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An approach for measuring and analyzing embodied carbon in the construction industry chain based on emergy accounting

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ABSTRACT

This study proposes a comprehensive approach to analyze the embodied carbon in China's construction industry by integrating carbon emission factors and an input–output model. The analysis covers the whole construction industry chain, including both direct and indirect carbon emissions. Moreover, this study introduces an emergy index system that incorporates the ternary diagram of materials science for environmental assessments, assessing resource allocation, development effectiveness, efficiency, and sustainability. The research measures the embodied carbon emissions for seven regions in China's construction industry, and compares the results from the perspective of the whole industry chain. The study reveals that indirect carbon emissions contribute significantly to the embodied carbon emissions in China's construction industry, and the central region exhibits the highest environmental loading rate among all regions. Additionally, the northern region shows the highest emergy yield rate, whereas the eastern and northeastern regions exhibit better sustainability in the development of the construction industry.

1. Introduction

The substantial increase in carbon emissions since the industrial revolution in the 19th century has caused significant concern worldwide. China recently proposed to reach the carbon emissions peak by 2030 and achieve carbon neutrality by 2060 during the 75th United Nations General Assembly. However, in 2020, China's CO_2 emissions reached a staggering 13.9 billion tons, representing 30 % of the global share, with buildings and construction accounting for 45.5 % of China's total energy consumption. China's construction industry continues to see an increasing proportion of CEs. Measuring embodied carbon proves challenging as the industry's supply chain involves upstream products as intermediate inputs and downstream consumption. To meet the 2030 CO_2 emission peak target, the construction industry needs to set annual carbon emission reduction targets and account for embodied carbon throughout each building's entire life cycle. Adopting a regionalized perspective in the relevant carbon reduction policies is crucial to achieving the "double carbon" target. In order to achieve this goal on time, the delineation of carbon emissions should be more refined and specific. It makes the implementation of carbon reduction strategies more targeted. According to the source of carbon emissions, this paper divides the embodied carbon emissions into direct carbon emissions and indirect carbon emissions. It facilitates the analysis of the main sources of carbon emissions and makes the policy measures more detailed and specific.

In the context of the "known low carbon with real high carbon" situation in the construction industry, macroscopic research tends to focus on CEs resulting from energy consumption in the production process, embodied carbon of energy-intensive industries, and unit intensity of embodied carbon. Microscopic research, on the other hand, focuses on analyzing energy consumption and carbon share during the single building materialization and use process to reduce direct energy consumption and emissions throughout a single building's life cycle (Zhao et al., 2023c). To measure embodied carbon emissions in the construction industry, various quantitative and evaluation methods have been applied. Zhang and Lin (2012) found that urbanization's impact on CEs decreases from west to east. Ren et al. (2014) examined the relationship between international trade, foreign direct investment, and embodied carbon emissions in China's industrial sectors using an econometric regression statistical model. The conventional method for measuring CE is the Carbon Emission Factor method, which outputs results by multiplying the activity data with the carbon emission factor. However, calculation accuracy can vary depending on the dimensions of the data inputted. Most researchers utilize the Input-Output Model to

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calculate an industry's embodied carbon. Similarly, Yu et al. (2017) calculated Australia's construction industry's total carbon footprint using the IOM. Jiang et al. (2022) showed that the structural optimization of energy consumption in the construction industry had a decreasing trend, with positive inhibition between energy intensity and input structure interaction.

In the current context of the construction industry, it is necessary to analyze the embodied carbon in the building stage of the construction industry from the perspective of the whole industrial chain. This can provide the Chinese government with sufficient and complete information on carbon emissions and help it formulate practical policies and measures to reduce emissions in the construction industry. Therefore, this study combines the CEF method and IOM to calculate the embodied carbon in the building stage at a regional level. Furthermore, the study utilizes unit emergy value (UEV) to calculate emergy indicators and provides a comprehensive and systematic analysis of various resources in the construction industry from multiple perspectives. Ternary diagrams are then drawn to analyze resource allocation status, development sustainability, and environmental load in the building stage. Finally, based on the evaluation and analysis, the study recommends corresponding policies for future development.

2. Literature review

2.1. Whole construction industry chain

The industrial chain encompasses the entire product derivative process, from procuring raw materials to final product output. It includes all involved links, extending upstream to the basic industry and downstream to the consumption field, reflecting the close connection between supply and demand in different industries and enterprises. From the perspective of the industrial supply chain, the construction industry considers upstream industry products as intermediate inputs, and construction products are also consumed by downstream industries or used as production factors. This supply and demand network interwoven between industries forms the entire construction industry chain.

Yu et al. (2015) considered residential buildings as research objects and divided the building life cycle into five stages: production period, construction period, demolition period, solid waste recycling, and disposal period. The building industry chain covers the entire life cycle of the building body, with the building stage including the production and transportation of building materials, construction and installation of buildings, the use stage involving operation and maintenance, and the demolition stage including scrapping and demolition of buildings and recycling of construction waste.

Fig. 1 illustrates the entire life cycle of a single building. To accurately account for CEs of a building, it is essential to consider its entire life cycle, from production to use and eventual demolition. However, simply summing up the CEs of individual buildings is not feasible, as they are all at different points in their respective life cycles. It is necessary to account for the CEs of buildings from a macro perspective at a given point in time, as shown in Fig. 2.

Gustavsson et al. (2010) calculated the CEs of 8-story wooden structure apartments at four stages: material acquisition and treatment, site construction, building operation, demolition, and material disposal. Related research on life cycle gas emissions has also been considered. Sharma et al. (2011) evaluated the energy consumption level of various buildings in different locations at each stage of their life cycle and calculated their greenhouse gas emission values. Wu et al. (2012) used life cycle assessment (LCA), a model evaluation method, calculate the energy consumption and CEs of China's office buildings, and evaluate the environmental factors with the greatest impact. Chau et al. (2015) and Zhang et al. (2016) compared building life cycle assessment and measured CEs at different stages. Luo et al. (2020) studied the building materialization stage and divided it into three processes: manufacturing, transportation, and site operation stages. Zhou et al. (2021) quantitatively assessed the CEs of buildings using LCA and rules for calculating CEs in the materialization stage.

2.2. Embodied carbon accounting

2.2.1. Carbon emission factors

The concept of embodied carbon originated from Wyckoff and Roop's (1994) study of the carbon content of manufactured products in international trade flows. To calculate embodied carbon emissions in the building stage, there are three main methods: CEF method, IOM, and the hybrid method. The CEF method is commonly used in the early stages of research to compile and summarize various data sources. Zhang et al. (2000) compiled a database of species-specific CEFs for 28 fuel combinations tested in China. Eggleston et al. (2006) provided default values of various parameters and the CEF method for all industries as required by the Intergovernmental Panel on Climate Change (IPCC) CEF database.

You et al. (2011) developed an LCA model using the CEF method and assessed the whole life cycle CEs of two typical structures of residential building systems separately. The results showed that steel concrete produced fewer CEs per unit area. Dezhi et al. (2015) established a "database of life-cycle carbon emission factors for buildings" in China. Using an LCA model, Zhang and Wang (2016b) calculated CEs throughout the entire life cycle of China's construction industry, and the results showed that the manufacturing and operation stages had the most significant contribution. Huan et al. (2022) compared the CEs of different buildings structures and dwellings.

2.2.2. Input-output model

The CEF method is widely used in the direct-CEs measurement of individual buildings or groups of buildings, while the IOM is frequently used at home and abroad to calculate the CEs between industries. Ochoa et al. (2002) used the input–output table to measure CEs over the entire life cycle of buildings in Britain, the United States, and Sweden. Currently, the application of the IOM has been gradually sophisticated. Liu et al. (2011) used the IOM to determine the impact of consumption

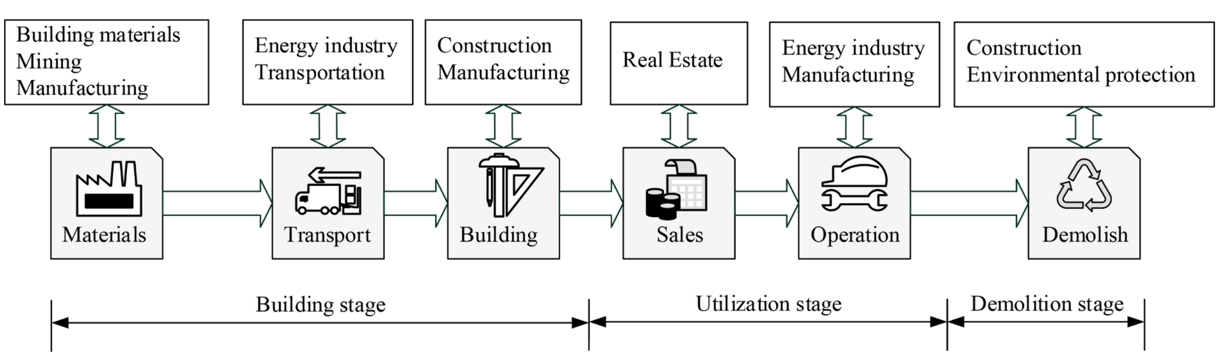

Fig. 1. Whole life cycle of a single building.

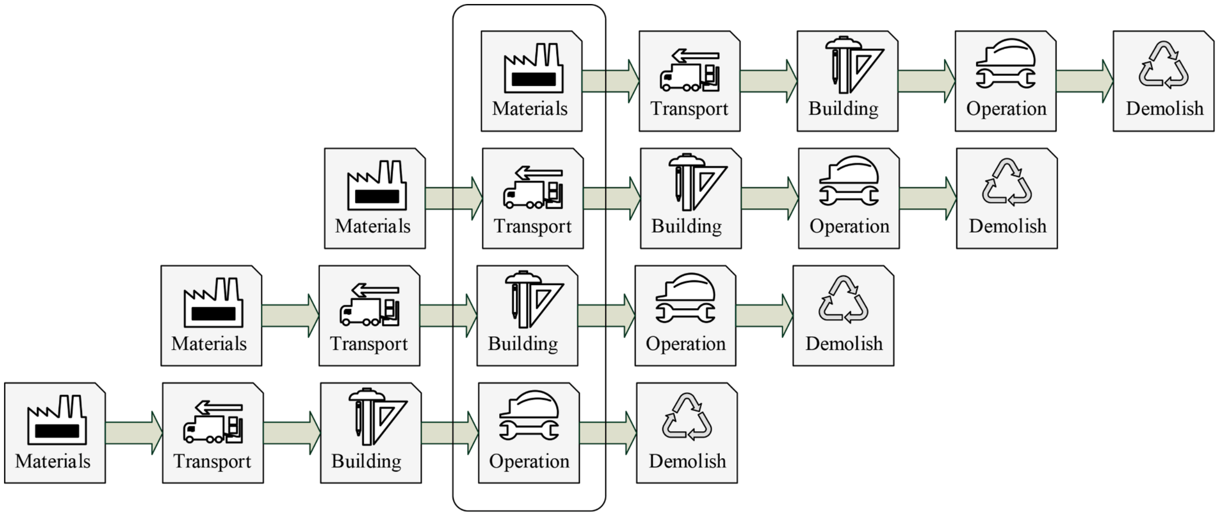

Fig. 2. The whole construction chain at a point in time.

increase behavior on the CEs of Chinese urban and rural residents. Zhu et al. (2012) built an IOM and calculated and analyzed indirect-CEs from household consumption in China over the past 14 years.

In recent years, various models have been combined. Huang et al. (2012) applied IOM and time-series analysis technologies to analyze the pollutants produced by the Norwegian construction industry. The results showed that the choice of low carbon materials is critical to reducing CE in the construction industry. Onat et al. (2014) combined IOM with LCA and concluded that the CEs in the use stage of buildings accounted for the highest proportion in the United States. Zhang and Wang (2016a) combined the process method with IOM to comprehensively analyze building energy consumption and CEs. Li et al. (2021) used mixed LCA to measure the specific CEs of rural residential buildings. The data showed that a significant reduction in net carbon emissions from buildings with wood and lightweight steel construction.

2.3. Emergy analysis

In terms of sustainable development in the construction industry, there is an objective and quantitative need to evaluate the economic, social, and environmental benefits of regional building energy systems. Odum (1989) developed the emergy theory, which uses solar emergy (sej) as a unifying unit to integrate different types of resources and evaluate and analyze the resource allocation, development sustainability, and environmental load of production processes in several countries. When measuring CEs in the construction industry, the lack of standardized units for various resources may lead to errors. Emergy accounting offers a solution by incorporating all renewable and non-renewable, local and imported inflows into an environmental inventory and converting different types of energy into solar emergy using UEVs.

Emergy analysis has been widely used in the construction industry. Meillaud et al. (2005) evaluated the energy of a building. Giannetti et al. (2006) studied the association of environmental loads, utilization, and benefits among system elements. Pulselli et al. (2007) evaluated the global sustainability of buildings at all stages and calculated composite indicators to assess the housing and construction industries. Hossaini et al. (2012) developed an emergy-based sustainability rating system to assess the role of environmental and related socio-economic factors throughout the life cycle of a building. Emergy analysis has also been applied to other fields, Zhang et al. (2010) and Andrić et al. (2015) used emergy analysis for the combustion process of biomass. Luo et al. (2015) studied different energy scenarios consisting of renewable and non-renewable energy sources. (Zhao et al., 2019, 2020, 2023a,b) applied the emergy ternary diagram to analyze the sustainability of eco-industrial parks and recycled concrete production systems.

Emergy analysis has been combined with other models. Baral et al. (2010) proposed a method mixed input–output emergy, to study the life cycle of energy. Reza et al. (2014) and Liu et al. (2017) adopted the emergy-LCA method and evaluated its economic benefit, environmental load, and sustainability. Zhao et al., (2022a, 2022b) coupled emergy accounting with system dynamics to stimulate the sustainability of an eco-industrial park and regional area.

3. Methodology

3.1. Materials

This study requires three main categories of data: energy consumption, CEFs, and input–output data. To obtain these, national data was sorted and summarized according to China's seven geographical regions: Northeast, Northern, Eastern, Central, Southern, Southwest, and Northwest, as shown in Fig. 3.

Table 1 shows the energy and materials consumption of construction industry, China in 2020.

Energy consumption is defined as the energy consumed by all industries involved in the construction chain. Energy consumption in the "Table of Energy Consumption by Industry" of the China Statistical Yearbook mainly includes coal, gasoline, coke, kerosene, fuel oil, diesel fuel, electricity, and natural gas (National Bureau of Statistics, 2021a). The construction materials consumed in the construction chain are defined as building material consumption. This part of the data was obtained from the "Table of Construction Material Consumption by Construction Enterprises by Region" in the China Construction Statistical Yearbook (China National Bureau of Statistics, 2021b). To improve the accuracy of the calculations, the industry categories were reorganized based on the National Economic Industry Classification and Codes and the China's Energy Statistical Yearbook (National Bureau of Statistics of China, 2021c). In this paper, the industry classification is adjusted to (1) Agriculture, forestry and fishery products and services industry, (2) Mining industry, (3) Manufacturing and repair industry, (4) Electricity, heat, gas and water production and supply industry, (5) Construction industry, (6) Transportation, storage and postal industry, (7) Wholesale and retail trade, accommodation and catering industry, (8) Real estate industry.

Fig. 3. Regional distribution map.

Table 1
Energy and materials consumption of the construction industry by regions.

	Northeast	Northern	Eastern	Southern	Central	Northwest	Southwest
Coal (ton)	1.83E+04	1.62E+06	3.54E+05	4.01E+04	2.95E+06	4.78E+05	5.06E+05
Coke (ton)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.10E+03	4.03E+04	5.56E+04
Gasoline (ton)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Kerosene (ton)	1.92E+05	6.32E+05	1.58E+06	5.64E+05	1.26E+06	3.50E+05	8.53E+05
Diesel (ton)	0.00E+00	1.80E+03	5.45E+04	2.80E+03	2.63E+04	2.40E+03	7.25E+04
Fuel oil (ton)	4.46E+05	2.07E+06	3.60E+06	4.71E+05	1.81E+06	9.77E+05	2.08E+06
Natural gas (m^3)	6.90E+03	1.41E+04	1.18E+05	1.67E+04	4.69E+04	1.86E+04	4.24E+04
Electricity (kWh)	5.10E+03	8.20E+03	1.09E+04	8.10E+03	1.60E+04	4.60E+03	5.50E+03
Steel (ton)	3.09E+07	7.92E+07	4.33E+08	1.68E+08	6.64E+07	1.55E+08	5.69E+07
Wood (m^3)	2.07E+07	3.46E+07	2.13E+08	1.16E+08	4.06E+07	9.31E+07	2.09E+07
Cement (ton)	4.42E+07	1.53E+08	1.11E+09	3.72E+08	1.56E+08	3.54E+08	1.28E+08
Glass (weight case)	1.74E+06	5.01E+06	1.25E+08	2.45E+07	1.44E+07	1.31E+07	2.74E+06
Aluminum (ton)	1.13E+06	2.22E+06	2.95E+07	1.12E+07	5.70E+06	1.01E+07	1.89E+06

3.2. Embodied carbon accounting model

In this study, the CEs accounting is primarily utilized during the building stage (see Fig. 4). Initially, an emergy flow system diagram of the entire construction industry chain is constructed. Then, the IOM is integrated with the CEF method to develop an emergy-based IOM-CEF model. The direct-CEs for the entire life cycle of buildings are assessed using the CEF method, while indirect-CEs are determined based on the emergy of input and output between departments. The total embodied carbon emissions are computed by summing up the direct-CEs and indirect-CEs.

3.2.1. Direct carbon emissions

The CEF method is a widely used approach to quantify CEs. The basic principle is to multiply the activity data by the CEF method for each source to estimate the CEs. In this study, activity data refers to the emissions generated from human activities in a defined area, such as energy consumption and material production. The direct-CEs are classified into two main categories: energy consumption and building materials. The CEs from energy consumption are estimated using the following formula:

$$EE = AD \times SC \times CEF \quad (1)$$

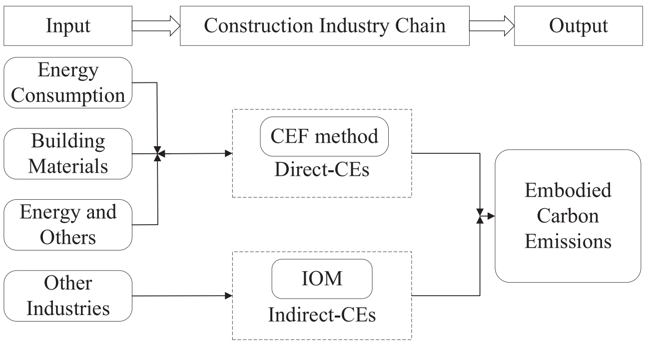

Fig. 4. Carbon emissions accounting.

where *EE* is energy CEs, unit: t; *AD* is activity data (usage of individual carbon emission sources) unit: ton, which is selected from the China Energy Statistical Yearbook (National Bureau of Statistics of China, 2021c); *SC* is the standard coal conversion factor, unit: tce/t.

The formula for calculating CEs from building materials is:

$$ME = AD \times CEF \times (1 + LR) \tag{2}$$

where *ME* is the carbon emission of building materials, unit: ton; *AD* is the activity data (the usage of individual carbon emission sources), unit: ton, which is selected from China Construction Statistical Yearbook (National Bureau of Statistics of China, 2021b); LR is the loss rate.

The formula for calculating direct-CEs is:

$$DC = EE + ME \tag{3}$$

where *DC* is direct-CEs, unit: ton; *EE* is energy CEs, unit: ton; *ME* is building material CEs, unit: ton.

3.2.2. Indirect carbon emissions

In this paper, indirect carbon emissions refer to the combined carbon emissions generated in the upstream and downstream industries with which they are associated. The input–output method is based on economic input–output tables and uses matrix modeling to quantify the correlation between industrial sectors in the economic system, and to measure the energy and carbon emissions required by the construction industry on a macro level. This method sets the direct carbon emission factors as diagonal matrices rather than simple row vectors. This allows not only to measure the embodied carbon emissions in the production process of the relevant industrial sectors caused by the final demand of the construction industry, but also to analyze the distribution of these embodied carbon emissions. This paper constructs input–output tables (Table 2) according to the seven regions of the country and then calculates the CE in the building stage. This table is divided into five matrix: *F*, *Y*, *X*, *V* and *X*'.

In addition, based on this table, the IOM formula is

$$TC = R \times B \times Y \tag{4}$$

Consumption factor matrix

$$A = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix}, a_{ij} = X_{ij}/X_j \tag{5}$$

A is the matrix of consumption factors, where X_{ij} are the elements in matrix *F*, *i* represents rows and *j* represents columns. The matrix *A* is obtained by computing the matrix *F* with the matrix *X*.

Complete demand coefficient matrix

$$B = (I - A)^{-1} = \begin{pmatrix} b_{11} & \cdots & b_{1n} \\ \vdots & \ddots & \vdots \\ b_{n1} & \cdots & b_{nn} \end{pmatrix} \tag{6}$$

Where *B* represents the complete demand coefficient matrix, *I* is the identity matrix, and *A* is the direct consumption coefficient matrix. After matrix calculation, the complete demand coefficient matrix is obtained.

Carbon emission intensity matrix of industrial sector

$$R = DC_i/X_i = \begin{pmatrix} r_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & r_n \end{pmatrix} \tag{7}$$

R is the Carbon emission intensity matrix. Where DC_i represents the direct-CEs of industry *i*, and the data source is the China Statistical Yearbook (National Bureau of Statistics of China, 2021a); X_i represents the total output of industry *i*.

④ Complete carbon emission coefficient matrix of industrial sector

$$TC = R \times B \times Y = (\,t_1 \quad \cdots \quad t_n\,)^T \tag{8}$$

The matrix *R* of each industry is multiplied by the matrix *B* and then right multiplied by the matrix *Y* to obtain the indirect-CEs of each industry.

3.3. Emergy assessment system

Emergy analysis is a new theory and method of system analysis created by H.T. Odum in the 1980 s. It converts all the different categories of energy, resources, products, and even services, which are not comparable items, into a uniform measure - the "solar emergy". Energies of different magnitudes need to be harmonized in units by means of *UEV* (Unit Emergy Value). *UEV* is defined as the amount of solar emergy per unit of energy or substance, usually in sej/J or sej/kg. It is a conversion factor used to determine the emergy of a service or product, which in this paper is determined from the data provided in the relevant literature

Table 2
Input-output table.

	Industry	Intermediate input x_{ij}				Final Requirements	Total output
		1	2	…	*n*		
Intermediate Inputs x_{ij}	1	*F*				*Y*	*X*
	2						
	…						
	n						
	Value Added	*V*					
	Total input	*X*'					

F: Flow matrix, represents the relationship among various industries, $(i \times i)$.
Y: Final demand, comprises components of GDP such as consumption investment, imports, exports, and government, $(i \times 1)$.
X: Total output value, $(i \times 1)$.
V: Value added, comprises wages and salaries, net profits, and indirect taxes and subsidies, $(1 \times i)$.
X': Total input value, $(1 \times i)$.

(Brown and Buranakarn (2003); Brown and Ulgiati (2002)). The basic formula is:

$$EM = EN \times UEV \tag{9}$$

EM refers to the solar emergy (sej) of an energy or substance; *EN* includes energy (j), substance (g) and value (yuan); *UEV* refers to the emergy conversion rate of an energy or substance, which reflects the difference between different emergy of energy.

3.3.1. Emergy ternary diagram

Giannetti et al. (2006) proposed a reference ternary diagram representation, which is an energy analysis method to study the relationship between the values of the various energy inputs to the system. The ternary diagram consists of an equilateral triangle. Each of its three vertices represents each different resource input to the system. Beginning in the 18th century, it has subsequently been widely used in the fields of geography, physical chemistry, and metallurgy. The ternary diagram can effectively evaluate the economic efficiency of an ecosystem, can visualize the resource allocation of the system, and can facilitate the full evaluation of the sustainability of the system. In this paper, the ternary diagram auxiliary lines are utilized to indicate the corresponding emergy indicators. It facilitates the effective analysis of resource allocation, economic efficiency and sustainability of the construction industry.

3.3.2. Drawing emergy flow system diagram

In this study, a detailed emergy system diagram (Fig. 5) is presented using H.T. Odum's (1989) "Energy System Language" legend. Fig. 5 displays the emergy flow system of the entire construction chain, encompassing both renewable resources including hydro, nuclear, wind, and solar energy, and non-renewable resources such as coke, natural gas, gasoline, coal oil, diesel, fuel oil, coal, and electricity. It also includes external inputs like glass, cement, steel, aluminum, and wood. Direct-CEs in the whole system are associated with the building stages, while indirect-CEs are linked to eight related industries. The entire construction chain generates input and output emergy from both non-renewable and renewable energy sources, as well as external inputs.

3.3.3. Emergy index system

By mapping the energy flows, this paper establishes three emergy indices to aid in the discussion of the building system, which can help in the sustainability analysis of the system: the Emergy Yield Ratio (*EYR*), the Environmental Load Ratio (*ELR*), and the Emergy Sustainability Index (*ESI*). Table 3 explains the specific criteria and parameters of the emergy indicators.

Relevant emergy indicators are calculated based on emergy accounting tables for each region. The meaning of the indicators and their calculation formulae are provided below.

Emergy yield rate (*EYR*):

$$EYR = (R + N + F)/F \tag{10}$$

where *R* is renewable resource, *N* is non-renewable resource, and *F* is input resource. *EYR* indicates the processing capacity to profit from local resources. When $EYR > 1$, it indicates high productivity and emergy efficiency. The system relies on the natural environment to generate benefits.

Environmental load rate (*ELR*):

$$ELR = (N + F)/R \tag{11}$$

ELR indicates the degree of pressure on the environment caused by renewable energy. When $ELR < 1$, it means that the system is under pressure on the environment. The economic system has a low effect on the natural system.

Emergy Sustainability Index (*ESI*):

$$ESI = EYR/ELR \tag{12}$$

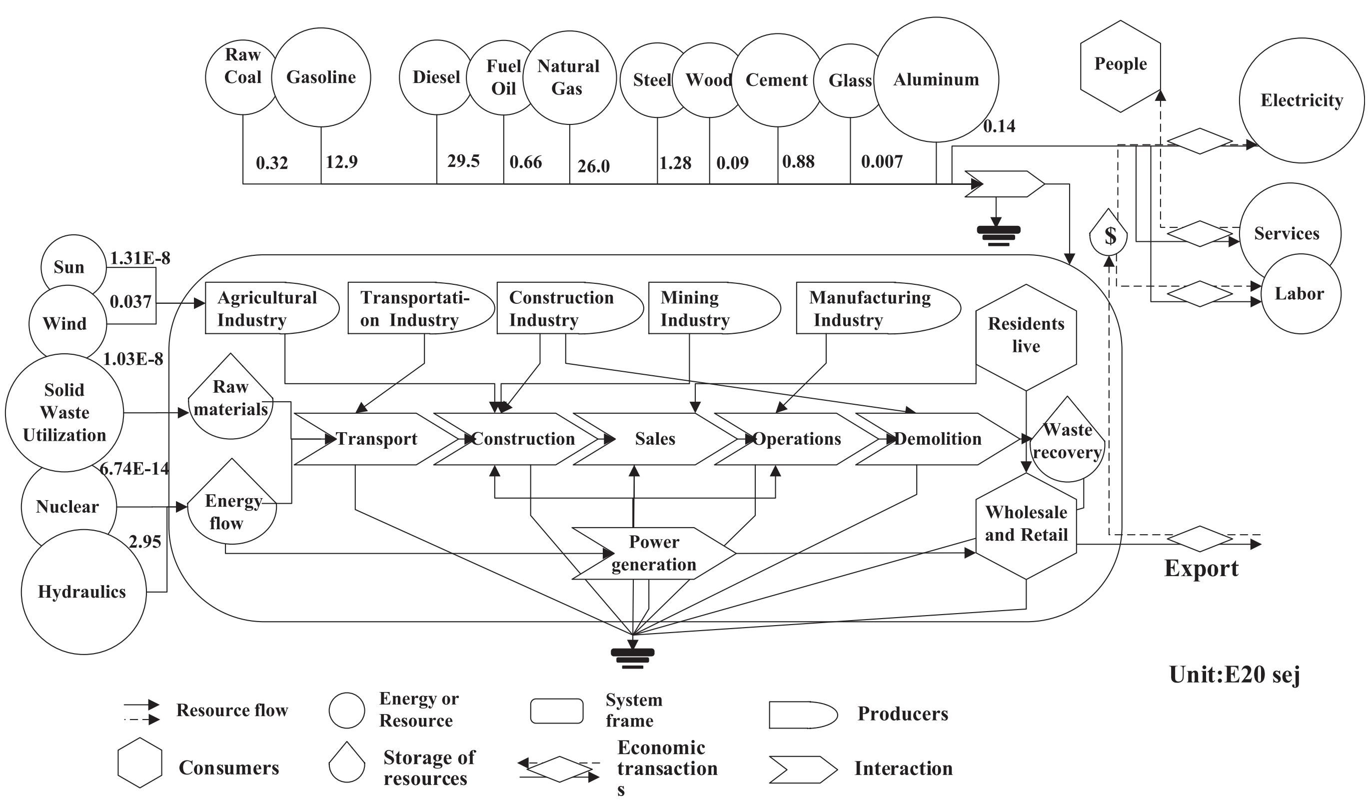

Fig. 5. Emergy flow system of the whole construction industry chain.

Table 3
Emergy indices used in this paper.

Name	Formula	Note	Source
Renewable Resources	*R*	Energy sources that can be constantly replenished or can be regenerated in a shorter period of time, including mainly solar and wind energy.	Based on data fromthe China Statistical Yearbook (2021) .
Local non-renewable resources	*N*	Energy sources that have been formed over billions of years and cannot be recovered in the short term, including mainly coal and oil.	Based on data from the China Statistical Yearbook (2021).
External input resources	*F*	The various types of additional resources invested in the system, which in this paper include mainly steel, lumber, etc.	Based on data from the China Construction Statistics Yearbook (2021).
Emergy yield rate	*EYR*	Ability to rely on local resources.	Based on the formula in Giannetti et al. (2006)
Environmental load rate	*ELR*	Loads on the environment and ecosystems.	Based on the formula in Giannetti et al. (2006)
Emergy Sustainability Index	*ESI*	Sustainable performance of the system.	Based on the formula in Giannetti et al. (2006)

ESI reflects the sustainability performance of the system. When one $< ESI < 10$, it indicates that the regional construction industry has good sustainability.

4. Results and discussion

4.1. Carbon emission accounting results

4.1.1. Direct carbon emissions

In this study, the CEF method is used to account for the seven regions of China in blocks according to formula (1)-(3). The Carbon Emission Factor method is currently more widely used and operational, and is convenient, straightforward and highly credible. This method has been recommended by the Intergovernmental Panel on Climate Change. However, the method requires carbon emission factor coefficients for various energy sources and materials. At present, China's database on this aspect is not sound enough, and the data collected from different sources may lead to some errors in the calculation results. In addition, the data statistics have greater difficulty. Only part of the building materials can be obtained from the macro industry statistics. According to the data of China Construction Statistical Yearbook, only steel, wood, cement, glass and aluminum are selected to accounting the carbon emission in construction material consumption. This will result in the calculation being smaller than the actual value. The calculation process for this section in this study is only listed for the North East (Table 4). The region (2020) has the largest contribution of diesel to CEs in energy consumption and steel to CEs in building materials.

As can be seen in Table 3, non-renewable energy sources account for 99.44 % of direct-CEs, while building materials account for only 0.56 %. Therefore, it is necessary to focus on the use of non-renewable energy sources to reduce direct-CEs. Among the types of carbon emission sources, coal oil, a non-renewable resource, makes the highest contribution to CEs (26.95 %). Steel among construction materials makes the highest contribution to CEs (66.84 %).

In Fig. 6, different colors are used to differentiate the distribution of CEs. Areas with low CEs are colored green and light green, areas with high CEs are colored red and light red, and areas with moderate CEs are colored orange and yellow, as shown in the legend. Table 5 provides a summary of direct-CEs for the seven regions in China. Among the sources of CEs, non-renewable energy accounts for 99.44 % of direct-CEs, while building materials account for only 0.56 %. Therefore, it is important to focus on the amount of non-renewable energy that can be used to reduce direct-CEs. Among the types of CE sources, coal oil is the largest contributor (26.95 %) among non-renewable resources. Among construction materials, steel makes the largest contribution (66.84 %). Fig. 6 shows the distribution of direct-CEs. The Southwest region is shown in green, indicating that direct-CEs in this region are low (1.78E+05 t) and have a low impact on the environment. The Northwest and Southern regions are shown in orange and yellow, indicating that direct-CEs from these regions are in the middle of the range (8.69E+06 t; 1.12E+06 t). It is important to take appropriate carbon reduction measures for these regions. The Central, Northern and Northeast regions show a light red color, indicating that direct-CEs are higher in these regions (3.64E+07 t; 1.09E+07 t; 1.68E+07 t). These regions should remain vigilant to prevent the continued growth of direct-CEs.

Among the sources of CEs, the highest non-renewable energy CEs were 3.63E+07 t in the Central region and 1.88E+05 t in the Eastern region, while the lowest non-renewable energy CEs were 1.12E+05 t in the Southwest region and 1.16E+04 t in the Northeast region. The sources of direct carbon emissions from the construction industry are concentrated in the central and eastern developed regions, while the contribution from the underdeveloped regions in the west is less. Among the types of non-renewable resource emission sources, the highest share by region is for Coal oil in the Northeast, Southern and Northwest; Diesel in the Northern, Central and Southwest; Natural gas in the Eastern. Unequal resource inputs in different regions can lead to disparities in direct carbon emissions. Steel in construction materials contributes the highest value to CEs. It is known that steel is the main material consumed in the construction industry.

4.1.2. Indirect carbon emissions

In this study, the matrix calculation is based on formula (4) - (8), using the IOM. The input–output method can measure the indirect carbon emissions of other industries linked to the construction industry in the production process, which improves the reliability and completeness of the life cycle inventory. However, the frequency of updating data in China's input–output table is slow and lacks continuity. The data is not updated in a timely manner, which affects the implementation of carbon reduction strategies. In addition, the input–output method utilizes the carbon emission intensity per unit of output value, which converts the economic data of each sector into carbon emission data. There are some differences between the conversion process and the actual situation timely, which will have some impact on the results. Here is an example of the calculation process for the Northeast only.

① Consumption factor matrix $A_{Northeast}$.

The consumption coefficient matrix is obtained by dividing the first quadrant element X_{ij} of the input–output matrix by the total inputs X_j in the corresponding column.

0.1639	0.0004	0.0849	0.0040	0.0076	0.0150	0.0186	0.0068
0.0007	0.0250	0.0195	0.1024	0.0171	0.0003	0.0000	0.0003
0.1184	0.0514	0.2407	0.0459	0.2454	0.1190	0.0543	0.0473
0.0046	0.0460	0.0164	0.1529	0.0108	0.0285	0.0183	0.0122
0.0009	0.0006	0.0004	0.0024	0.0121	0.0030	0.0025	0.0033
0.0092	0.0090	0.0131	0.0200	0.0424	0.0571	0.0260	0.0120
0.0205	0.0179	0.0441	0.0186	0.0540	0.0187	0.0322	0.0331
0.0136	0.0376	0.0285	0.0617	0.0706	0.1003	0.1235	

Table 4
Calculation of Direct-CEs in the Northeast.

		Consumption	Unit	CEF	Standard coal conversion factor	Unit	Direct-CEs (ton)
Energy Consumption	Raw Coal	1.63E+04	ton	0.725	0.686	tce/t	2.98E+04
	Gasoline	1.71E+05	ton	0.554	1.471	tce/t	5.12E+05
	Diesel	4.07E+05	ton	0.592	1.457	tce/t	1.29E+06
	Fuel Oil	9.70E+03	ton	0.619	1.429	tce/t	3.15E+04
	Natural Gas	5.30E+07	m^3	0.427	1.143E-044	tce/m^3	9.49E+03
	Electricity	3.26E+09	kWh	0.275	1.229E-044	tce/kWh	4.05E+05
Building Materials	Steel	3.09E+07	ton	2.67	—	tce/t	8.73E+07
	Wood	2.07E+07	ton	0.31	—	tce/t	6.80E+06
	Cement	4.42E+07	ton	0.07	—	tce/t	3.14E+06
	Glass	8.71E+04	Weight boxes	1.4	—	tce/t	1.26E+05
	Aluminum	1.13E+06	ton	15.8	—	tce/t	1.89E+07
Total							1.19E+08

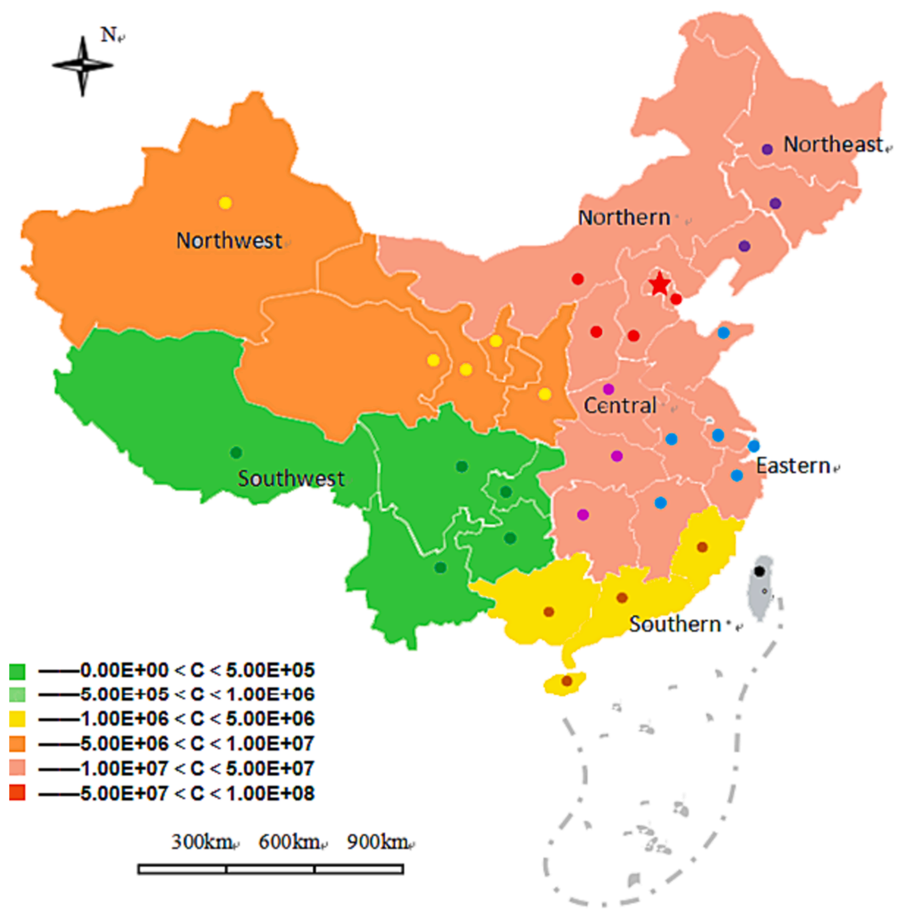

Fig. 6. Direct-CEs distribution map.

Table 5
Table of direct-CEs Unit: ton.

	Category	Northeast	Northern	Eastern	Central	Southern	Southwest	Northwest
Non-renewable energy CEs	Raw Coal	2.11E+06	2.97E+06	2.65E+04	6.48E+06	2.47E+05	1.45E+04	1.29E+06
	Gasoline	5.12E+05	2.98E+04	0.00E+00	1.29E+06	3.15E+04	9.49E+03	4.05E+05
	Kerosene	4.88E+06	6.61E+05	1.39E+04	1.02E+07	5.05E+05	2.04E+04	3.77E+06
	Diesel	4.20E+06	5.38E+06	8.01E+04	7.03E+06	7.86E+04	2.87E+04	8.57E+05
	Fuel Oil	1.70E+06	7.10E+04	8.63E+03	1.75E+06	5.42E+04	8.24E+03	1.12E+06
	Natural Gas	2.36E+06	9.23E+05	1.96E+05	6.66E+06	1.09E+05	9.14E+03	5.26E+05
	Power	1.06E+06	8.72E+05	7.71E+03	2.98E+06	6.91E+04	2.13E+04	7.03E+05
Building materials CEs	Steel	8.73E+03	2.24E+04	1.23E+05	4.76E+04	1.88E+04	4.38E+04	1.61E+04
	Wood	6.80E+02	1.14E+03	7.01E+03	3.82E+03	1.33E+03	3.06E+03	6.86E+02
	Cement	3.14E+02	1.09E+03	7.91E+03	2.64E+03	1.10E+03	2.52E+03	9.10E+02
	Glass	1.26E+01	3.61E+01	9.02E+02	1.76E+02	1.04E+02	9.47E+01	1.97E+01
	Aluminum	1.89E+03	3.73E+03	4.94E+04	1.87E+04	9.55E+03	1.69E+04	3.17E+03
Direct-CEs	1.68E+07	1.09E+07	5.21E+05	3.64E+07	1.12E+06	1.78E+05	8.69E+06	

Table 6
Carbon Emission Intensity in Northeast China.

	Industry	R
(1)	Agriculture, forestry and fishery products and services industry	0.088
(2)	Mining industry	1.101
(3)	Manufacturing and repair industry	1.624
(4)	Electricity, heat, gas and water production and supply industry	8.418
(5)	Construction industry	0.107
(6)	Transportation, storage and postal industry	0.932
(7)	Wholesale and retail trade, accommodation and catering industry	0.068
(8)	Real estate industry	0.166

② Complete demand factor matrix $B_{Northeast}$.

The unit matrix I is subtracted from the consumption factor matrix A, and then inverse matrixed to finally obtain the full demand factor matrix B.

1.2177	0.0106	0.1404	0.0180	0.0497	0.0406	0.0354	0.0201
0.0062	1.0336	0.0306	0.1274	0.0279	0.0088	0.0051	0.0044
0.1989	0.0833	1.3560	0.0985	0.3606	0.1896	0.0989	0.0868
0.0127	0.0597	0.0319	1.1928	0.0270	0.0432	0.0285	0.0209
0.0015	0.0011	0.0012	0.0036	1.0133	0.0040	0.0034	0.0043
0.0165	0.0139	0.0239	0.0305	0.0556	1.0676	0.0334	0.0186
0.0368	0.0266	0.0687	0.0345	0.0802	0.0362	1.0456	0.0464
0.0349	0.0589	0.0646	0.1052	0.1190	0.1428	0.1631	

③ Carbon emission intensity of the production sector $R_{Northeast}$.

The carbon emission intensity of each industry R is obtained by dividing the direct carbon emissions DC_i of each industry by the total output X_i of each industry, as detailed in Table 6 below.

④Complete Carbon Emission Factor Matrix $TC_{Northeast}$.

The carbon emission intensity R of each industry is multiplied by the complete demand factor matrix B, and then right is multiplied by the final demand column matrix Y to obtain the complete carbon emission factor matrix TC. Collating the indirect-CEs calculations for the building stage shows that the indirect-CEs of the construction industry in Northeast China is 1.66E+07 t, as detailed in Table 7 below.

The indirect-CEs of each region are summarized in Table 8, and the distribution of indirect-CEs is shown in Fig. 7. The Central region is shown in red, indicating that the highest indirect-CEs in this region are 6.91E+07 t. Therefore, the direct-CEs in this region should be effectively controlled. The Northwest region is shown in green, indicating that the lowest indirect-CEs are 1.28E+05 t. Therefore, CEs from this region have a small environmental impact. The Northern, Northeast and Southwest regions show a light red color, indicating that these regions have higher direct-CEs of 3.09E+07 t, 1.66E+07 t and 1.98E+07 t respectively. Continued growth in indirect-CEs should be avoid in these regions. The Eastern and Southern regions are shown in yellow, indicating that the indirect-CEs from these regions are in the middle of the range, at 1.65E+06 t;2.66E+06 t respectively. Appropriate carbon reduction measures should be taken for these regions. In the indirect carbon emissions of related professions caused around the production of buildings, the central developed regions contribute a great deal, while the western underdeveloped regions cause less indirect carbon emissions in the production of buildings. Therefore, promoting the implementation of carbon emission reduction technology development in developed regions is the focus of energy conservation and emission reduction in the future.

Table 7
Table of indirect-CEs in the Northeast Unit: ton.

	Industry	indirect-CEs
(1)	Agriculture, forestry and fishery products and services industry	5.25E+06
(2)	Mining industry	1.45E+07
(3)	Manufacturing and repair industry	4.62E+08
(4)	Electricity, heat, gas and water production and supply industry	1.83E+08
(5)	Construction industry	1.66E+07
(6)	Transportation, storage and postal industry	2.93E+07
(7)	Wholesale and retail trade, accommodation and catering industry	5.29E+06
(8)	Real estate industry	4.13E+07

4.1.3. Embodied carbon emissions

Table 9 presents the embodied carbon emissions by regions in China, while Fig. 8 illustrates the distribution of these emissions. The results show that indirect-CEs account for 65.15 % of the embodied carbon emissions, while direct-CEs account for 34.85 %. As a result, indirect carbon emissions from related industries arising from construction production are higher than direct carbon emissions from energy consumption. It is noteworthy that in underdeveloped regions, such as Northeast and Northwest, direct-CEs are higher than indirect-CEs; while in developed regions, such as Central, Eastern, and Southern, indirect-CEs are higher than direct-CEs. The Central region stands out with the highest embodied carbon emissions of 1.06E+08 t, as indicated by the red color in the figure. Therefore, the carbon emissions caused by energy consumption and related industries in the central developed regions should be given priority attention. On the other hand, the Eastern region has the lowest embodied carbon emissions of 2.17E+06 t. The Northern, Northeast, and Southwest regions are shown in light red, indicating higher embodied carbon emissions of 4.19E+07 t, 3.35E+07 t, and 1.98E+07 t, respectively. In order to prevent the growth of embodied carbon emissions in these areas, appropriate measures should be taken to reduce non-renewable resources and to reduce carbon emissions from related industries caused by building production. Finally, the Eastern and Southern regions, depicted in yellow, have low levels of indirect-CEs at 2.66E+06 t and 2.17E+06 t, respectively. These regions should implement measures to reduce carbon emissions from industries related to the production of buildings.

4.2. Emergy analysis

4.2.1. Calculation of emergy index

In this study, the UEV of each resource is utilized to calculate the emergy of local renewable, non-renewable, and external input resources, as demonstrated in Table 10. For illustrative purposes, only the Northeast region is used as an example.

Table 11 presents the emergy evaluation indicators for the construction industry computed using equations (9)-(11).

4.2.2. Resources line analysis

The resources line in Fig. 9, which corresponds to R, N, and F, is a solid line parallel to the bottom edge. It enables a comparison of the structure of resource utilization by the product or process. EYR and EIR correspond to the resource line F, while ELR corresponds to the resource line R. The resource line F reveals that all seven regions move towards the lower right slope of the ternary diagram, close to the apex of the non-renewable resource N. This implies that the regions consume more primary energy and building materials, leading to the release of greenhouse gases and pollutants that increase pressure on the natural environment and cause damage. The proportion of non-renewable resources N in each province is $N_{Eastern} > N_{Central} > N_{Northern} > N_{Southwest} > N_{Southern} > N_{Northeast} > N_{Northwest}$. The Eastern region has the highest quantity of non-renewable resource inputs compared to other regions.

By examining the resource line R, it is clear that the points in all seven regions are far from the top of R. The corresponding ELR for each region are as follows: $ELR_{Central} = 109.43 > ELR_{Southern} > ELR_{Southwest} > ELR_{Eastern} > ELR_{Northern} > ELR_{Northeast} > ELR_{Northwest} = 12.31$. The fact that the ELR is greater than 10 for all regions indicates that the system is exerting more pressure on the environment and utilizing more non-renewable energy. Increasing the use of renewable energy should be considered in order to reduce the environmental impact and embodied carbon emissions of buildings. The environmental load is the highest in

Table 8
Table Indirect-CEs Unit: ton.

	Northeast	Northern	Eastern	Central	Southern	Southwest	Northwest
Industry (1)	5.25E+06	2.64E+07	7.61E+07	1.15E+07	8.22E+06	1.29E+07	5.13E+06
Industry (2)	1.45E+07	1.89E+08	1.67E+08	3.88E+07	7.88E+06	3.32E+07	3.36E+07
Industry (3)	4.62E+08	2.67E+09	1.32E+10	1.26E+09	8.33E+08	5.78E+08	2.94E+08
Industry (4)	1.83E+08	7.37E+08	3.70E+09	3.77E+08	3.46E+08	2.95E+08	3.05E+08
Industry (5)	1.66E+07	3.09E+07	1.65E+06	6.91E+07	1.53E+06	1.96E+07	1.28E+05
Industry (6)	2.93E+07	1.65E+08	1.19E+09	7.06E+07	1.35E+08	7.24E+07	2.73E+07
Industry (7)	5.29E+06	1.71E+07	1.27E+08	9.48E+06	1.17E+07	1.07E+07	5.34E+06
Industry (8)	4.13E+07	1.85E+08	1.13E+09	7.81E+07	1.34E+08	8.32E+07	4.73E+07

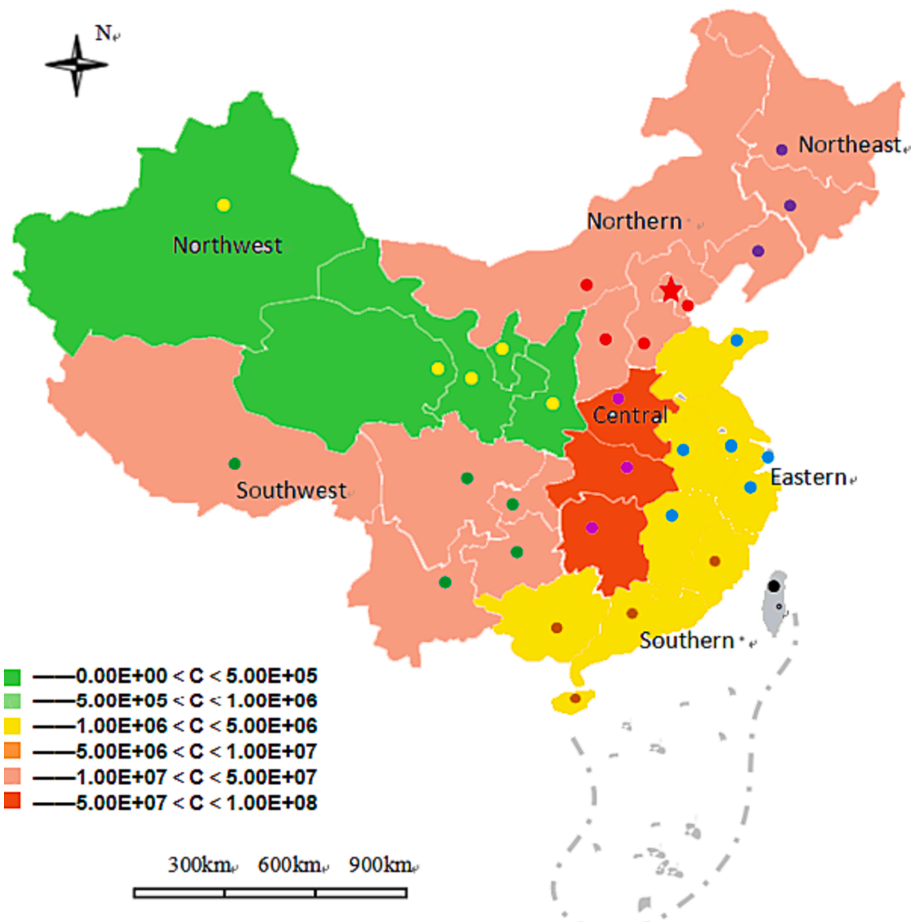

Fig. 7. Indirect-CEs distribution map.

Table 9
Table of embodied carbon emissions Unit: ton.

	Direct-CEs	Indirect-CEs	Embodied carbon emissions
Northeast	1.68E+07	1.66E+07	3.35E+07
Northern	1.09E+07	3.09E+07	4.19E+07
Eastern	5.21E+05	1.65E+06	2.17E+06
Central	3.64E+07	6.91E+07	1.06E+08
Southern	1.12E+06	1.53E+06	2.66E+06
Southwest	1.78E+05	1.96E+07	1.98E+07
Northwest	8.69E+06	1.28E+05	8.82E+06
Total	7.47E+07	1.40E+08	2.14E+08

the Central region and the lowest in the Northwest. The resource input for embodied carbon emissions from the construction industry mainly comes from *N*. The trend in *EYR* for each region is as follows: $EYR_{Northern} = 49.96 > EYR_{Northeast} > EYR_{Central} > EYR_{Southern} > EYR_{Southwest} > EYR_{Eastern} > EYR_{Northwest} = 10.39$. The results reveal that *EYR* is greater than one in all regions, indicating that the system is highly productive and energy-efficient. The northern region has the highest *EYR*, whereas the northwest region has the lowest *EYR*. The point in the northwest region of the figure is furthest from vertex *N*, indicating that this region has the least amount of non-renewable energy and the lowest environmental load. The points in the other regions are all near the vertex *N*, indicating that these regions have more non-renewable energy and higher environmental loads. It is evident that the embodied carbon emissions from the construction industry have caused significant environmental damage. Furthermore, the protection of the ecological environment needs to be prioritized, and reducing non-renewable energy use and environmental loads are focused on, particularly in the Central region.

4.2.3. Sensitive line analysis

The sensitivity line, as shown in Fig. 10, connects a point to a vertex. This line indicates that the share of resources corresponding to that vertex changes along the line, while the share of inputs of the other two types of resources remains constant. The line connecting vertex *N* to point 2 also passes through point 1. Any point on this line represents a

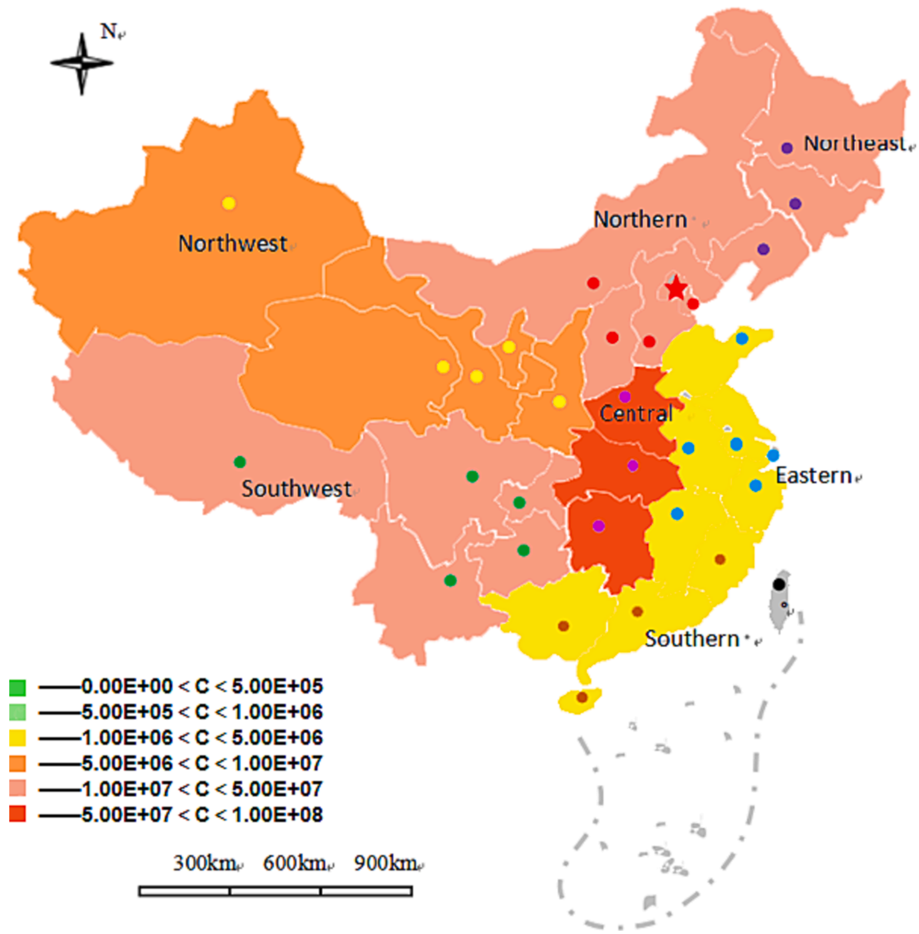

Fig. 8. Map of embodied carbon ratio.

Table 10
Table of emergy accounting.

Category	Projects	Unit	Raw data	UEV	Emergy
Local Renewable Resources (R)	Solar	kWh	1.43E+08	2.55E+05	1.31E+12
	Hydraulics	kWh	1.87E+08	1.00E+00	6.74E+06
	Wind power	kWh	4.77E+08	2.18E+11	3.74E+18
	Nuclear emergy	kWh	3.36E+08	8.49E+04	1.03E+12
	Solid Waste Utilization	kWh	1.71E+12	1.73E+06	2.95E+20
Local non-renewable resources (N)	Raw Coal	ton	1.63E+07	1.97E+12	3.21E+19
	Gasoline	ton	1.71E+08	7.55E+12	1.29E+21
	Kerosene	ton	0.00E+00	7.40E+12	0.00E+00
	Diesel	ton	4.06E+08	7.26E+12	2.95E+21
	Fuel Oil	ton	9.69E+06	6.84E+12	6.63E+19
	Natural Gas	m^3	3.81E+04	7.80E+12	2.97E+17
	Power	kWh	3.27E+09	7.96E+11	2.60E+21
External input resources (F)	Steel	ton	3.08E+10	4.15E+09	1.28E+20
	Wood	m^3	1.03E+10	8.79E+08	9.09E+18
	Cement	ton	4.42E+10	1.98E+09	8.75E+19
	Glass	Weight boxes	8.72E+07	7.87E+09	6.86E+17
	Aluminum	ton	1.13E+09	1.27E+10	1.43E+19
Total					2.40E+20

process. As it moves from point 2 to point 1, the amount of non-renewable resources gradually decreases. Therefore, the sustainability of point 2 can be improved by changing the amount of non-renewable resources and maintaining the ratio between economic investment and the amount of renewable resources. Similarly, the lines connecting the *R* vertex and *F* vertex to the points show that the fact should also be paid to that adjusting the share of use of renewable resources and construction materials can improve their sustainability. The sensitivity lines show decision makers the way to achieve economic and environmental goals.

4.2.4. Sustainability line analysis

A sustainability line is a line that can represent a sustainability index (Fig. 11). It starts from point *N* and moves in the direction of *R* and *F*, dividing the triangle into sustainability regions. The closer the point to *R* in the phase diagram, as represents the greater its sustainability index. It helps to delineate the various regions of the system development sustainability in the ternary diagram. An *ESI* value of <1 suggests that the system cannot sustain long-term sustainability. From the figure, it is evident that the *ESI* in the Northern and Northeast regions falls within

Table 11
Emergy evaluation indicators.

Indicators	*N* (sej)	*R*(sej)	*F*(sej)	*ELR*	*EYR*	*ESI*
Northeast	6.94E+21	2.99E+20	2.40E+20	24.04	31.22	1.30
Northern	3.22E+22	8.80E+20	6.77E+20	37.41	49.96	1.34
Eastern	6.16E+22	1.02E+21	4.52E+21	64.96	14.86	0.23
Central	3.84E+22	3.66E+20	1.64E+21	109.43	24.67	0.23
Southern	1.57E+22	1.85E+20	6.79E+20	88.43	24.34	0.28
Southwest	2.63E+22	4.10E+20	1.52E+21	67.81	18.61	0.27
Northwest	4.51E+21	4.09E+20	5.24E+20	12.31	10.39	0.84

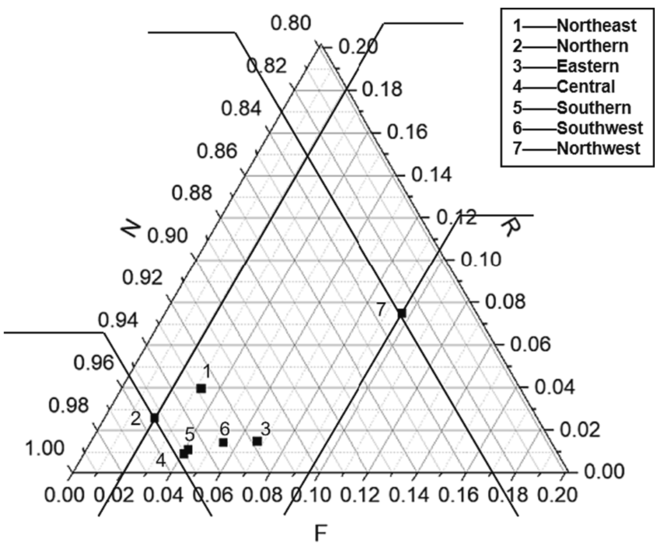

Fig. 9. Resources Line.

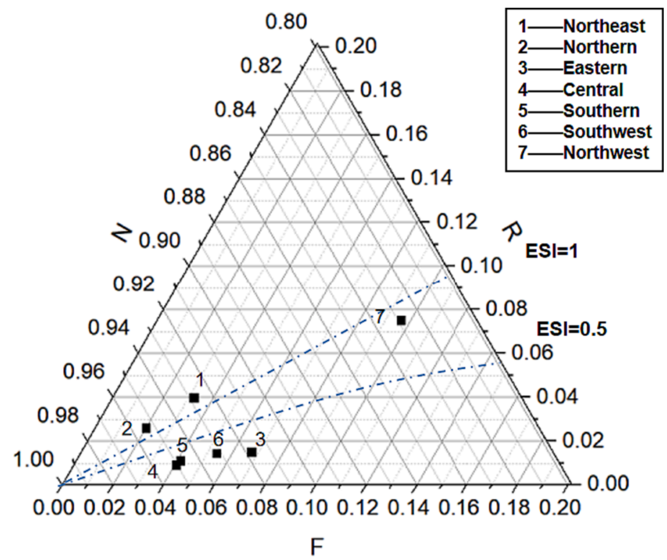

Fig. 11. Sustainability Line.

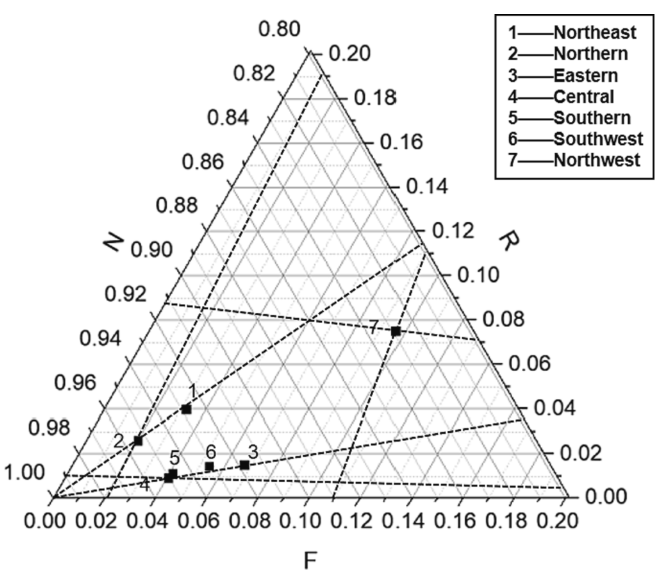

Fig. 10. Sensitive lines.

the range of (1, 10), indicating better building sustainability in these regions. On the contrary, the Eastern, Central, Southern, Southwest, and Northwest regions have an *ESI* outside this range, indicating low construction sustainability in these regions. All of these regions are reliant on external resource inputs, which puts increasing pressure on the natural resources of the region, reducing their sustainability.

5. Conclusion and policy implications

The following conclusions are drawn: Based on the carbon emission analysis perspective, the direct carbon emission sources have the highest share of non-renewable energy, with Coal oil accounting for the highest share. Indirect-CEs account for about 60 % of the embodied carbon emissions. It is clear that indirect-CEs account for a large proportion of the embodied carbon emissions. The central region is the main embodied carbon emission area. Based on the perspective of emergy analysis, the *ELR* of the national construction building stage are all greater than 10. It indicates that the system is putting more pressure on the environment and non-renewable energy sources are being used more. The central region has the highest environmental load and should be the focus area. The *EYR* for the construction building stage are all-greater than one. The Northern region has the highest *EYR*, which indicates that the system is more productive and energy efficient. The Eastern, Central, Southern, Southwest and Northwest regions have a lower potential for building sustainability. In the context of different regional development and economic activities, the construction rate is consistent with the level of economic development. The construction rate of China's construction industry has disparities due to regional differences, showing a gradually decreasing pattern from the central to the western part of the country. Combining the economic activity data and outcome data of each region for relevant analysis, it can be seen that the construction rate and embodied carbon emissions are higher in the central developed region, and the environmental load of this region is higher, and the sustainability of the construction is lower; in the western underdeveloped region, the construction rate and embodied carbon emissions are lower, and the environmental load of this region is lower.

Therefore, the economic activities of the regions have a relationship with the findings of this paper. The higher the construction rate are, the higher the embodied carbon emissions are, meanwhile, the higher the environmental load are, and the lower the building sustainability are.

The model developed in this study is valuable for analyzing the entire construction industry chain in China and holds relevance for shaping the carbon emission reduction strategy in construction. Drawing from the study's insights, several policy implications emerge. Firstly, the promotion of renewable energy sources, such as solar or wind power, during construction processes can significantly diminish embodied carbon emissions. Secondly, a targeted reduction in the consumption of diesel and gasoline resources, especially in regions with identified high environmental loads like the central area, should be a governmental focus. Thirdly, enhancing sustainability in regions with lower potential for building sustainability (Eastern, Central, Southern, Southwest, and Northwest) can be achieved through policies promoting the use of sustainable materials and energy-efficient building practices. By implementing these strategies, the Chinese government can effectively curtail embodied carbon emissions in the construction sector, encourage the adoption of renewable energy, and elevate overall industry sustainability. This aligns with existing efforts in China's building planning, as outlined in the 14th Five-Year Plan for Building Energy Efficiency and Green Building Development, which emphasizes targets like an 8 % replacement rate of renewable energy in urban buildings by 2025 and exceeding 55 % in electricity consumption for building energy.

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CRediT authorship contribution statement

Yu Zhao: Methodology, Writing – original draft. **Yanan Xu:** Data curation. **Miao Yu:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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