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Article

Sustainability Study of a Residential Building near Subway Based on LCA-Emergy Method

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Abstract: In the context of ecological building and green building popularity, building sustainability assessment is becoming more and more important. In this paper, a comprehensive evaluation platform by coupled LCA method and energy method was designed, verified, and analyzed to assess the sustainability of the building system. The main results illustrated that the construction stage is the most critical stage in terms of emergy angle. From a sustainability perspective, the Emergy Sustainability Indicator was at a moderate level (1.0141), which can be considered to increase the proportion of renewable energy and reduce the proportion of non-renewable resources to improve the sustainability degree. Of the three scenarios designed, the second scenario has the best sustainability in the building system. The unit emergy value of the whole building was also shown to demonstrate the unit emergy of an individual. In order to verify the accuracy of the data, a sensitivity analysis was conducted. Finally, two types of positive measures are proposed to ameliorate the environmental sustainability in the building system, containing the increasing proportion of renewable energy and using recycled building materials.

Keywords: building system; life cycle assessment (LCA); emergy method; renovation scenario; sustainability

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1. Introduction

Facing the exhaustion of non-renewable energy and the increasingly serious environmental pollution, sustainable architecture has positive effects in the face of these dilemmas. Especially in China, the energy consumption of buildings and rapid urbanization are particularly serious in the past thirty years. According to the report on the state of the environment in China, 3.9 billion tons of raw coal and 200 million tons of crude oil were consumed in 2020, also causing serious environmental pollution and energy crisis [1]. A sustainable building can effectively reduce the consumption of fossil energy and environmental pollution. In this paper, the related studies of sustainable building are concerned.

The evaluation of sustainable building is a hot research topic at present. Many scholars have made in-depth studies. Generally speaking, they can be divided into three categories, which are sustainable building assessment, architectural construction, and different building types. From the perspective of sustainable building assessment, such as Roostaie et al.

executed the resilience indicators in building sustainability assessment frameworks [2]. The green building retrofit strategies have been carried out through a building-scale food-energy-water nexus [3]. Cloud-based sustainability assessment system has been used for the sustainability decision-making process of building systems [4]. Taking the residential building as an example, the rapid assessment method was adopted to evaluate sustainability in the building system [5]. From the point of view of architectural construction, such as some authors study the social sustainability assessment framework to manage sustainable construction in residential buildings [6]. The critical criteria benchmark of residential buildings in a tropical climate has been built based on a sustainability perspective [7]. A BIM-based Life Cycle Sustainability Assessment method has been considered to perform environmental, economic, and social assessments during the building design process [8]. Based on different building types, several studies have been executed, such as Sustainable renewal of buildings is a major challenge and several researchers have completed the literature review [9]. The school building system has been assessed based on a sustainable angle [10]. Various sustainability retrofits of building in the tropical climate have been executed by multi-criteria decision-making [11]. The sustainability of Heating, Ventilation, and Air-Conditioning systems has been summarized in Buildings [12]. Building sustainability assessment system trends have been predicted through a comprehensive bibliometric mapping method [13]. Given the sustainability perspective, green building rating systems have been studied [14]. From a sustainability perspective, modern high-rise timber buildings were chosen to assess [15].

To date, there are many methods for building system design and evaluation. Therein, the emergy approach [16] has an obvious advantage to assess sustainability, which can realize a unified platform to compare the different systems to confirm the sustainability level. It can be used for a lot of systems, such as agricultural studies [17,18], city system [19,20], green building direction [21,22], production system [23,24], ecology [25], pollutant treatment system [26] and traffic field [27], etc.

The details of energy in the building system can be described as follows: For instance, the emergy theory and building information modeling were combined into a building system to evaluate sustainability [28]. For building refurbishment, several strategies have been conducted based on the emergy-LCA method [29]. As the basic components of a building system, building materials sustainability has been also a concern by scholars [30–32]. By using emergy evaluation, the major highway building was assessed for decision making in Italy [33]. Take a zero-energy building, for example, American scholars have redefined zero-energy buildings based on the emergy approach [34]. Lin and William studied the high-density and high-rise buildings by using emergy analysis to calculate density parameters [35]. To measure the renovation effect, emergy method has been selected to assess environmental performance [36]. Hwang and William considered the emergy analysis for building uncertainty [37]. By integrating the emergy method, energy analysis, and Taguchi-regression method, the building system has been evaluated [38].

However, a series of weaknesses can be found in these articles, including: (1) old emergy calculation baseline; only a few articles use the latest emergy baseline to calculate. (2) Lack of life cycle assessment (LCA) angle to evaluate in building system; in this literature, only part of the building system was selected for evaluation, such as only building materials, etc. (3) Incomplete emergy indicators; to achieve the whole emergy sustainability evaluation result, complete evaluation indicators need to be provided for reference. The above three disadvantages demonstrate that it is necessary to have a new assessment in building system based on emergy approach.

This paper aims to assess the ecological sustainability of building systems through the LCA-emergy method. Meanwhile, three renovation scenarios were designed and implemented in the case building, which provide a reference for the sustainable development of future architecture.

Finally, the structure of the whole article is organized as follows: after the introduction section, Section 2 is the methodology, including research framework, emergy approach introduction, life cycle stages confirmation, various inputs calculation, three renovation scenarios, sustainable indicators, unit emergy value calculation, and sensitivity analysis. Section 3 is the case study. Section 4 displays the results and discussion, involving basic emergy calculated tables, renovation phase emergy calculation, LCA-emergy analysis, emergy indicator analysis, sustainability analysis, and sensitivity analysis. Section 5 discusses the preventive strategies and positive suggestions. Finally, the main conclusions are summed up in Section 6.

2. Methodology

2.1. Research Framework

The overall research framework is displayed in Figure 1. Firstly, the research boundary was confirmed, including all phases of the building's life cycle, which are the building material stage, construction stage, operation stage, renovation stage and demolition stage, etc. Secondly, the resource input was defined, involving material, energy, and humor service. Thirdly, the assessment indicators were prepared and listed, mainly having the Environmental loading ratio (ELR), Emergy yield ratio (EYR), and Emergy sustainability index (ESI). In the end, three renovation scenarios (A, B, C) were conducted in the building. Through an assessment of a series of indexes, the sustainability of three building systems were calculated and analyzed in this paper.

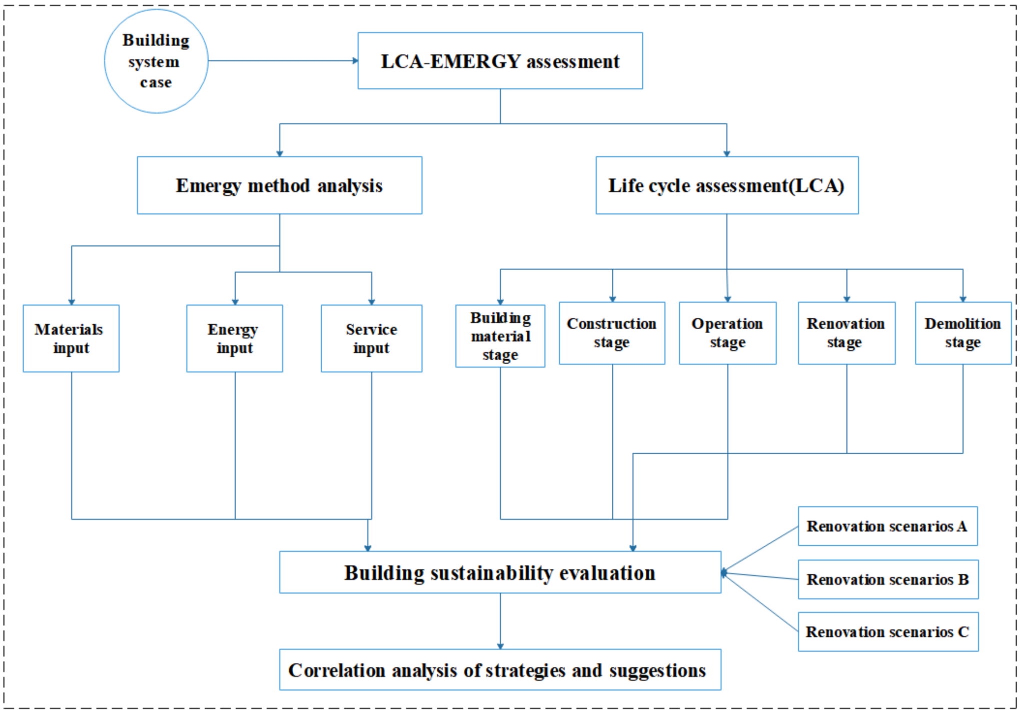

Figure 1. LCA-Emergy research framework.

2.2. Emergy Approach

Emergy methodology is a tool to assess the sustainability of the system and was proposed by H.T. Odum firstly [16], which can provide a comprehensive platform to compare different types of inputs, such as energy, mass, service, etc. By utilizing emergy theory, the relationship between economy, society, and environment, can be evaluated quantitatively. The unit of emergy is the solar joule (sej) the emergy diagram has been designed and displayed in Figure 2.

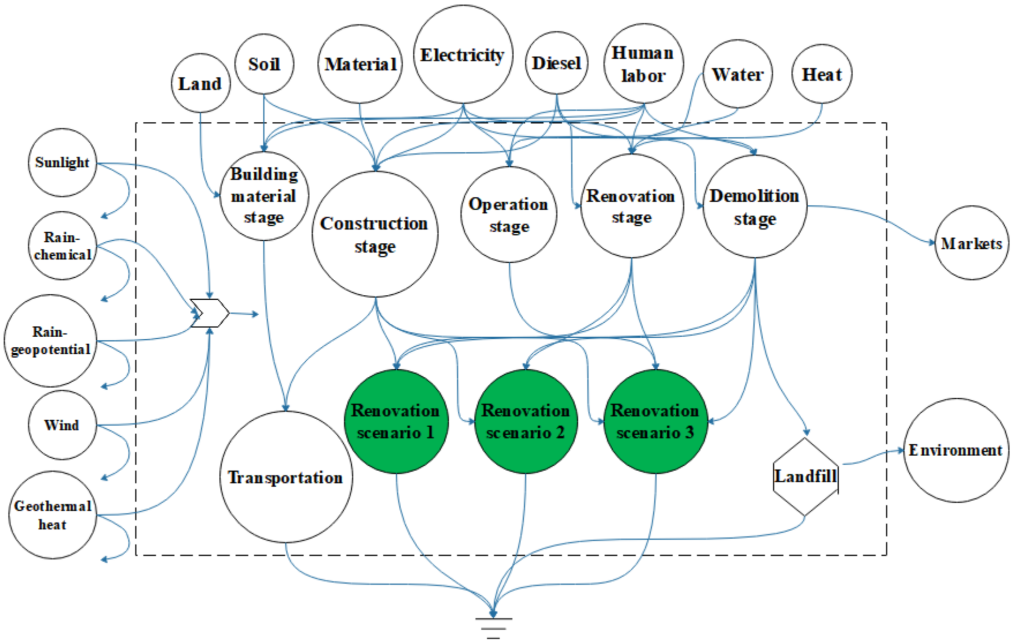

Figure 2. Emergy diagram of the whole building system.

There are three basic steps to calculate the process: (i) define and confirm the boundary of the evaluated system, containing the main system part, renewable input, nonrenewable input, emission, and output parts; (ii) primary emergy table to compute for further analysis; (iii) adopting a series of indicators to analyze the sustainable state in the building system, including Emergy intensity, Emergy per RMB, Emergy density, Renewability rate, Nonrenewability rate, Nonrenewability rate of purchased resource, Purchased emergy dependence level, Emergy investment ratio, Environmental loading ratio, Emergy yield ratio, and Emergy Sustainability Indicator, etc.

In addition, before emergy calculation, the baseline should be selected. To date, there are five types, which are 9.44×10^{24} sej/year [16], 9.26×10^{24} sej/year [39], 15.83×10^{24} sej/year [40], 15.2×10^{24} sej/year [41], and 12×10^{24} sej/year [42]. This paper uses the latest emergy baseline (12×10^{24} sej/year) for the emergy calculation.

2.3. Life Cycle Stages Confirmation

In order to conduct the emergy analysis for the building system, five phases have been described in detail, as follows:

(1) Building material stage This stage mainly involves the type and input of building materials, such as cement, brick, steel, concrete, water, lime, sand, wood, etc. These building materials are mainly used in the construction of building infrastructure.

(2) Construction stage During the construction phase, there are six subsystems to consider and calculate, as follows:

- Infrastructure subsystem: it can be divided into the building envelope, inter construction, basic interior, civil works, etc.
- Water supply and sewerage treatment subsystem: inner and outer water supply system, sewerage system, civil engineering, construction operations.
- Heat subsystem: piping system, heat exchange works, related civil works, and construction operations.
- Electrical subsystem: building inner electricity installation, outer grid connection engineering, related civil works, and construction operations.
- Elevator subsystem: infrastructure elevator system and installation, related civil works, and construction operations.

- Other subsystems: Fire alarm system installation, telephone and video system installation, related civil works, and construction operations.

(3) Operation stage The operation phase mainly involves the following links.

- Heat subsystem: for the building indoor heating, to ensure the comfort of the human body; Hot water for use.
- Electricity subsystem: for lighting use, cooling use, and electrical equipment use.
- Water subsystem: tap use and hot water use.
- Maintenance works: civil work of operation stage.

(4) Renovation stage Building renovation involves the improvement of building envelope thermal performance and power regeneration system (Solar power subsystem installation and related construction operations).

(5) Demolition stage

- Demolition works: building disintegration construction and related civil work.
- Separation works: select recyclable materials and recyclable materials.
- Recycling works: reuse recycled materials and related civil work.
- Landfilling works: Landfill for materials that cannot be recycled.

2.4. Various Inputs Calculation in the Building System

There are eight types of several inputs. All resource inputs have been listed, as follows:

(1) Land use

Due to fact that the building will lead to permanent soil erosion and make the land lose biocapacity. The emergy of soil erosion can be calculated as [43]:

$$E_L = V_L \times \rho_L \times F_L \times E_L \times UEV_L \quad (1)$$

where V_L is the excavated soil volume (m^3); ρ_L represents the soil density (kg/m^3); F_L is the organic matter in the soil (%); E_L shows the soil energy value (J/kg); while UEV_L is the unit emergy value of used land for building system (Sej/J).

(2) Soil irradiation

There are the inputs of solar irradiation on the building site [44,45]. The heat gains include the value during the building operation period. The emergy of solar radiation on the construction site can be got, as:

$$E_S = A_S \times I_S \times (1 - \beta) \times T_S \times UEV_S \quad (2)$$

where A_S is the construction site surface (m^2); I_S is the annual amount of solar radiation (J/m^2yr); β is the ground albedo value; T_S is the construction time (yr); UEV_S is the unit emergy value of solar energy.

E_e represents the solar gains emergy flow on the building envelope and could be obtained, as follows:

$$E_e = Q_e \times T_e \times UEV_S \quad (3)$$

where Q_e are the annual solar gains on the envelope (J/yr); T_e is the building operation total time (yr).

(3) Materials

Entire material in all five stages of the building lifetime needs to be calculated, as follows:

$$E_{m,i} = m_{i,j} \times UEV_{i,j} \quad (4)$$

where $E_{m,i}$ is the emergy flow of all subsystem construction (sej); $m_{i,j}$ is the used material amount (kg); $UEV_{i,j}$ is the unit emergy value of all materials (sej/kg).

(4) Electricity

There are two types of electricity used in the building system. On kind is the electricity which is got from on-site generators by diesel fuel. Another is the electricity from the power grid. The total emergy flow of electricity can be got by using Equation (5).

$$E_{el} = R_{el} \times T_{el} \times UEV_{el} \quad (5)$$

where R_{el} is the annual electricity used value (J/yr); T_{el} is the time (yr); UEV_{el} is the unit emergy value of electricity (Sej/J).

(5) Water

The total water emergy consumed in the building construction can be obtained from Formula (6).

$$E_{w1} = V_w \times \rho_w \times UEV_w \quad (6)$$

The emery flow of water consumed and used (domestic hot water) can be obtained as Equation (7).

$$E_{w2} = \eta_w \times \mu_w \times \rho_w \times 365 \times T_w \times UEV_w \quad (7)$$

where V_w is the water used in the construction stage (m^3); ρ_w is the water density (kg/m^3); ρ_w is the unit emergy value of water (sej/kg); η_w is the specific daily water consumption per occupant (m^3/person/day); μ_w is the number of occupants (person).

(6) Heat

The heat emergy flow of the whole building lifetime can be computed as Formula (8):

$$E_{heat} = C_{heat} \times T_{heat} \times UEV_{heat} \quad (8)$$

where C_{heat} is the heat amount annually (J/yr); T_{heat} is the time (yr); UEV_{heat} is the unit emergy value of heat value (sej/J) [46].

(7) Diesel fuel

Because of the huge usage of diesel fuel during the construction phase, the diesel fuel usage needs to be calculated based on emergy methods, which are material transportation, workers transportation, machinery transportation, and electricity generators.

The emergy flow of transportation can be computed, as follows in Equation (9) [47]:

$$E_m = N_m \times D_m \times HV_m \times UEV_m \times F_m \times (1 + \mu_m) \quad (9)$$

where N_m is the deliveries number (del.); D_m is the distance of one delivery (km); HV_m is the low heating value of diesel fuel (J/1); UEV_m is the unit emergy value of diesel fuel (sej/J); F_m is the used fuel of transportation vehicle (1/km); μ_m is the transportation vehicle fuel consumption ratio.

The number of deliveries and vehicle consumption ratio have the relationship, as follows:

$$N_m = \sum_{j=1}^{N} m_{i,j}/C_{max} \quad (10)$$

$$\mu_m = \frac{F_m}{F_{m1}} \quad (11)$$

where C_{max} is the transportation vehicle's maximum capacity (kg); F_m is the used fuel without a load (1/km).

The emergy flow of workers can be got as follows [48]:

$$E_{worker} = N_w \times D_w \times HV_w \times UEV_w \times F_w \times C_w \quad (12)$$

where N_w is the worker number; D_w is the engineering date (days); HV_w is the daily distance (km); C_w is the car's average fuel consumption (1/km).

The emergy of heavy machines can be obtained, as follows:

$$E_{machine} = N_{ma} \times HV_{ma} \times UEV_{ma} \times F_{ma} \times (1 + \theta) \quad (13)$$

$$\theta = \frac{F_{ma1}}{F_{ma}} \quad (14)$$

N_{ma} is operation hours (h); F_{ma1} and F_{ma} are hourly fuel consumption with and without load, respectively (1/h); θ is the used fuel ratio.

The emergy flow of the fuel to produce electricity can be calculated as follows:

$$E_{ele} = \chi_{ele} \times A_{ma} \times HV_{ma} \times UEV_{ma} \quad (15)$$

where χ_{ele} is the generator fuel consumption (1/m^2).

(8) Human service

The used human labor can be obtained, as follows:

$$E_h = \delta_h \times UEV_h \quad (16)$$

where δ_h are the working hours of one employee (h); UEV_h is the unit emergy value of human service (sej/h).

2.5. Three Renovation Scenarios

In this paper, three improvements have been conducted to the building system, including thermal performance improvement and enhancing the clean electricity usage proportion. To perfect the building's thermal performance, the new insulation layers have been used on the building envelope. Meanwhile, a double-insulated glass window has been also utilized and installed for improved thermal effect in the building system. Finally, new solar photovoltaic panels were designed on the side to generate electricity for the usage of the building.

- Renovation scenario 1: The main difference is the application of the 20 cm vacuum insulating board as the layer on walls;
- Renovation scenario 2: The main difference is the application of a double-insulated glass window as the improved window;
- Renovation scenario 3: The main difference is the application of the new solar photovoltaic panels to get the clean power;
- In addition, the same conditions apply to the three scenarios.

Theoretically speaking, when the renovations have been executed, the entire emergy of the building system is lower than the state without renovation measures. However, the renovation processes need more material input and energy input, resulting in a higher emergy input than the imagined result. Thus, the optimal result should be got based on the final calculation.

2.6. Sustainable Indicators

Table 1 shows the main indexes based on emergy angle, as follows:

Table 1. Emergy indicators.

Note	Items	Index	Expression	Meanings
1	Renewable resource emergy	R	R	Renewable input
2	Nonrenewable resource emergy	N	N	Nonrenewable input
3	Energy emergy	E	E	Non-energy emergy input
4	External input emergy	F	F	Artificial emergy input
5	Labor and service emergy	L	L	Labor and service input
6	Total emergy usage	U	U	The whole emergy

Table 1. *Cont.*

Note	Items	Index	Expression	Meanings
7	Emergy input	I	I	Holistic emergy investment
8	Emergy intensity	E_p	U/P	Emergy per unit area
9	Emergy per RMB	E_e	U/M	Emergy per unit economy
10	Emergy density	E_d	U/A	Emergy per unit person
11	Renewability rate	R_e	R/U	Renewable proportion
12	Nonrenewability rate	N_r	N/U	Nonrenewable proportion
13	Nonrenewability rate of purchased resource	N_p	F/N	Purchased resource rate
14	Purchased emergy dependence level	P_e	F/U	Purchased emergy rate
15	Emergy investment ratio	EIR	F/(R + N)	Building investment level
16	Environmental loading ratio	ELR	N/R	Environmental pressure
17	Emergy yield ratio	EYR	(R + N + F)/F	Ability to obtain emergy
18	Emergy Sustainability Indicator	ESI	EYR/ELR	Sustainable degree

- Emergy intensity (Ep) is defined as the emergy per unit area, which interprets the emergy production proportion.
- Emergy per RMB (Ee) is the emergy per economy (sej/RMB), and it demonstrates the relation between ecological emergy and economy.
- Emergy density (Ed) is the emergy per person (sej/per), which explains the emergy per capita.
- Renewability rate (Re) is a ratio that demonstrates the relationship between renewable input and the entire emergy. A higher renewability ratio illustrates a better ecological level.
- Nonrenewability rate (Nr) is the proportion between the nonrenewable emergy and total emergy. Higher Nr represents a worse ecological level.
- The nonrenewability rate of purchased resource (Np) reveals purchased resource emergy input level. Higher Np means a worse sustainable degree.
- Purchased emergy dependence level (Pe) displays the competitiveness of the system. Bigger Pe means a stronger competitive power.
- Emergy investment ratio (EIR) is the rate of purchased emergy and the sum of renewable emergy and nonrenewable emergy. It interprets the economic input degree. The lower the EIR is, the weaker the system competitiveness is.
- The environmental loading ratio (ELR)is the proportion between nonrenewable emergy and purchased emergy. The standard can be clearly defined, which are low values (ELR < 2), medium intensity (3 < ELR < 10), and high environmental load (ELR > 10).
- Emergy yield ratio (EYR) is the emergy production ability and can positively evaluate the competitiveness of a system. The higher the EYR is, the better the consequence of the system is.
- Emergy sustainability index (ESI): ESI can be obtained based on EYR and ELR, which explains the sustainability of the system. In general, three standards can be referenced, including ESI < 1 (Unsustainable), 1 < ESI < 5 (Medium situation), and ESI > 5 (Sustainable) in the long term [49].

2.7. Unit Emergy Values (UEVs) Calculation

From the emergy perspective, Unit emergy values (UEVs) are the pivotal concept, which reflects the unit energy rate. The lower the UEVs is, the stronger the system competitiveness is. Generally speaking, it can be divided into three forms, which are emergy of per unit of energy (J), substance (g), and economic ($), so the unit of UEV is sej/j, sej/g, and sej/$. In a system, greater UEV demonstrates a higher hierarchy.

2.8. Sensitivity Calculation

In order to keep the accuracy of the calculation, the sensitivity analysis has been executed. The general equation is as follows:

$$E_{si} = [(H + \varphi) \times i] \times [(K + \gamma) \times i] \quad (17)$$

where E_{si} is the emergy; H is the input, involving various input elements; K is the UEVs (unit emergy values); φ and γ are the errors of H and K, respectively.

3. Case Study

A residential building adjacent to a subway station was selected as the case study. From Figures 3–7, the basic model diagrams have been presented. This building is located in Nanjing, which has a north subtropical humid climate. The annual mean temperature is 15.4 °C, the annual extreme temperature is 39.7 °C, and −13.1 °C. The building has an area of about 5000 square meters and was built in 2013. The total budget cost is 80 million yuan, and 120 people are expected to use it. As a residential building, there are 28 units to meet the needs of the residents. The building is a reinforced concrete structure with seven floors and full-brick facades with polystyrene panels for insulation. The parking garage is located on the ground floor. During the renovation, a solar photovoltaic system will be installed on the roof in the future. The building has an independent heating system with natural gas boilers. The electricity consumption can be got from the power grid company.

According to national standards [50], the life of the entire building has 70 years. Because the building is near a subway station, the facade is affected by vibrations, which needs to consider the reinforcement measures (Updated every 7 years). Hence, in this paper, nine years (2027, 2034, 2041, 2048, 2055, 2062, 2069, 2076, 2083) were designed and arranged for renovations.

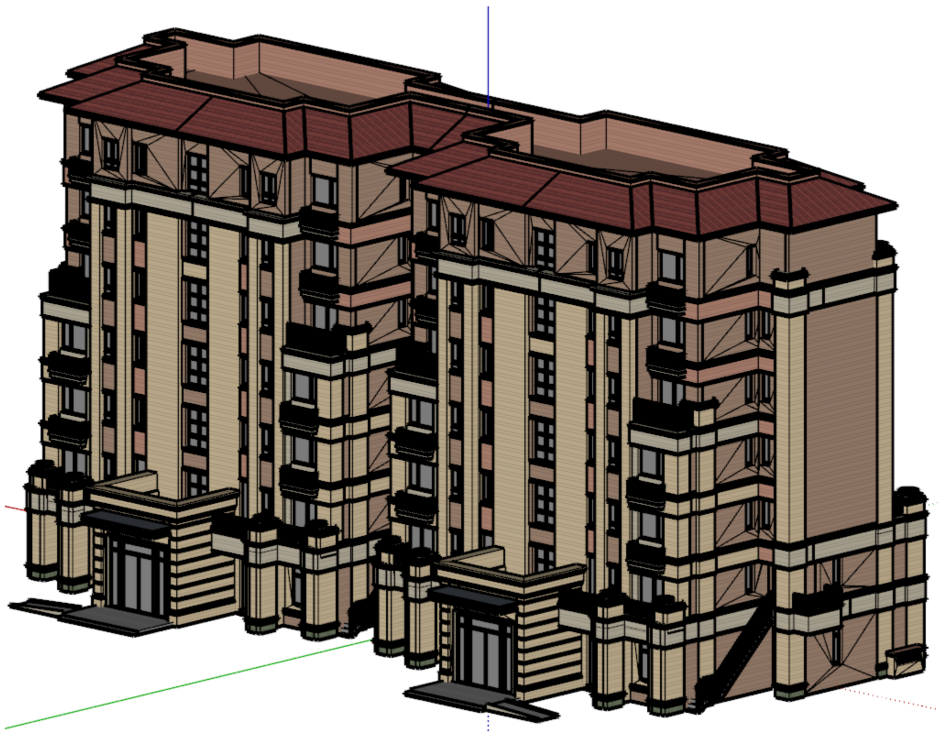

Figure 3. 3D building update model (Front).

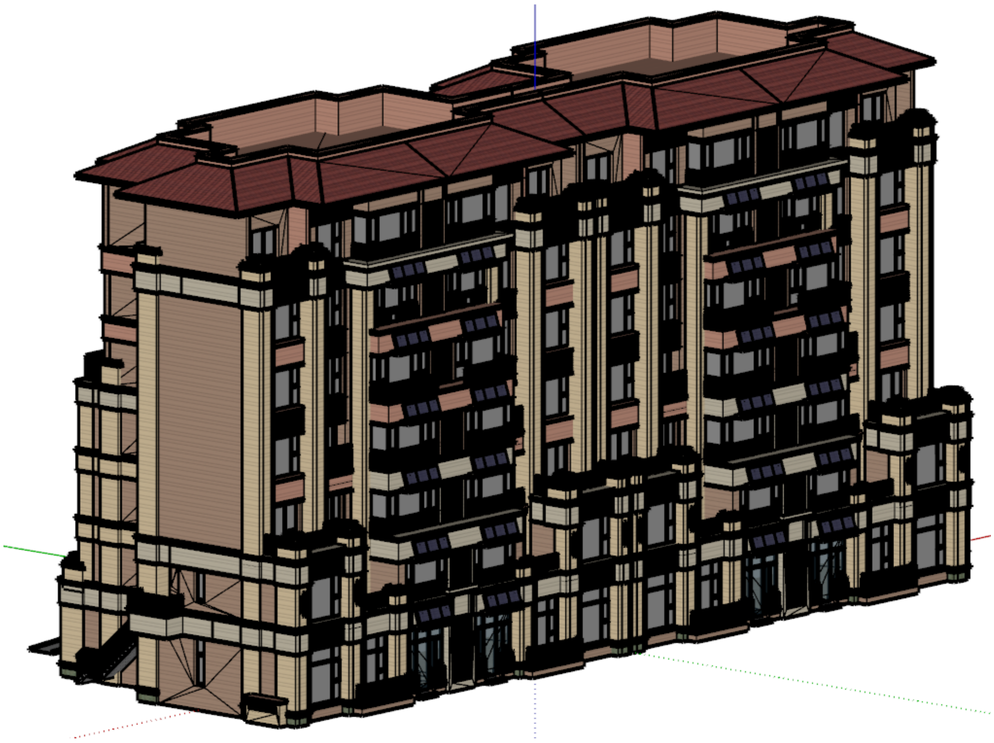

Figure 4. 3D building update model (Back).

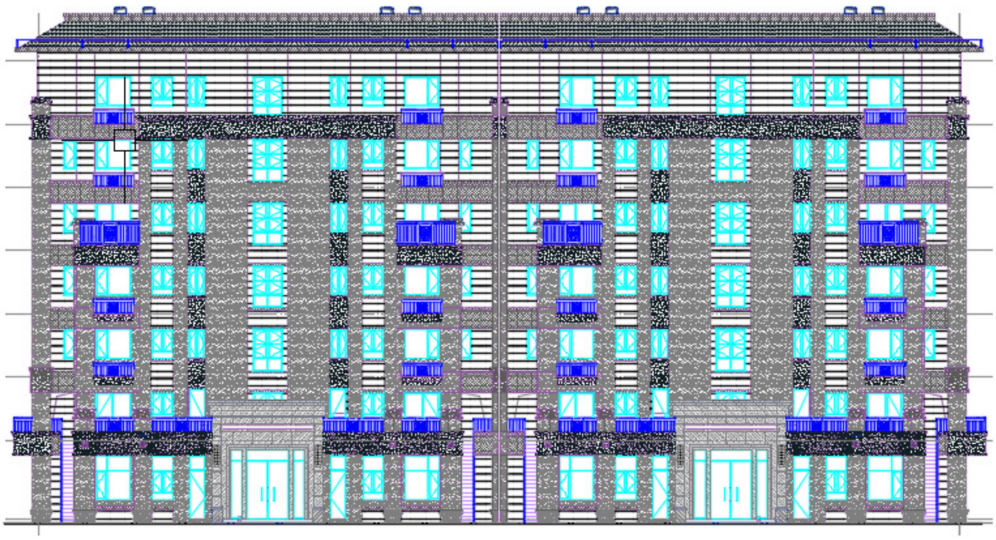

Figure 5. The facade update (view A).

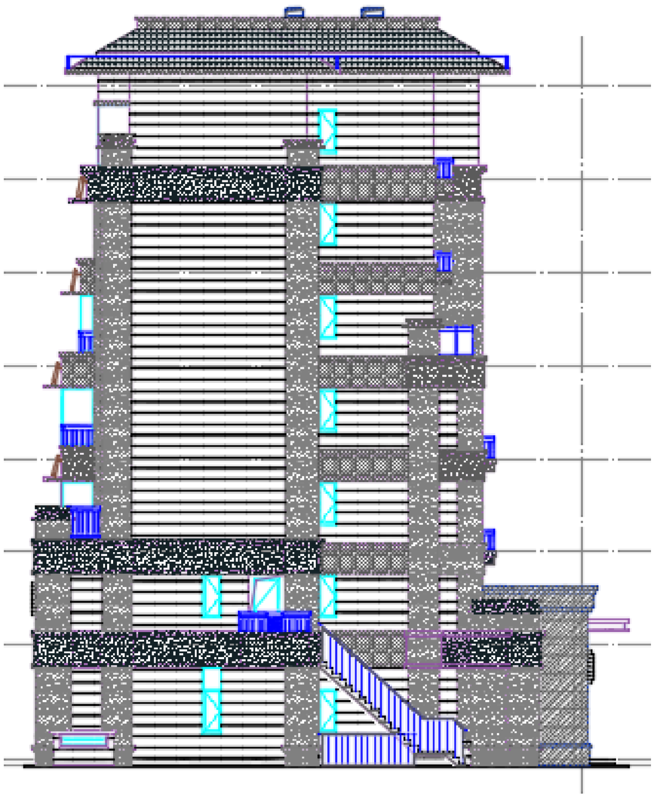

Figure 6. The facade update (view B).

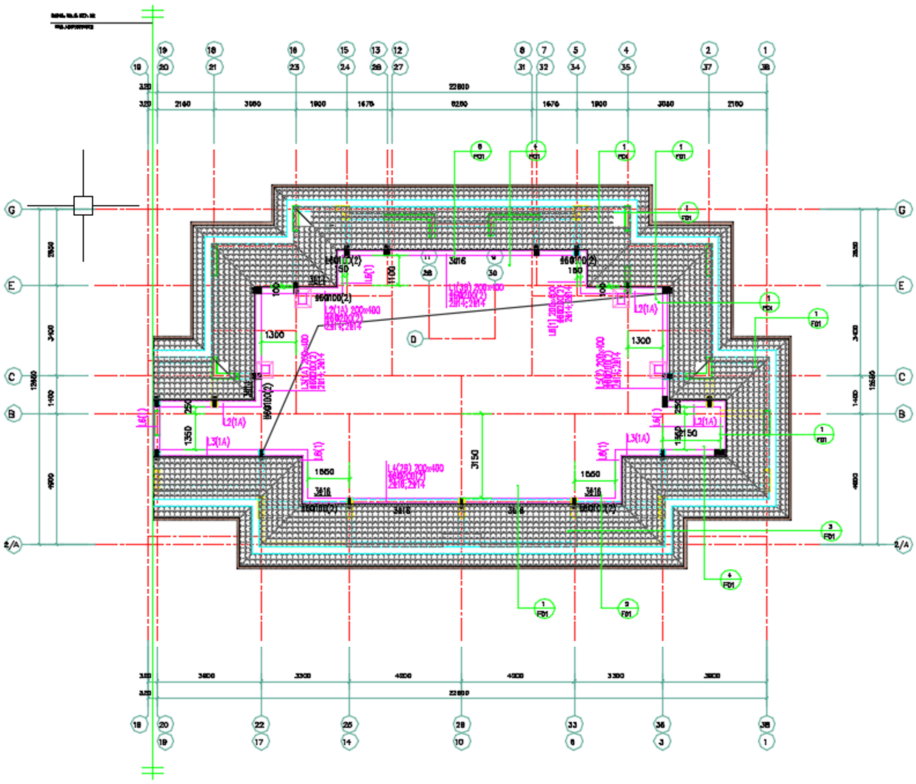

Figure 7. Roof renewal construction.

4. Results and Discussion

4.1. Basic Emergy Calculated Tables

In this section, four stages of the building system have been selected and calculated, including Tables 2–5.

Table 2. Emergy table of Building materials.

Item	Data	Unit	UEVs	UEVs Ref.	Emergy (sej)
Gravel	9.19×10^6	kg	1.27×10^{12}	[51]	1.17×10^{19}
Brick	3.91×10^6	kg	2.79×10^{12}	[43]	1.09×10^{19}
cement	1.76×10^6	kg	2.94×10^{12}	[21]	5.17×10^{18}
Lime	7.72×10^4	kg	1.28×10^{12}	[52]	9.89×10^{16}
Sand	5.07×10^5	kg	1.27×10^{12}	[21]	6.44×10^{17}
Water	1.68×10^6	kg	2.67×10^9	[16]	4.49×10^{15}
Iron	3.67×10^5	kg	3.15×10^{12}	[45]	1.15×10^{18}
Wood	7.57×10^4	kg	6.68×10^{11}	[45]	5.06×10^{16}
Polyester	5.45×10^3	kg	7.34×10^{12}	[53]	4.00×10^{16}
Adhesive	1.26×10^4	kg	7.25×10^{11}	[53]	9.17×10^{15}
Bituminous	4.64×10^3	kg	2.4×10^{12}	[54]	1.11×10^{16}
Glass	2.49×10^4	kg	1.07×10^{12}	[43]	2.67×10^{16}
Steel	1.31×10^6	kg	2.1×10^{12}	[55]	2.76×10^{18}
Aluminum	2.57×10^2	kg	9.65×10^{11}	[45]	2.48×10^{14}
Galvanized steel	1.01×10^4	kg	3.53×10^{12}	[56]	3.55×10^{16}
Ceramic tile	1.06×10^5	kg	2.43×10^{12}	[57]	2.57×10^{17}
Polystyrene	6.78×10^3	kg	5.23×10^{12}	[45]	3.54×10^{16}
Paint	2.50×10^4	$	1.94×10^{13}	[43]	4.86×10^{17}
Fly ash	5.01×10^3	kg	1.78×10^{13}	[21]	8.91×10^{16}
PVC	1.59×10^3	kg	7.49×10^{12}	[43]	1.19×10^{16}
Roof tile	8.08×10^4	kg	2.79×10^{12}	[43]	2.25×10^{17}
Diesel fuel	1.10×10^{12}	J	1.36×10^5	[16]	1.50×10^{17}
		Total			3.38×10^{19}

Table 3. Emergy table of Building construction stage.

Item	Data	Unit	UEVs	UEVs Ref.	Emergy (sej)
Environmental Inputs					
Land use	6.16×10^{12}	J	9.42×10^4	[43]	5.81×10^{17}
Solar irradiation	1.38×10^{13}	J	1.00	[16]	1.38×10^{13}
	Total				5.81×10^{17}
Service Input					
Diesel fuel for generators	3.61×10^9	J	1.28×10^{12}	[16]	4.62×10^{21}
Heavy machinery diesel	4.78×10^9	J	1.27×10^{12}	[16]	6.07×10^{21}
Employees transport diesel	2.34×10^{10}	J	2.67×10^9	[16]	6.24×10^{19}
Human labor	4.13×10^3	h	3.15×10^{12}	Cal.	1.30×10^{16}
	Total				1.08×10^{22}
Water Supply and Sewerage System Construction					
Galvanized steel	2.54×10^4	kg	3.53×10^{12}	[56]	8.97×10^{16}
PVC	1.75×10^5	kg	7.49×10^{12}	[43]	1.31×10^{18}
Polystyrene	1.15×10^3	kg	6.7×10^{12}	[51]	7.70×10^{15}
Brass	3.93×10^2	kg	1.33×10^{12}	[46]	5.23×10^{12}
Polypropylene	2.77×10^1	kg	7.49×10^{12}	[56]	2.07×10^{12}

Table 3. *Cont.*

Item	Data	Unit	UEVs	UEVs Ref.	Emergy (sej)
Water Supply and Sewerage System Construction					
Cast iron	4.44×10^{2}	kg	3.37×10^{12}	[51]	1.50×10^{15}
Glass fiber	1.78×10^{0}	kg	2.28×10^{12}	[55]	4.06×10^{12}
Steel	3.47×10^{3}	kg	2.1×10^{12}	[55]	7.28×10^{15}
Iron	3.33×10^{1}	kg	3.15×10^{12}	[45]	1.05×10^{14}
Ceramic	6.88×10^{3}	kg	2.43×10^{12}	[57]	1.67×10^{16}
Glass	1.66×10^{3}	kg	1.07×10^{12}	[43]	1.78×10^{15}
Cement	2.20×10^{2}	kg	2.94×10^{12}	[21]	6.46×10^{14}
Water	1.10×10^{0}	kg	2.67×10^{12}	[16]	2.95×10^{12}
Gravel	1.44×10^{2}	kg	1.27×10^{12}	[51]	1.83×10^{14}
Diesel fuel	1.46×10^{10}	J	1.36×10^{5}	[16]	1.99×10^{15}
Total					1.44×10^{18}
Heating and Cooling Systems					
Steel	5.52×10^{3}	kg	2.1×10^{12}	[55]	1.16×10^{16}
Polypropylene	1.25×10^{3}	kg	6.7×10^{12}	[51]	8.34×10^{15}
Aluminum	4.34×10^{3}	kg	9.65×10^{11}	[45]	4.19×10^{15}
Glass wool	4.34×10^{3}	kg	7.28×10^{12}	[58]	3.16×10^{16}
Brass	4.34×10^{3}	kg	1.33×10^{13}	[46]	5.77×10^{16}
Stainless steel	4.34×10^{3}	kg	5.25×10^{12}	[16]	2.28×10^{16}
Galvanized steel	4.34×10^{3}	kg	3.53×10^{12}	[56]	1.53×10^{16}
Copper	4.34×10^{3}	kg	1.52×10^{12}	[55]	6.59×10^{15}
Diesel fuel	4.34×10^{3}	J	1.36×10^{5}	[16]	5.90×10^{8}
Total					1.58×10^{17}
Electricity Installations					
Copper	3.96×10^{3}	kg	1.52×10^{12}	[55]	6.02×10^{15}
Aluminum sheet	5.94×10^{1}	kg	1.25×10^{12}	[59]	7.42×10^{13}
Galvanized steel	4.94×10^{1}	kg	3.53×10^{12}	[56]	1.74×10^{14}
Steel	7.71×10^{3}	kg	2.1×10^{12}	[55]	1.62×10^{16}
Rubber	5.55×10^{1}	kg	5.48×10^{12}	[52]	3.04×10^{14}
Polyester	7.40×10^{1}	kg	7.34×10^{12}	[53]	5.43×10^{14}
Iron	3.01×10^{3}	kg	3.15×10^{12}	[45]	9.48×10^{15}
Ceramics	3.20×10^{1}	kg	2.43×10^{12}	[57]	7.77×10^{13}
Plastic	5.24×10^{2}	kg	4.37×10^{12}	[45]	2.29×10^{15}
Glass	4.59×10^{2}	kg	1.07×10^{12}	[43]	4.91×10^{14}
Diesel fuel	1.89×10^{9}	J	1.36×10^{5}	[16]	2.57×10^{14}
Total					3.59×10^{16}
Telecommunications System Installations					
Copper	1.79×10^{2}	kg	1.52×10^{12}	[55]	2.72×10^{14}
PVC	3.82×10^{3}	kg	7.49×10^{12}	[43]	2.86×10^{16}
Aluminum sheet	8.56×10^{1}	kg	1.25×10^{12}	[59]	1.07×10^{14}

Table 3. *Cont.*

Item	Data	Unit	UEVs	UEVs Ref.	Emergy (sej)
Telecommunications System Installations					
Plastic	7.53×10^3	kg	4.37×10^{12}	[45]	3.29×10^{16}
Brass	5.54×10^0	kg	1.33×10^{13}	[46]	7.37×10^{13}
Aluminum	1.58×10^2	kg	9.65×10^{11}	[45]	1.53×10^{14}
Glass	2.93×10^0	kg	1.07×10^{12}	[43]	3.13×10^{12}
Steel	4.64×10^1	kg	2.1×10^{12}	[55]	9.74×10^{13}
Diesel fuel	1.83×10^9	J	1.36×10^5	[16]	2.49×10^{14}
		Total			6.25×10^{16}
Elevator Systems					
Steel	2.05×10^3	kg	2.1×10^{12}	[43]	4.31×10^{15}
Rubber	2.63×10^1	kg	5.48×10^{12}	[52]	1.44×10^{14}
Iron	2.79×10^3	kg	3.15×10^{12}	[45]	8.79×10^{15}
glass	1.63×10^{-1}	kg	1.07×10^{12}	[43]	1.75×10^{11}
Diesel fuel	2.01×10^9	J	1.36×10^5	[16]	2.74×10^{14}
		Total			1.35×10^{16}

Table 4. Emergy table of operation phase.

Item	Data	Unit	UEVs	UEVs Ref.	Emergy (sej)
Solar	4.67×10^{14}	J	1	[16]	4.67×10^{14}
Electricity	9.52×10^{12}	J	6.39×10^4	Cal.	6.08×10^{17}
Heat	5.30×10^{13}	J	2.01×10^6	[46]	1.07×10^{20}
Water	6.33×10^8	kg	2.67×10^9	[16]	1.69×10^{18}
Maintenance	2.80×10^5	m^2	4.3×10^{13}	[43]	1.20×10^{19}
		Total			1.21×10^{20}

Table 5. Emergy table of demolition phase.

Item	Data	Unit	UEVs	UEVs Ref.	Emergy (sej)
Recycling Part					
Glass	2.74×10^4	kg	2.21×10^{11}	[60]	6.05×10^{15}
Iron and steel	1.76×10^6	kg	2.31×10^{11}	[52]	4.06×10^{17}
Plastic and PVC	2.16×10^5	kg	2.22×10^{11}	[52]	4.81×10^{16}
Aluminum	4.56×10^3	kg	2.21×10^{11}	[52]	1.01×10^{15}
Bricks	3.93×10^6	kg	2.03×10^7	[61]	7.99×10^{13}
Concrete	1.09×10^7	kg	1.19×10^{12}	[62]	1.29×10^{19}
Diesel fuel	6.58×10^{11}	J	1.36×10^5	[46]	8.95×10^{16}
		Total			1.35×10^{19}
Landfill Process					
Non-recycled materials	3.04×10^6	kg	2.1×10^{11}	[61]	6.39×10^{17}
Diesel fuel	1.46×10^{11}	kg	1.36×10^5	[61]	1.99×10^{16}
		Total			6.59×10^{17}

4.2. Renovation Phase Emergy Calculation

Three renovation scenarios have been calculated in Table 6, including insulating board renovation, glass window renovation, and solar photovoltaic panels renovation.

Table 6. Emergy table of renovation phase.

Item	Data	Unit	UEVs	UEVs Ref.	Emergy (sej)
Renovation Scenario 1					
Polystyrene	5.54×10^3	kg	5.23×10^{12}	[45]	2.90×10^{16}
Cement	1.21×10^4	kg	2.94×10^{12}	[21]	3.57×10^{16}
Water	7.57×10^3	kg	2.67×10^9	[16]	2.02×10^{13}
Diesel fuel	2.14×10^9	J	1.36×10^5	[16]	2.91×10^{14}
Total					6.50×10^{16}
Renovation Scenario 2					
Glass	2.28×10^4	kg	1.07×10^{12}	[60]	2.44×10^{16}
Aluminum	1.76×10^3	kg	9.65×10^{11}	[52]	1.70×10^{15}
Diesel fuel	2.14×10^9	J	1.36×10^5	[16]	2.91×10^{14}
Total					2.64×10^{16}
Renovation Scenario 3					
Glass	8.32×10^3	kg	1.16×10^4	[60]	1.25×10^{16}
Aluminum	2.89×10^3	kg	4.05×10^3	[52]	3.90×10^{15}
Copper	2.51×10^3	kg	3.51×10^3	[55]	5.34×10^{15}
Polyurethane	1.01×10^3	kg	1.41×10^3	[44]	9.88×10^{15}
Glass wool	8.9×10^2	kg	1.25×10^3	[58]	9.07×10^{15}
Diesel fuel	4.41×10^{10}	J	6.17×10^{10}	[16]	8.40×10^{15}
Total					4.91×10^{16}
Additional Resource and Service					
Solar irradiation	1.14×10^{12}	J	1	[16]	1.14×10^{12}
Electricity	7.22×10^{10}	J	6.39×10^4	Cal.	4.62×10^{15}
Human labor	3.36×10^2	h	1.36×10^{13}	Cal.	4.57×10^{15}
Employees transport	1.90×10^5	J	1.36×10^5	[16]	2.59×10^{10}
Total					9.19×10^{15}

4.3. Life Cycle Assessment and Emergy (LCA-Emergy) Analysis

Through the five stages analysis in the building system, a fact can be found that the main emergy contributor is the construction stage (1.08×10^{22} sej), followed by operation stage (1.21×10^{20} sej), building material stage (3.38×10^{19} sej), demolition stage (6.59×10^{17} sej) and renovation stage (total 1.5×10^{17} sej). Therein, in terms of proportion angle, the construction stage is much larger than the other stages, because it needs a series of resource and energy inputs to complete the building construction.

(1) Building material stage analysis

From the point of building material view to analyze, there are 22 inputs to the building material system. Among them, the most important factors are gravel (1.17×10^{19} sej), brick (1.09×10^{19} sej), cement (5.17×10^{18} sej), steel (2.76×10^{18} sej) and iron (1.15×10^{18} sej), accounting for 34.62%, 32.25%, 15.3%, 8.17% and 3.4% of total building material emergy, respectively (in Figure 8).

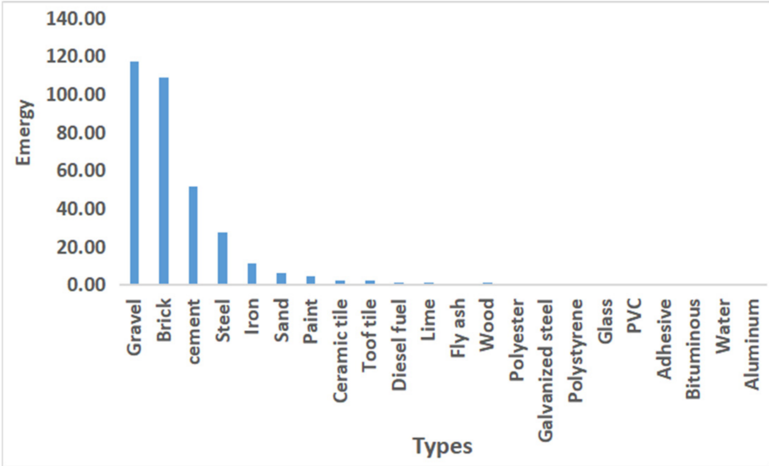

Figure 8. The proportion of each material input (unit: 10^{17} sej).

(2) Construction stage analysis

For construction stage, it entails seven subsystems, which are environmental inputs, service input, water supply, sewerage system construction, heating, and cooling systems, electricity installations, telecommunications system installations, and elevator systems. Therein, service input plays an essential role in the construction stage. In particular, diesel fuel for generators and heavy machinery diesel is the major consumption.

For the environmental inputs subsystem, two primary elements have been selected and considered, which are land use and solar irradiation, respectively. Land use is the main input part from an emergy perspective.

The water supply and sewerage subsystem is also an indispensable link for the building system. This paper has 15 types of resource inputs. PVC, Galvanized steel, and Ceramic work the primary effect on the water supply and sewerage subsystem (see Table 3).

Heating and cooling subsystems have nine inputs. The three most important factors are brass, glass wool, and stainless steel, which account for 70.9% (sum of three inputs) for heating and cooling subsystems (in Figure 9).

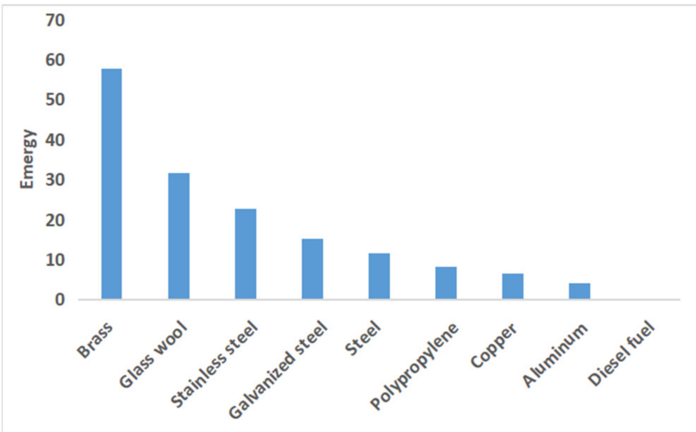

Figure 9. All inputs of heating and cooling subsystems (unit: 10^{15} sej).

As the important infrastructure of the building system, Electricity installations, Telecommunications system installations, and Elevator systems are necessary, but they have a secondary effect based on an emergy view.

(3) Operational stage analysis

In Table 4, the operational stage emergy has been listed and shown, the crucial input is heat, which has the dominant position.

(4) Operational stage analysis

Table 5 displays the emergy distribution of the demolition phase. On the one hand, concrete is the major input element, accounting for 92.8% of the recycling part emergy; on the other hand, for the Landfill process, non-recycled materials are the central wastes that need to be disposed of.

(5) Renovation stage analysis

Analysis from the emergy of the entire building system, the renovation phase doesn't have enough influence and plays a secondary role. However, this phase provides renewable resources and energy supplements for the building system and is the necessary means to maintain the use of the building.

By comparing with three renovation scenarios in line with emergy, renovation scenario 1 provides more inputs than renovation scenario 2 and renovation scenario 3 on the basis of sustainability alone, renovation scenario 2 can be considered more.

4.4. Emergy Indicator Analysis

Table 7 shows the ecological indicators of the building system. Therein, 1–7 items are the basic input and 8–18 items are the primary evaluated indicators. The specific analysis is as follows:

Table 7. Emergy indicators analysis.

Note	Items	Index	Values
1	Renewable resource emergy	R	1.21×10^{20} sej
2	Nonrenewable resource emergy	N	1.08×10^{22} sej
3	Energy emergy	E	1.07×10^{20} sej
4	External input emergy	F	1.22×10^{20} sej
5	Labor and service emergy	L	1.30×10^{16} sej
6	Total emergy usage	U	1.1×10^{22} sej
7	Emergy input	I	1.1×10^{22} sej
8	Emergy intensity	E_p	8.92×10^{19}
9	Emergy per RMB	E_e	1.34×10^{14}
10	Emergy density	E_d	2.14×10^{18}
11	Renewability rate	R_e	0.0113
12	Nonrenewability rate	N_r	0.982
13	Nonrenewability rate of purchased resource	N_p	0.0112
14	Purchased emergy dependence level	P_e	0.0109
15	Emergy investment ratio	EIR	0.00109
16	Environmental loading ratio	ELR	89.256
17	Emergy yield ratio	EYR	90.5164
18	Emergy Sustainability Indicator	ESI	1.0141

- Emergy intensity (E_p) is 8.92×10^{19} sej/person, which presents the unit emergy per person and can be regarded as the embodiment of competitiveness.
- Emergy per RMB (Ee) is 1.34×10^{14} sej/RMB. It is an economic index of the system, illustrating the economic competitiveness of the system.
- Emergy density (Ed) is 2.14×10^{18} sej/m^2, which displays a relatively high degree of unit emergy per area.
- The renewability rate (Re) is 0.0113, revealing a low renewable rate. It needs to supplement renewable emergy to improve the sustainability of the system.
- The nonrenewability rate (Nr) is 0.982, which uncovers an excessive resource input and brings considerable pressure on the evaluated system.

- The nonrenewability rate of purchased resources (Np) is 0.0112, which illustrates the weak economic emergy input and the need to adjust the economic relationship between economic input and system state.
- The purchased emergy dependence level (Pe) is 0.0109, expounding the system competitiveness. Greater Pe means stronger external emergy input.
- The emergy investment ratio (EIR) is 0.00109, which shows a low investment in the building system.
- The environmental loading ratio (ELR) is 89.256. It is a high degree of environmental stress. According to the related standard [49], when ELR is more10, the system is within a high environmental load level.
- Emergy yield ratio (EYR) is 90.5164, which represents a better input for the building system.
- Emergy Sustainability Indicator (ESI) is 1.0141. It is the most vital indicator of sustainability in terms of emergy theory. Based on the literature [49], the result is relatively acceptable, but there is still a need to improve the level of sustainability in the long run.

4.5. Sustainability Analysis of the Renovation Stage Subsystem

Based on Table 1, the key indicators have been selected and considered, which are the Environmental loading ratio (ELR), Emergy yield ratio (EYR), and Emergy Sustainability Indicator (ESI), respectively. In Table 8, three renovation scenarios have been calculated to assess the subsystem state.

Table 8. Sustainability indexes of renovation scenario.

No.	Item	Indicators	Value
		Renovation scenario 1	
1	Environmental loading ratio	ELR-1	7.07
2	Emergy yield ratio	EYR-1	1.14
3	Emergy Sustainability Indicator	ESI-1	0.1414
		Renovation scenario 2	
1	Environmental loading ratio	ELR-2	2.87
2	Emergy yield ratio	EYR-2	1.35
3	Emergy Sustainability Indicator	ESI-2	0.4692
		Renovation scenario 3	
1	Environmental loading ratio	ELR-3	5.34
2	Emergy yield ratio	EYR-3	1.19
3	Emergy Sustainability Indicator	ESI-3	0.2222

Aking the ELR as an example, it has the biggest value in renovation scenario 1, followed by renovation scenario 3 and renovation scenario 2. The reason for this phenomenon is that renovation scenario 1 uses the most emergy than others, resulting in more stress in renovation scenario 1. From the EYR point of view, there is not much difference between the three renovation scenarios. In renovation scenario 2, the EYR has the highest value, demonstrating it has higher productivity and is more efficient. According to the accepted standard [49], the optimal sustainability effect is in renovation scenario 2 (ESI = 0.3692). Compared with renovation scenario 2, renovation scenario 1 has a poor sustainability rate (ESI = 0.1414). Renovation scenario 3 is in an intermediate state of sustainability (in Figure 10).

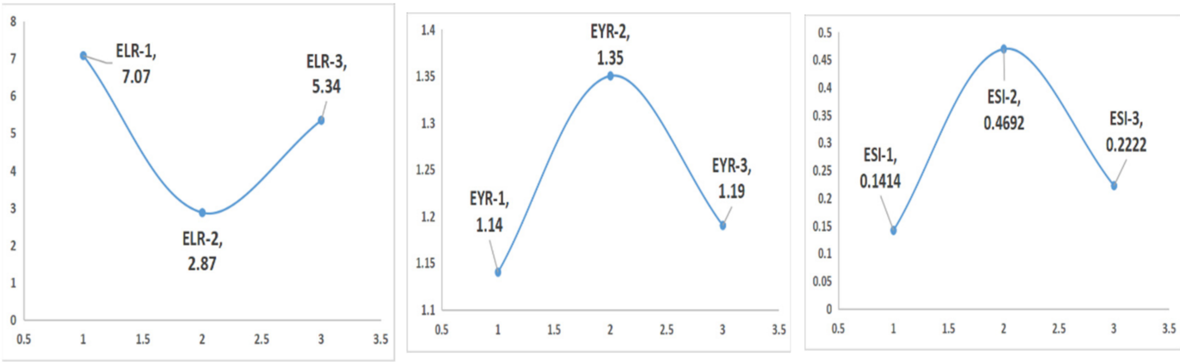

Figure 10. Key indicators comparison.

4.6. Unit Emergy Values (UEVs)

In this paper, the unit emergy values have been focused on and calculated. From the point of view of the whole building, UEVs are 2.14×10^{18} sej/m^2 (in Table 7), which displays a relatively high degree of unit emergy per area. Two reasons should be responsible for this result. On the one hand, the value represents the judgment of the whole life cycle of the building rather than one stage; On the other hand, this calculation is based on 70 years of statistics. Despite this, it is higher than others and illustrates the building system needs to enhance its sustainability in the long term.

To demonstrate and display the results more clearly, through literature search, a series of articles on building and emergy have been found in the last ten years. The specific details have been compared in Table 9. Through the analysis of various indicators, at present, the articles have not carried out a comprehensive UEVs calculation and analysis in the building system based on LCA-emergy methodology. This article fills the gap following the latest data. To date, the UEVs (2.14×10^{18} sej/m^2) of the building system could be optimized by the replacement of renewable materials, adjusting of structure, and development of renewable energy.

Table 9. Comparative analysis of literature.

Author	Baseline	UEVs	LCA Angle	Emergy Angle	Country	Year	Ref.
Heather Rothrock	Old	×	×	√	USA	2014	[63]
Pulselli et al.	Old	×	×	√	Italy	2014	[64]
Hwang et al.	Old	×	×	√	USA	2015	[38]
Zhiwen et al.	Old	×	×	√	China	2015	[22]
Hwang and William	Old	×	×	√	USA	2015	[65]
Eugene P. Law et al.	Old	×	×	√	USA	2017	[34]
Hwang et al.	New	×	√	√	USA	2017	[35]
Jae and William	New	×	×	√	USA	2017	[36]
Thomas and Praveen	New	×	×	√	India	2020	[30]
Wenjing et al.	None	×	√	√	China	2021	[28]
Suman et al.	None	×	×	√	USA	2021	[66]
This paper	New	√	√	√	China	2022	~

4.7. Sensitivity Analysis

In order to obtain the detailed sensitivity analysis, two assumptions are executed as follows (Table 10).

Table 10. Ecological indicator changes between former and latter.

Items	Index	10% Reduction		5% Increment	
		Former	Latter	Former	Latter
Renewability rate	R_e	0.0113	0.0122	0.0113	0.0105
Nonrenewability rate	N_r	0.982	0.8836	0.982	1.0309
Nonrenewability rate of purchased resource	N_p	0.0112	0.0126	0.0112	0.0108
Purchased emergy dependence level	P_e	0.0109	0.0123	0.0109	0.0106
Emergy investment ratio	EIR	0.0109	0.0124	0.00109	0.0106
Environmental loading ratio	ELR	89.256	80.3306	89.256	93.7190
Emergy yield ratio	EYR	90.5164	81.6639	90.5164	94.9426
Emergy Sustainability Indicator	ESI	1.0141	1.0166	1.0141	1.0131

Hypothesis 1 (H1). *Choosing the primary contributor in the building system, a 10% reduction emergy is implemented, and others remain unchanged to adjust the floating of the pivotal indicator. The dominating contributor contains the construction stage, operation stage, and building material stage (from Section 4.3). The staple indicators have eight items, including Renewability rate, Nonrenewability rate, Nonrenewability rate of purchased resource, Purchased emergy dependence level, Emergy investment ratio, Environmental loading ratio, Emergy yield ratio, and Emergy Sustainability Indicator.*

Hypothesis 2 (H2). *Five percent emergy increment was conducted to assess the prime indexes changes. All the other states remain the same as hypothesis 1.*

In Figures 11 and 12, the variation ranges of various indicators have been shown under the 10% emergy reduction hypothesis. Therein, EIR has the biggest change (−13.76%), followed by Pe (−12.84%), Np (−12.5%), Nr (10.02%), ELR (10%), EYR (9.78%), Re (−7.96%) and ESI (−0.25%). As the most critical indicator of sustainability, ESI fluctuates by only −0.25%, which manifests the sensitivity change can be accepted and it has good stability to keep the accurate results.

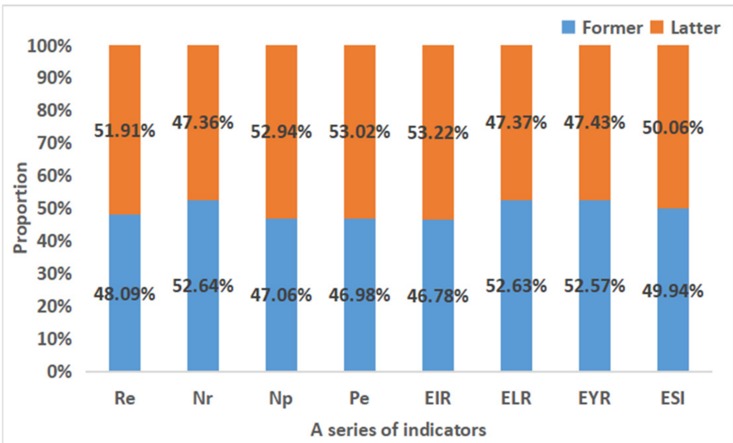

Figure 11. Comparison of former and latter based on 10% reduction.

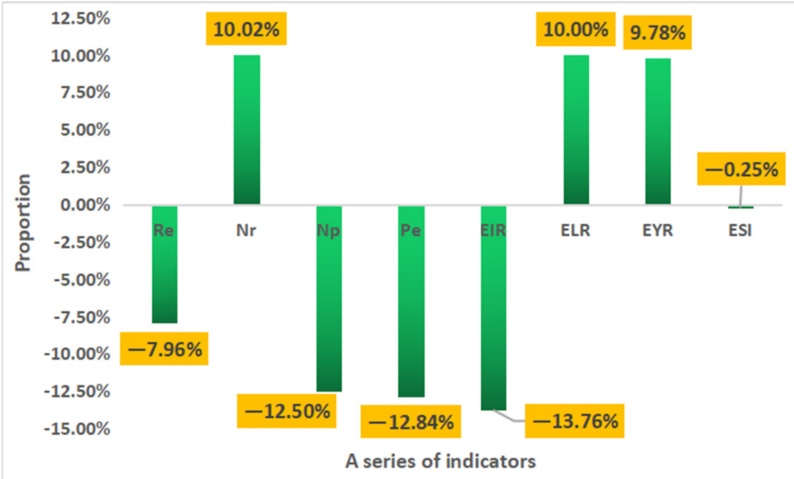

Figure 12. The variation range of key indicators based on a 10% reduction.

Figures 13 and 14 detail variation ranges of key indicators based on the 5% increment hypothesis. The absolute values of changes from largest to smallest are Re (−7.08%), ELR (5%), Nr (4.98%), EYR (4.89%), Np (−3.57%), Pe (−2.75%), EIR (−2.75%) and ESI (−0.1%), respectively. ESI hardly changes and also verifies the building system stability.

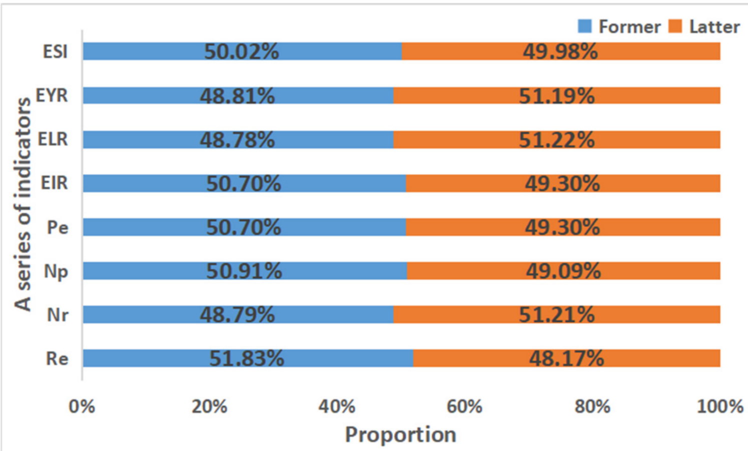

Figure 13. Comparison of former and latter based on 5% increment.

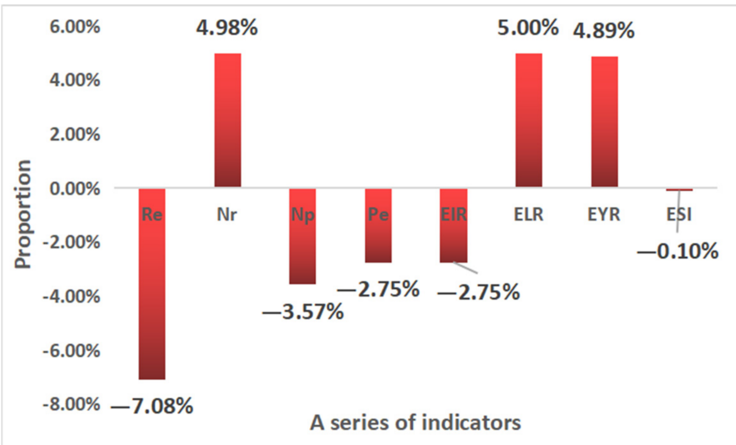

Figure 14. The variation range of key indicators based on a 5% increment.

5. Strategies and Suggestions

From the above analysis (Section 4), it can be seen that the sustainability of the whole building system needs to be optimized and improved. This paper adopts two ways to enhance the sustainability in the building system, involving increasing the proportion of renewable energy and using recycled building materials.

(1) Enhancing renewable energy proportion in the building system

In the building system, renewable energy plays a positive effect on sustainability. However, until now, there is not enough sustainable energy to contribute to the system (see Section 4.1). In order to perfect the energy structure, a series of new renewable energy types should be considered and adopted, involving solar power, hydropower and wind power, etc. Taking the renovation scenario as an example, if the proportion of renewable energy is increased to 20%, the overall ESI of the system can be improved by 61.24%. However, the development of renewable resources is limited by several defects, such as enormous investment, professional and technical barriers, and geographical conditions. To expand the use of renewable energy, financial subsidies and favorable tax policies should be considered to adopt. Fortunately, a number of researchers have been working on this, including solar power, hydropower, wind power, etc. For example: For the weaknesses of solar power generation, intermittency and aggregation were investigated and studied in China [67]. In addition, a novel concentrated solar power system is proposed and analyzed, which provides great competitiveness and high efficiency [68]. The relationship between hydropower generation and drought was investigated by some authors in Brazil [69]. The valley stress distribution characteristics of hydropower engineering projects were a concern in China [70]. By integrating the machine learning method and fluid dynamic analysis, urban wind speed and wind power were discussed [71]. To predict wind power, a comprehensive approach was attempted Based on a Hybrid Granular Chaotic Time Series Model [72].

(2) Circulating material substitution

Another feasible method is the alternative use of recycled materials. In this study, the nonrenewable resource is the main contributor to the building system, accounting for more than 90% of total emergy (approximately 98.2%), so using reproducible material is an effective way to promote sustainability. For instance, if 20% of the nonrenewable resource is replaced in the building system, the ELR indicator can increase by 25% and will greatly reduce the pressure on the environment. Therefore, a lot of scholars have spent a lot of time implementing alternative materials, containing industrial slag, construction waste, metallurgical waste, mining waste, fuel waste, chemical waste, etc. For example, through the use of recyclable materials [73], the sustainability of the system can be enhanced and improved. So in this article, we can try the same approach for better sustainability in the building system.

6. Conclusions

According to the LCA-Emergy angle and perspective, a residential building near the subway was selected, investigated, and analyzed in this paper; the main conclusions are summarized as follows:

(1) Through the five stage analysis in the building system, a fact can be found that the main emergy contributor is the construction stage, followed by the operation stage, building material stage, demolition stage, and renovation stage.
(2) Emergy Sustainability Indicator (ESI) is 1.0141, which is the most vital indicator of sustainability in terms of emergy theory. Based on the related standard, the result is relatively acceptable, but there is still a need to improve the level of sustainability in the long run.
(3) Compared with renovation scenario 2, renovation scenario 1 has a poor sustainability rate (ESI = 0.1414). Renovation scenario 3 is in an intermediate state of sustainability.

(4) From the point of view of the whole building, UEVs are 2.14×10^{18} sej/m^2, which displays a relatively high degree of unit emergy per area.
(5) Two assumptions are executed (10% reduction and 5% increment), which have both verified the building system stability.

In the last part, two strategies and suggestions were conducted to enhance the sustainability of the building system, including increasing the proportion of renewable energy and using recycled building materials.

In this article, the LCA-emergy methodology was adopted to assess the sustainability of the building system. Its most obvious advantage is that it can combine and integrate the advantages of the emergy method with the advantages of the LCA method. At the same time, for other architectural cases, this method can be popularized and applied and it has extensive reference significance for related researchers.

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