% and 21.1%, respectively. By the 50th year of operation, the energy distribution becomes 87.4% for the operational stage and 9.11% for the building material stage. As the building system's life cycle increases, there is a gradual increase in the proportion of energy attributed to the operational stage while the energy associated with the building material stage decreases correspondingly. From an energy perspective, it is evident that the operational stage and building material production stage are crucial components that should be emphasized in sustainable design.

To calculate the energy performance of different stages in the entire building system, calculations and presentations were also carried out for 5-year and 10-year periods. Figure 7 clearly illustrates that the operational energy consumption of the building system increases with the lengthening of the period, and the growth rate is irregular, which is related to the usage cycle and patterns of the building.

The unit energy value reference can be found in the literature [19].

4.1.2. Sustainable Indicator and Feedback Subsystem Analysis

To analyze the sustainability of building systems from an energy perspective, three indicators are adopted: Energy Yield Ratio (EYR), Environmental Loading Ratio (ELR), and Energy Sustainability Indicator (ESI). At the same time, the three types of feedback subsystems have different impacts on the variations of sustainability parameters in the entire building system. This section mainly compares and analyzes the effects of the three types of feedback subsystems.

Figure 8 shows the trends in sustainability indicators. From Figure 8A, it can be observed that different feedback systems have a significant impact on the sustainability of the entire building system. Taking ELR as an example, the cross-feedback subsystem performs better than the open-loop and closed-loop feedback subsystems. This demonstrates the necessity of cross-feedback systems, as they can significantly optimize the sustainability indicators of the building system and improve their accuracy.

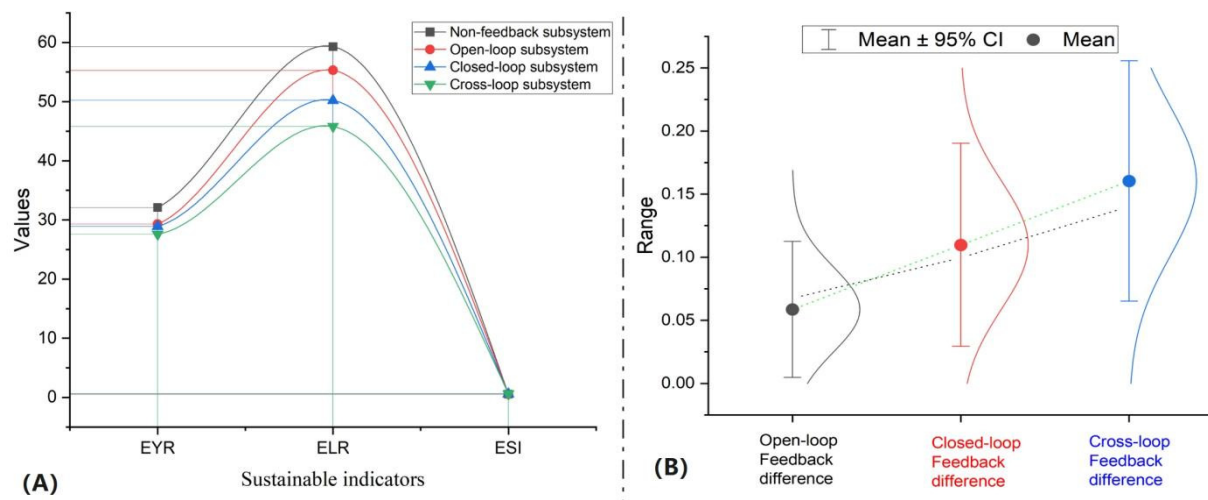


Figure 8. Sustainability parameter variations of three types of feedback subsystems. (A) Sustainable indicators. (B) Three types of feedback structures.

For the non-feedback system, the three parameters of the building system are EYR (32.1), ELR (59.3), and ESI (0.541), indicating a need to improve the overall sustainability level of the building system (in Figure 8A). Figure 8B illustrates the error correction variations of the three types of feedback subsystems, clearly showing that the cross-feedback subsystem has the largest correction magnitude. The correction magnitudes for the three parameters are EYR (14.1%), ELR (22.7%), and ESI (11.3%).

4.1.3. Sensitivity Analysis Based on Emergy View

For a building system, sensitivity analysis is essential, and its advantages are as follows: (1) Sensitivity analysis can validate the accuracy and robustness of building models. By observing the variations of indicators caused by different parameter changes, the stability and reliability of the model can be evaluated. (2) Sensitivity analysis results can provide valuable reference information for decision makers. By understanding the impact of each parameter on sustainability indicators, decision makers can better formulate strategies and measures to improve the sustainability performance of building systems. (3) Sensitivity analysis can assist design teams in making informed decisions at different stages of building projects to achieve more sustainable designs. By understanding the impact of different design choices on sustainability indicators, design teams can optimize and adjust to maximize the level of sustainability in building systems.

In this study, sensitivity analysis is conducted to validate the variations of sustainability indicators. Three types of models are designed to assess the magnitude of changes in EYR, ELR, and ESI based on data variations of 5%, 8%, and 10%, respectively. Since the production stage of building materials and the operational stage of buildings have the most significant impact on the sustainability of building systems, the basic data selected for analysis mainly focus on these two stages.

Figure 9 reveals the variations in sensitivity magnitude for four sets of sustainability parameters. Figure 9a represents the sensitivity variations under three hypothetical models without considering feedback subsystem states. Overall, the data fluctuations under all four conditions exhibit a relatively smooth trend, indicating the robustness and stability of the entire building system data.

Compared to the input mode of the non-feedback subsystem, the models with feedback systems show a certain degree of data variation. Taking the ESI parameter of the 5% basic data variation model as an example, the respective fluctuations for the four sets are 9.1% (No feedback subsystem), 8.2% (Open-loop feedback subsystem), 7.9% (Closed-loop feedback subsystem), and 5.4% (Cross-loop feedback subsystem). This outcome demonstrates that

the building system's sustainability is more stable when coupled with a cross-feedback subsystem.

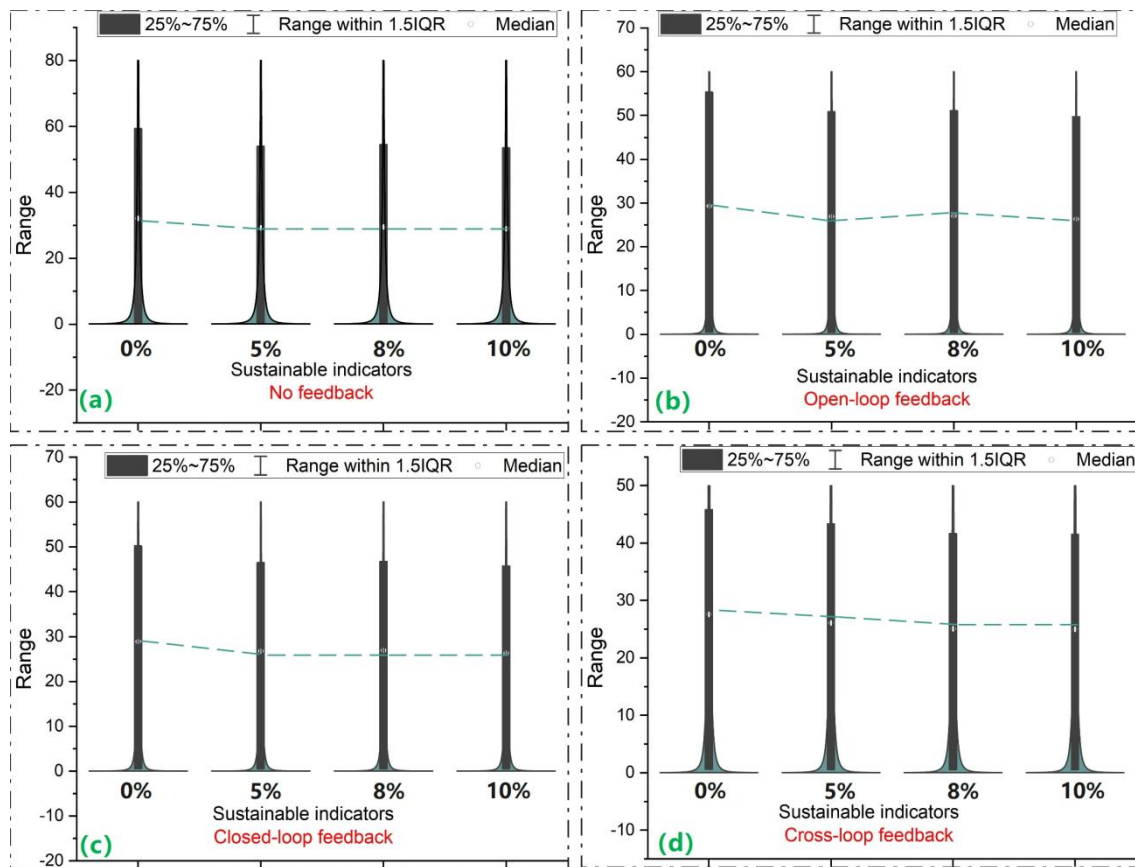


Figure 9. Sensitivity variations of sustainability indicators. (a) No feedback. (b) Open-loop feedback. (c) Closed-loop feedback. (d) Cross-loop feedback.

4.2. Carbon Emission Analysis

In addition to the energy perspective, carbon emissions analysis is also a crucial aspect of sustainable research on building systems. This section includes the calculation of carbon emissions in five stages of the building system. The purpose is to identify the primary carbon emission sources and verify three types of feedback effects. Finally, the sensitivity of the results will be examined. The carbon emission factors for this section can be referred to in reference [42].

4.2.1. LCA-Carbon Emissions Analysis

The carbon emissions calculation of the building system's life cycle includes five stages. The building materials stage involves nine primary building materials' carbon emissions. The construction and transportation stage includes calculations for six subsystems, namely, labor services, water supply and sewage treatment, HVAC systems, power installation systems, communication engineering, etc. The operational stage of the building focuses on calculating electricity, heating, and water supply. The demolition stage involves the recycling and use of materials such as cement, steel, glass, diesel, etc., Figure 10 reveals their variation patterns.

Figure 10 depicts the distribution of carbon emissions across the five stages. Based on calculations of carbon emissions over a 50-year lifespan of a commercial building, from Figure 10A, it can be observed that the operational stage of the building accounts for the majority of carbon emissions, significantly higher than the other four stages. The next significant contributors are the building materials production stage and the building

construction stage, followed by building transportation and demolition. In Figure 10B, a quantitative calculation of the carbon emissions distribution across each stage is presented. The operational stage has the highest carbon emissions, accounting for approximately 85.6%. The building materials production stage comes next, at around 7.3%, followed by the construction stage at about 6%. Building transportation and demolition stages have a relatively small contribution, estimated at approximately 1.1%. This indicates that, in the long term, the operational stage of the building dominates in terms of carbon emissions. Additionally, the production of building materials and the construction stage are also significant sources of carbon emissions that require carbon reduction optimization.

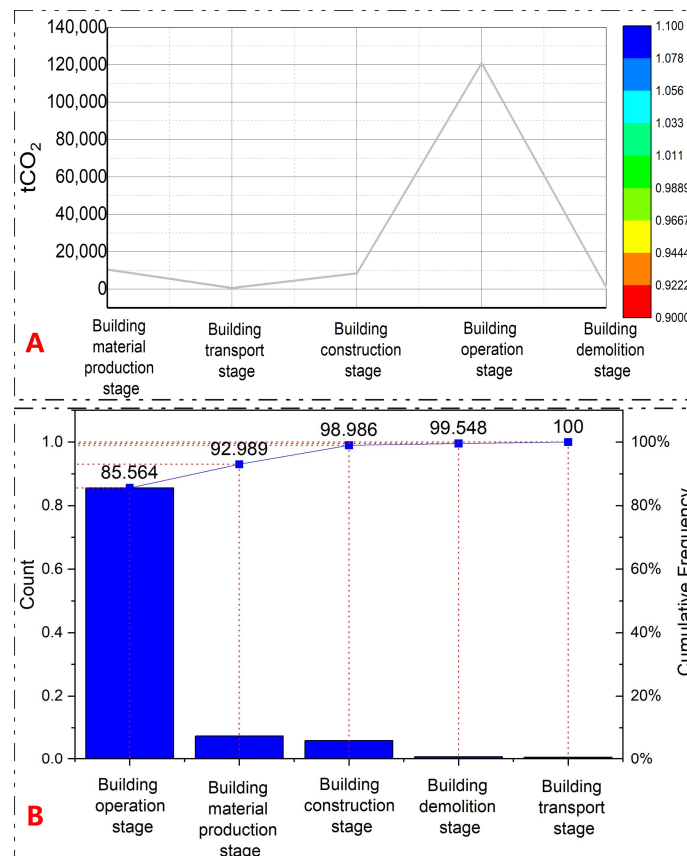


Figure 10. Distribution of carbon emissions throughout the life cycle. (A) Carbon dioxide emissions. (B) Proportion of five stages.

By conducting a calculation of the life cycle carbon emissions, it is possible to identify the main sources of carbon emissions and provide guidance for the development of corresponding emission reduction strategies and measures. This helps in designing more sustainable and low-carbon building systems. Conducting a life cycle carbon emissions analysis enhances awareness and understanding of carbon emissions issues, thereby promoting the movement of the construction industry towards low carbon and sustainable development.

Please refer to Appendix A (Tables A1–A4) for the detailed calculation process.

4.2.2. Feedback Subsystem Analysis Based on Carbon Emission Perspective

The three feedback subsystems also have an impact on carbon emissions in the building system. In this section, the analysis of the carbon emission trends across the five stages of the building system helps determine the effects of the three feedback systems and validates the data stability under the influence of feedback systems. Figure 11 presents the intention

of this section, while Figure 11 correspond to the uncertainty variations under open-loop, closed-loop, and cross-feedback subsystems, respectively.

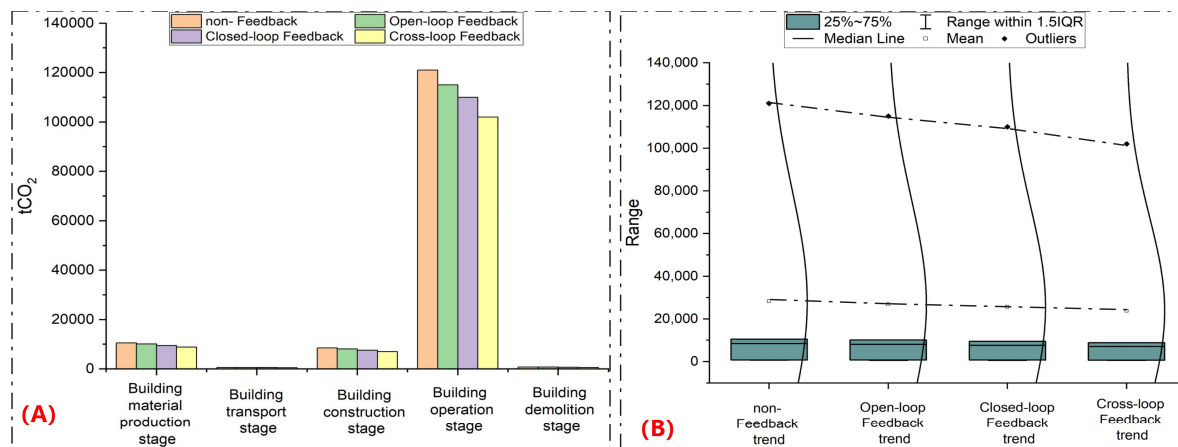


Figure 11. Impact of feedback systems on carbon emissions and their trends. (A) The stability changes under four feedback modes. (B) The variations in carbon emissions.

Figure 11A presents the calculation and statistics of carbon emissions variation across the five stages of the building system, highlighting the changes in data with the variation of feedback subsystems. Taking the operational stage as an example, compared to a building system without feedback subsystems, the open-loop feedback subsystem has a relatively smaller impact (reducing by approximately 5.1%) than the closed-loop feedback subsystem (reducing by approximately 8.81%). The cross-feedback subsystem exhibits the most significant impact, with a difference in carbon emissions of approximately 15.8%. This phenomenon indicates that the feedback subsystems of the building system can effectively correct carbon emissions and reduce errors.

Figure 11B showcases the stability changes in the data structure under four feedback modes. From the trend, it can be observed that after incorporating feedback corrections, the center of gravity of carbon emissions data in the entire building system shifts downward, indicating increased stability. This aligns with the variations in carbon emissions shown in Figure 11A.

By collecting and analyzing extensive operational data of the building system, the feedback correction subsystems can provide valuable references for future design and improvement, promoting continuous improvement and sustainable development of the building system.

4.2.3. Sensitivity Analysis from Carbon Emissions View

To verify the stability of carbon emissions data for the entire building system, uncertainty analysis was conducted in this section. Based on the assumption that the underlying data varies by 5%, 8%, and 10%, the changes in carbon emissions for five stages were calculated. The trend of these changes was analyzed to validate the effectiveness. Figure 12 visually presents the varying trends.

Figure 12 presents uncertainty analysis for four different states. Compared to the open-loop feedback subsystem, the closed-loop feedback subsystem exhibits the highest fluctuation (with a difference of approximately 5.4%). It is followed by the cross-feedback subsystem (with a difference of approximately 3.1%), and lastly, the open-loop feedback subsystem (with a difference of approximately 1.92%). This phenomenon also indicates that the cross-feedback subsystem has the least impact on building sustainability and can effectively reduce errors in carbon emissions.

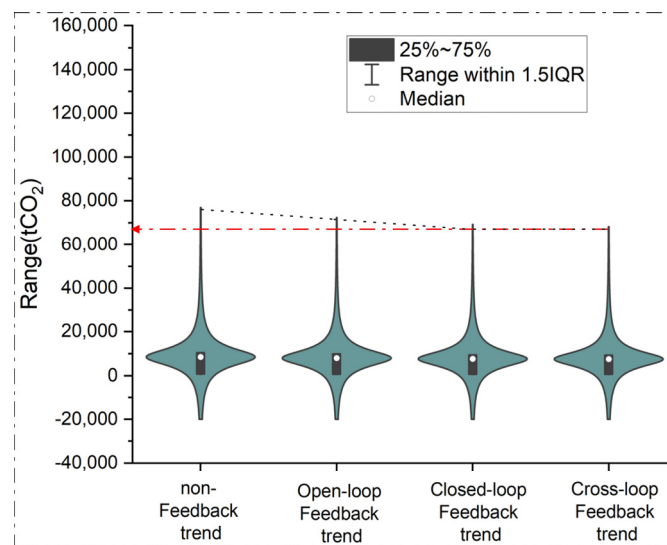


Figure 12. Uncertainty analysis of carbon emission view.

5. Neural Network Predictive Analysis

In this section, a neural network prediction model is trained to predict the energy performance and carbon emissions of the building system. Taking into account the Energy Sustainability Index (ESI) and carbon emissions, the changes in these two indicators over a period of 30 years are analyzed. This analysis allows us to determine the sustainability changes of the entire building system. Figure 13 illustrates the 30-year trends in energy value index and carbon emissions.

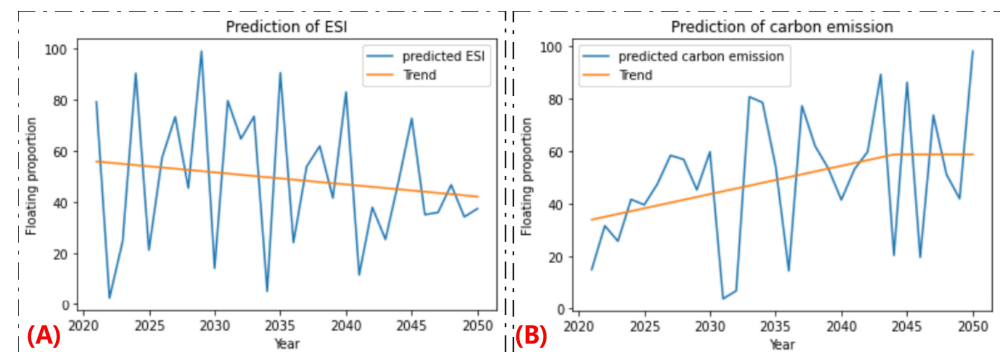


Figure 13. Predicted trends of energy value index and carbon emissions. (A) Prediction of ESI. (B) Prediction of carbon emission.

From the perspective of ESI analysis, Figure 13A reveals the 30-year trends in energy value sustainability parameters of the entire building system. It is evident that the ESI gradually decreases over time, indicating a decrease in sustainability effectiveness from an energy value standpoint as the building system ages. From the view of carbon emissions analysis, Figure 13B demonstrates the trends in carbon emissions as the building ages. It is clearly observed that carbon emissions show an increasing trend, which is attributed to the input of substantial material flow, energy flow, and information flow during the building's operational phase.

Researchers have also studied the details and applications of neural networks in building systems. For instance, one study employed linear time series neural networks to evaluate the state space model of HVAC systems [43]. Another study utilized statistical and analytical methods to design a neural network model for predicting solar-powered building electricity demand [44]. Neural network methods have also been used to develop predictive control logic for heating systems and their relationship with buildings using

artificial neural networks [45]. As hot water systems are a major energy consumption component in buildings, neural networks have been applied to develop prediction models for water heating systems [46]. Currently, neural network methods have been widely applied in various subsystems of buildings, such as electricity, heating, and lighting. However, there is limited research on sustainable prediction analysis for the entire building system. This paper primarily focuses on prediction research in the fields of ecological energy value and low-carbon aspects.

In summary, neural networks have the ability to learn and discover complex patterns within data, thereby providing more accurate prediction outcomes. By using neural networks for prediction, we can obtain precise and reliable estimates of the changes in building sustainability. Through a deeper understanding of the intricate relationships between energy value, carbon emissions, and other indicators within the building system, we can gain better insights into the trends and influencing factors of overall sustainability. It can also offer decision makers valuable information and insights regarding building sustainability. This information can guide the design, operation, and improvement of building systems, facilitating the achievement of sustainable development objectives.

Overall, neural networks enable us to uncover complex patterns and make accurate predictions, providing decision makers with essential knowledge about building sustainability. This knowledge can be utilized to guide the design, operation, and improvement of building systems, ultimately achieving sustainable development goals.

6. Improvement Verification

6.1. Landscape Measure

Landscape engineering not only enhances the aesthetic level of the building system but also effectively improves the ecological level of the building system when integrated into architectural projects. Additionally, it can contribute to carbon reduction to a certain extent. This section attempts to couple landscape design with the building system and analyze its impact on building sustainability from an energy perspective. Figure 14 illustrates the framework of integrating landscape engineering with the building system.

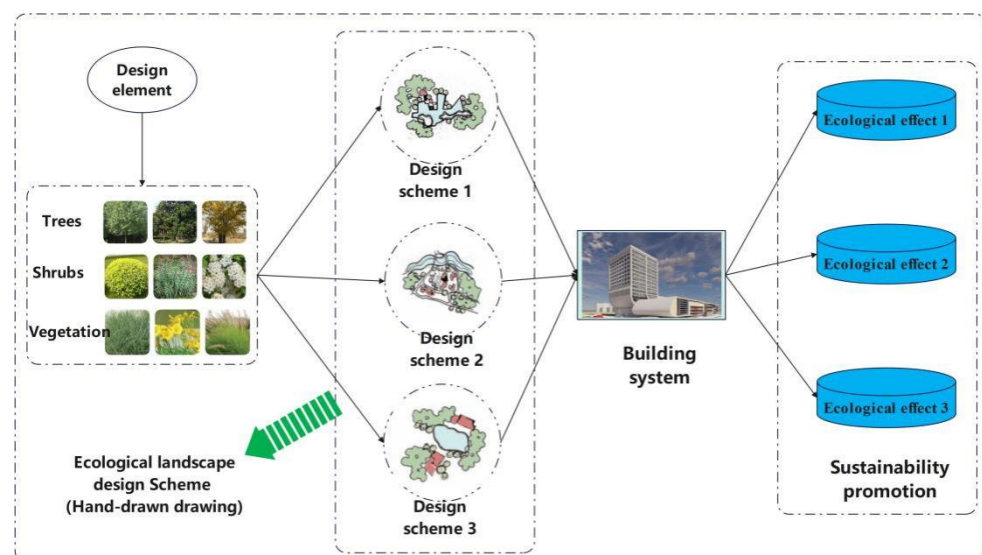


Figure 14. Integration of landscape engineering with building system framework.

Data from three types of landscape design patterns were collected, and through energy calculations for each type, the differences in sustainability indicators (EYR, ELR, and ESI) were analyzed. Figure 15 reveals the variations that different types of landscapes bring to the building system.

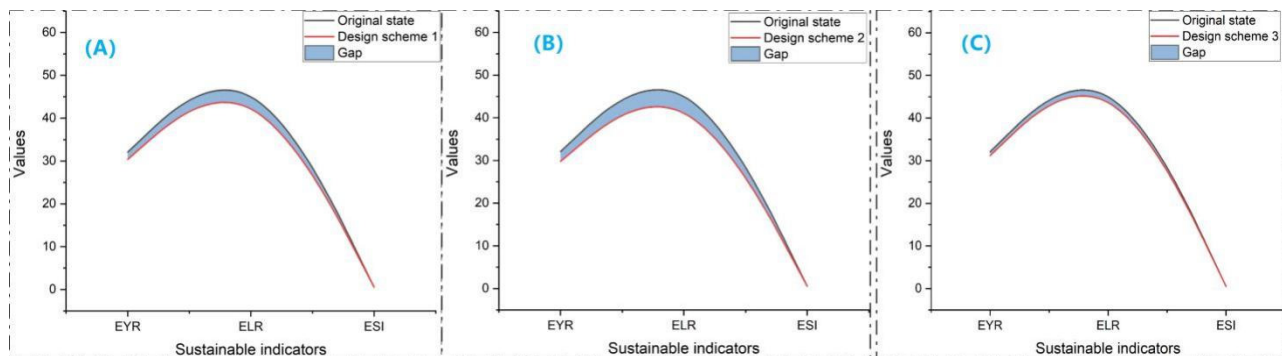


Figure 15. The impact of landscape engineering on the sustainability of building systems. (A) Design scheme 1. (B) Design scheme 2. (C) Design scheme 3.

Figure 15 illustrates the impact of landscape engineering on sustainable parameters under three design patterns. It is evident that the effect of Figure 15B is superior to Figure 15A,C. Through analysis of landscape engineering, it can be observed that landscape design pattern 2 (Figure 15B) exhibits better biodiversity compared to patterns 1 and 3. Although landscape engineering contributes to enhancing the sustainability of building systems, the improvement achieved is not significant, with sustainable enhancements of 1.98%, 2.41%, and 1.19%, respectively, for the three landscape design patterns discussed in this section. To achieve a substantial improvement in ecological effectiveness of landscape engineering on a larger scale, it is necessary to expand the ecological area of the landscape.

6.2. Carbon Sink Measure

Due to the extensive use of concrete materials in building systems, concrete has the ability to absorb carbon dioxide, thereby achieving carbon reduction. In this section, a simulation calculation was conducted using the concrete molecular-level carbonation theory estimation model to check the effect of carbon absorption by concrete.

The molecular-level carbonation theory estimation model is as follows [47]:

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

where $[Ca(OH)_2]^0$, $[CSH]^0$, $[C_3S]^0$, $[C_2S]^0$ and represent the initial concentrations of various carbonizable substances; D_{CO_2} represents the effective diffusion coefficient of carbon dioxide in concrete; $[CO_2]^0$ represents the concentration of carbon dioxide on the surface of concrete; d represents the amount of carbon absorption, and t represents time.

Based on the concrete usage in this case, the estimated carbon absorption by the concrete material over a 50-year operational period of the building system is approximately 300 t, accounting for about 2.47% of the total carbon emissions of the building system. As this is an estimation, there may be some margin of error in the results. However, it demonstrates that concrete contributes to carbon reduction through carbon dioxide absorption, which is crucial for achieving sustainability goals and targets.

7. Conclusions

This study conducted an emergy analysis and carbon emissions calculation on a building case to analyze the sustainability of the building system from two perspectives. The effectiveness analysis and validation of three types of feedback subsystems were also carried out. Finally, a neural network model was utilized to predict the dynamic trends of the building system's sustainability. This study provides valuable references for architects and managers.

The main research findings are as follows:

1. From an emergy perspective, the operational phase of the building and the production phase of building materials are the primary contributors, accounting for over 90% of the total emergy consumption. The Emergy Sustainability Index (ESI) analysis indicates a value of 0.541, which is below the standard value of 1, suggesting that there is room for improvement in the overall sustainability of the building system. The three types of feedback subsystems have varying impacts on the sustainability of the building, with the cross-feedback subsystem having the most significant effect, followed by the closed-loop feedback subsystem, and lastly, the open-loop feedback subsystem.
2. From a carbon emissions perspective, as the building system operates over time, the carbon emissions during the operational phase become increasingly dominant. The feedback subsystems can effectively mitigate the carbon emissions of the building system, with the cross-feedback subsystem having the best performance.

For enhancing the overall sustainability of the building system, strategies focusing on ecological landscape design and concrete carbon sinks were considered. Both approaches contribute to some extent to the sustainability of the building system, but the specific effectiveness needs to be verified through further validation of the strategies.

The ecological and carbon emissions coupling method can be applied during the architectural design phase to estimate the sustainability of the entire building system after the building budget is determined. This method can guide the construction of the entire building. If it is found that the burden of material flow, energy flow, information flow, etc., is too high, attempts can be made to optimize the budget and provide feedback to the design phase in order to optimize the entire building design.

This method is also beneficial for the management of the entire building system. For example, as part of the construction process, sub-engineering disciplines, such as electrical engineering, civil engineering, transportation engineering, water supply engineering, etc., have all applied this method for predictive analysis, thereby optimizing the entire construction process and enhancing sustainability.

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Appendix A

Table A1. The carbon emission calculation of material production.

Item	Data	Unit	Carbon Emission Factors	Carbon Emission	Unit
Steel	6.05×10^5	kg	2.67 tCO ₂ /t	1.61×10^3	tCO ₂
Cement	7.15×10^7	kg	0.07 tCO ₂ /t	5.01×10^3	tCO ₂
Gravel	1.68×10^4	kg	16 kgCO ₂ /kg	2.69×10^2	tCO ₂
Brick	8.03×10^5	kg	0.24 kgCO ₂ /kg	1.93×10^2	tCO ₂

Table A1. *Cont.*

Item	Data	Unit	Carbon Emission Factors	Carbon Emission	Unit
Lime	5.39×10^5	kg	0.44 tCO ₂ /t	2.37×10^2	tCO ₂
Water	3.04×10^5	M ³	0.82 kgCO ₂ /m ³	2.49×10^2	tCO ₂
Iron	8.67×10^5	kg	2.05 tCO ₂ /t	1.78×10^3	tCO ₂
Wood	6.39×10^5	kg	0.31 kgCO ₂ /kg	1.98×10^2	tCO ₂
Glass	6.65×10^5	kg	1.4 kgCO ₂ /kg	9.31×10^2	tCO ₂

Table A2. The carbon emission in the building construction and transport stage.

Item	Data	Unit	Carbon Emission Factors	Carbon Emission	Unit
Labor and service					
Diesel fuel	4.68×10^1	t	3.797 tCO ₂ /t	1.78×10^2	tCO ₂
Machinery diesel	2.59×10^2	t	3.797 tCO ₂ /t	9.82×10^2	tCO ₂
Transport diesel	1.82×10^2	t	3.797 tCO ₂ /t	6.93×10^2	tCO ₂
Water supply and sewage system treatment facilities					
Steel	3.72×10^5	kg	2.67 tCO ₂ /t	9.92×10^2	tCO ₂
PVC	6.00×10^3	kg	4.79 kgCO ₂ /kg	2.87×10^1	tCO ₂
Polypropylene	5.70×10^3	kg	5.98 tCO ₂ /t	3.41×10^1	tCO ₂
Ceramic	4.16×10^5	kg	0.74 tCO ₂ /t	3.08×10^2	tCO ₂
Glass	3.01×10^4	kg	1.4 kgCO ₂ /kg	4.20×10^1	tCO ₂
Cement	3.81×10^6	kg	0.07 tCO ₂ /t	2.67×10^2	tCO ₂
Water	3.43×10^4	m ³	0.82 kgCO ₂ /m ³	2.82×10^1	tCO ₂
Gravel	4.30×10^3	kg	16 kgCO ₂ /kg	6.88×10^1	tCO ₂
Diesel fuel	1.56×10^1	t	3.797 tCO ₂ /t	5.93×10^1	tCO ₂
Heating and cooling systems					
Steel	2.33×10^4	kg	2.67 tCO ₂ /t	6.23×10^1	tCO ₂
Aluminum	3.00×10^3	kg	15.8 tCO ₂ /t	4.74×10^1	tCO ₂
Copper	4.38×10^3	kg	3.73 tCO ₂ /t	1.63×10^1	tCO ₂
Diesel fuel	9.60×10^1	t	3.797 tCO ₂ /t	3.65×10^2	tCO ₂
Electricity installations					
Copper	8.80×10^3	kg	3.73 tCO ₂ /t	3.28×10^1	tCO ₂
Aluminum sheet	3.16×10^3	kg	15.8 tCO ₂ /t	4.99×10^1	tCO ₂
Galvanized steel	3.75×10^3	kg	15.8 tCO ₂ /t	5.93×10^1	tCO ₂
Steel	5.93×10^3	kg	15.8 tCO ₂ /t	9.36×10^1	tCO ₂
Rubber	4.58×10^3	kg	2.4 tCO ₂ /t	1.10×10^1	tCO ₂
Polyester	5.13×10^2	kg	72.65 tCO ₂ /t	3.73×10^1	tCO ₂
Ceramics	4.44×10^4	kg	0.74 tCO ₂ /t	3.29×10^1	tCO ₂
Plastic	6.52×10^3	kg	7.83 kgCO ₂ /kg	5.10×10^1	tCO ₂

Table A2. *Cont.*

Item	Data	Unit	Carbon Emission Factors	Carbon Emission	Unit
Glass	2.51×10^4	kg	1.4 kgCO ₂ /kg	3.51×10^1	tCO ₂
Diesel fuel	1.11×10^1	t	3.797 tCO ₂ /t	4.20×10^1	tCO ₂
Telecommunications system					
Copper	3.41×10^4	kg	3.73 tCO ₂ /t	1.27×10^2	tCO ₂
PVC	4.05×10^4	kg	4.79 kgCO ₂ /kg	1.94×10^2	tCO ₂
Aluminum sheet	4.84×10^4	kg	15.8 tCO ₂ /t	7.64×10^2	tCO ₂
Plastic	1.41×10^4	kg	7.83 kgCO ₂ /kg	1.10×10^2	tCO ₂
Brass	2.74×10^4	kg	3.73 tCO ₂ /t	1.02×10^2	tCO ₂
Aluminum	4.09×10^4	kg	15.8 tCO ₂ /t	6.46×10^2	tCO ₂
Glass	5.39×10^4	kg	1.4 kgCO ₂ /kg	7.54×10^1	tCO ₂
Steel	4.12×10^4	kg	15.8 tCO ₂ /t	6.50×10^2	tCO ₂
Diesel fuel	1.15×10^0	t	3.797 tCO ₂ /t	4.37×10^2	tCO ₂
Elevator system					
Steel	6.07×10^3	kg	15.8 tCO ₂ /t	9.60×10^1	tCO ₂
Rubber	6.98×10^3	kg	2.4 tCO ₂ /t	1.67×10^1	tCO ₂
Diesel fuel	1.71×10^2	t	3.797 tCO ₂ /t	6.50×10^2	tCO ₂

Table A3. The carbon emission of the building operation stage.

Item	Data	Unit	Carbon Emission Factors	Carbon Emission	Unit
Electricity	1.11×10^8	kWh	0.7025 kgCO ₂ /kWh	7.82×10^4	tCO ₂
Heat	2.14×10^7	J	0.002 tCO ₂ /J	4.28×10^4	tCO ₂
Water	5.41×10^5	m ³	0.82 kgCO ₂ /m ³	4.44×10^2	tCO ₂

Table A4. The carbon emission of the building demolition stage.

Item	Data	Unit	Carbon Emission Factors	Carbon Emission	Unit
Glass	2.84×10^5	kg	1.4 kgCO ₂ /kg	3.98×10^2	tCO ₂
Steel	1.52×10^5	kg	2.05 tCO ₂ /t	3.12×10^2	tCO ₂
Concrete	6.15×10^5	kg	0.13 kgCO ₂ /kg	8.00×10^1	tCO ₂
Diesel fuel	1.18×10^3	kg	3.797 tCO ₂ /t	4.43×10^0	tCO ₂

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