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Comparison of Carbon Emissions in the Whole Life Cycle of Buildings of Different Structural Types

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Abstract. From the strategic consideration of sustainable development, it is the general trend to develop new building systems in the 21st century to select ecological environment building materials that consume as little resources as possible, have little impact on the ecological environment, and have high recycling rates. Relying on the life cycle evaluation (LCA) theory, the total life cycle of carbon accounting model is established in this paper. Moreover, to explore methods of reducing carbon emissions in buildings and the selection of suitable structure types and structural materials, this paper focuses on two different structure types: heavy structure (steel structure, reinforced concrete structure) and light structure (wood structure, light steel structure). Starting with the corresponding structural materials, quantitative measurement and comparative analysis of the whole life cycle's carbon emissions are carried out. The results of the research show that in terms of carbon emissions per unit building area per year, light structure < heavy structure; wood structure < light steel structure < steel structure < reinforced concrete structure.

Keywords. Whole life cycle of buildings, carbon emissions, structure types, structural materials

1. Introduction

At present, the resources used by China's construction industry makes up 40%-50% of the national resource utilization, and the energy consumed makes up about 30% of all the energy consumption of the whole society [1]. Greenhouse gas emissions are calculated only according to the terminal energy consumption. At this phase, the annual greenhouse gas emissions from existing buildings in China account for about 28% of the total social emissions [2]. The study on the implied carbon emissions of energy consumption in 27 industrial sectors shows that the implied carbon emissions of the construction industry are the largest. In 2002, the implied carbon emissions of the construction industry accounted for 26.47% of the implied carbon emissions of all sectors [3]. However, there is no specific data on how much greenhouse gases are emitted per unit building area per year by buildings with different structures.

This paper uses LCA (life cycle evaluation) theory. It establishes the evaluation

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mode of carbon emission in buildings' life cycle, and calculates the carbon emission of heavy structure (steel structure, reinforced concrete structure) and light structure (wood structure, light steel structure) building life cycle. The aim is to objectively identify the carbon emission of buildings and provide reference for the construction industry to set emission reduction indicators.

2. Carbon Emissions of Buildings' All Life Cycle

2.1. Life Cycle Evaluation's Theory Frame

In 1990, Society of Environmental Toxicology and Chemistry (SETAC) first systematically put forward the concept of full life cycle evaluation, which is defined as the process of environmental load evaluation by quantifying and identifying the material and energy utilization of products, production processes and activities and the environmental emissions caused. The whole life cycle is the mining, processing, transportation, use, reuse, maintenance, recycling and final treatment of raw materials [4]. There are four parts in the basic structures of SETAC: impact evaluation, improvement evaluation, inventory analysis, and target scope determination.

2.2. Life Cycle Evaluation Steps and Methods

Life cycle evaluation includes three steps: (1) Determining goals and scope: This step includes compiling and evaluating the input, output and potential environmental impact of a product system in the life cycle, characterizing the impact of the system and process on the environment and its degree. (2) Checklist analysis: In this paper, the process-based checklist analysis is adopted. Based on the process analysis, the research system is divided into a series of processes or activities within its boundary. Through the input and output analysis of the unit process or activity, the corresponding List of inputs and outputs of the system expressed in functional units. (3) Impact evaluation: It's the most critical step in life cycle evaluation, and this phase is called life cycle impact evaluation [5].

3. Carbon Emission Evaluation of Building Life Cycle

3.1. Accounting System Boundary

A building's carbon emission in its life cycle refers to the total amount of CO_2 emitted to the external environment due to the consumption of energy and resources. Within the boundary of the building's life cycle system, it shall contain a collection of a series of intermediate products and unit process flows forming the building entity and function, including the production of building materials and the processing, transportation, construction and installation of components and parts, the operation and maintenance of buildings during their service life, recycling, demolishing and disposal [6].

3.2. List Analysis

Collect basic data in phases and perform relevant calculations to obtain the total input and output of this phase as the basis for evaluation. This is the main task of analyzing the building's carbon emission list in all the life cycle [7].

3.3. Evaluation Function Unit

In order to make the evaluation results consistent and comparable [8], the annual carbon emission per square meter of building area is used as the evaluation index. This can effectively eliminate the impact of different building scale and design life. Therefore, the functional unit of carbon emission accounting for a building's total life cycle is the annual carbon emission per unit building area. The unit of measurement is $kg\cdot m^{-2}\cdot yr^{-1}$ (equation (1)).

$$BCE=(Eman+eu+d)/\ (S\cdot T) \tag{1}$$

where, BCE is the carbon emission evaluation value of building life cycle; E_{man} refers to carbon emission in physicochemical phase; E_{man} is the weighted value of carbon emission in the operation, use, demolition and recovery phase (there is a long-time delay in this phase, so weighting is considered); S is the total building area; T is the service life of the building [9-10].

4. Analysis and Comparison of Building Carbon Emission of Different Structure Types and Structural Materials

4.1. Data Source and Carbon Emission Accounting

This paper selects four low-rise residential buildings with similar architectural design, including heavy structure (steel structure, reinforced concrete structure) and light structure (wood structure and light steel structure), with a construction period of 1a and a service life of 50a. Through the quantitative accounting of the building's carbon emissions in each phase of the life cycle, the structure types and structural materials are compared and analyzed from the two perspectives of the percentage of carbon emissions in every phase of the life cycle and the percentage of carbon emissions in every phase of the annual unit building area (50-year service life) (Tables 1-2 and Figures 1-4).

Table 1. Percentage of buildings' carbon emission in all the life cycle with four different material structure types.

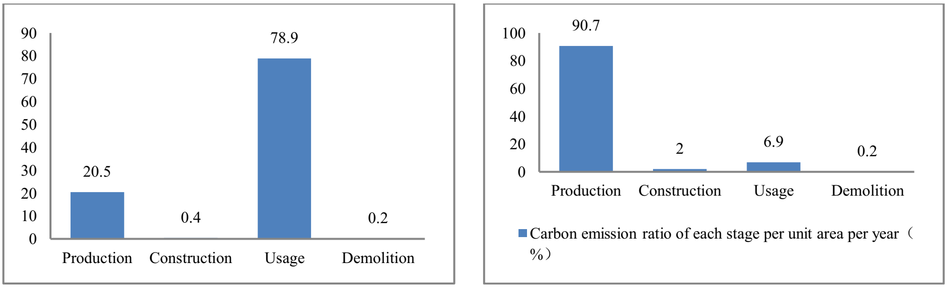
Structure type		Carbon emission ratio of each phase (%)			
		Production phase (%)	constructing phase (%)	Usage phase (%)	Demolition phase (%)
Heavy structure	Steel structure	20.5	0.4	78.9	0.2
	Reinforced concrete structure	16	3.1	73.4	7
Light structure	Wood structure	3.3	0.7	95.86	0.04
	Light steel structure	5.1	0.8	94	0.04

Table 2. Percentage of buildings' carbon emission per unit building area per year in each phase with four different material structure types (50-year service life).

Structure type		**Carbon emission ratio of each phase (%)**				**Annual carbon emission per unit building area ($kg \cdot m^{-2} \cdot yr^{-1}$)**
		Production phase (%)	constructing phase (%)	Usage phase (%)	Demolition phase (%)	
Heavy structure	Steel structure	90.7	2	6.9	0.2	75.62
	Reinforced concrete structure	58	11.3	5	25.3	82.52
Light structure	Wood structure	55.5	11.8	31.9	0.6	63.57
	Light steel structure	65	10.4	23.9	0.5	71.33

(1) Heavy structure

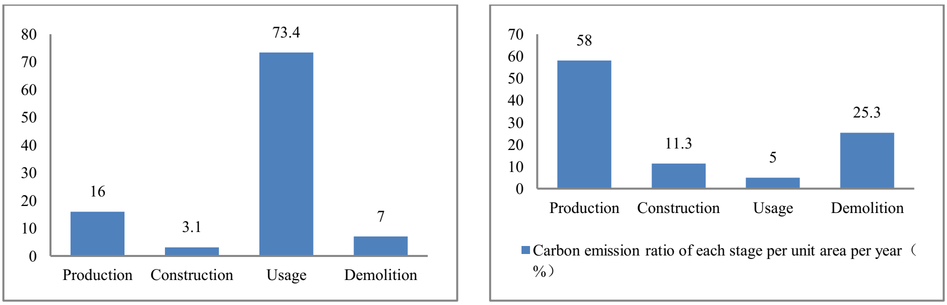
(a) Steel structure (Figure 1)



(a) (b)

Figure 1. (a) Percentage of carbon emission in each phase of steel structure; (b) Percentage of carbon emission per unit area of steel structure in each phase every year.

(b) Reinforced concrete structure (Figure 2)



(a) (b)

Figure 2. (a) Percentage of carbon emission in each phase of reinforced concrete structure; (b) Percentage of carbon emission of reinforced concrete structure in each phase per unit area every year.

(2) Light structure

(a) Wood structure (Figure 3)

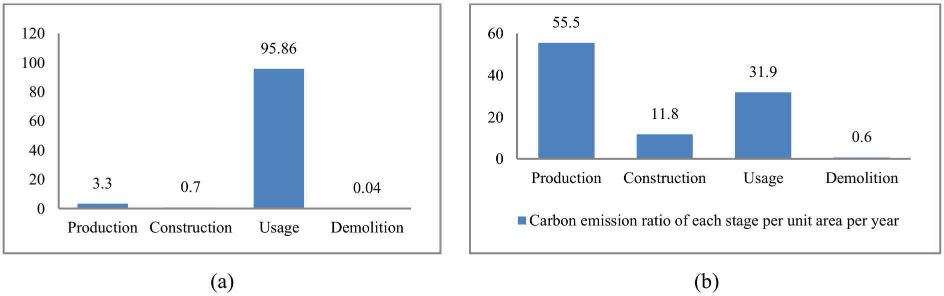


Figure 3. (a) Percentage of carbon emission in each phase of wood structure; (b) Percentage of carbon emission per unit area of wood structure in each phase every year.

(b) Light steel structure (Figure 4)

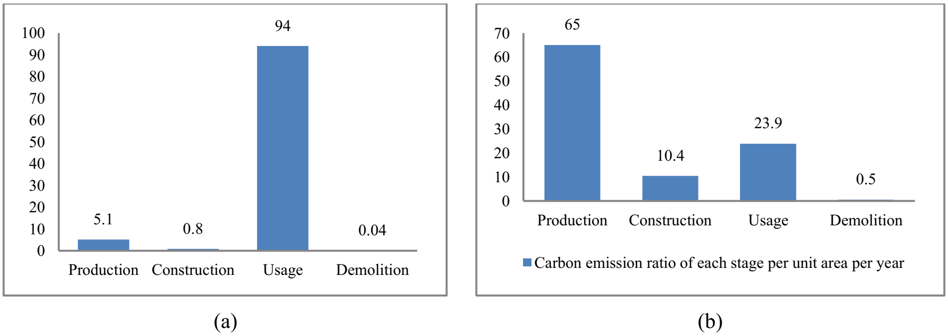


Figure 4. (a) Percentage of carbon emission in each phase of light steel structure; (b) Percentage of carbon emission of light steel structure in each phase per unit area every year.

4.2. Analysis and Discussion

It can be found from the chart on the left:

Comparison of all structure types:

(1) The percentage of carbon emissions in every phase of buildings' all whole life cycle is roughly as follows: building materials production phase (5%-20%), building constructing phase (0.4%-4%), building using phase (75%-95%), building demolishing phase (0.05%-5%), from large to small: building using phase, building material producing phase, building constructing phase and building demolishing phase;

(2) The percentage of carbon emissions in buildings' use phase is the highest, up to 70% or more, of which the carbon emissions of light structures exceed 90%;

(3) Regardless of heavy structure or light structure, the carbon emissions in the building material producing phase are higher than those in the constructing and demolishing phases;

(4) Regardless of heavy structure or light structure, the percentage of the sum of building using phase and building material producing phase is 90% or more;

From the above analysis, it can be seen that the building using phase is the main phase of building carbon emission and the key phase of carbon reduction. We should reduce carbon emissions in the use phase. Only in this way can the carbon emissions of the building be reduced as a whole.

Comparison between heavy structure and light structure:

(5) For heavy structure, the percentage of carbon emissions in every phase of all the life cycle of buildings is roughly as follows: building material producing phase (18%), building constructing phase (3%), building using phase (75%), building demolishing phase (4%); from large to small: building using phase, building material producing phase, building demolishing phase and building constructing phase;

(6) For light structure, the percentage of carbon emission in every phase of all the life cycle of the building is roughly as follows: building material producing phase (4%), building constructing phase (0.9%), building using phase (95%), building demolishing phase (0.1%), from large to small: building using phase, building material producing phase, building constructing phase and building demolishing phase;

(7) The carbon emission ratio of heavy structure (18%) in the building material producing phase is significantly higher than that of light structure (about 4%);

(8) The percentage of the sum of heavy structures in the construction and demolition phase (7%) is significantly higher than that of light structures (1%);

From the above analysis:

The carbon emission ratio of heavy structure in the building material producing phase is higher than that of light structure, which is due to the selection of structural materials. The engineering wood used in wood structure buildings in light structure, including specification wood, OSB and I-joist, has carbon emission coefficients of 30.3 $kgCO_2/m^3$, 550 $kgCO_2/t$ and 380 $kgCO_2/t$ respectively. Among the four main structure types of heavy structure, the amount of concrete makes up the vast majority of all the building materials. According to the quality principle, concrete is the main research object of building materials, and cement is the main component of concrete and the main source of carbon emission of concrete. The carbon emission coefficient of cement is 1220 $kgco_2/t$, which is much higher than that of the three main building materials of engineering wood. For the light steel structure in the light structure, the carbon emission coefficient of steel, the main building material, is 6470 $kgco_2/t$, which is higher than that of cement. However, due to the buildings that meet the use function under the same conditions, the amount of cement required for the heavy structure is much higher than that of the light steel structure, so the carbon emission percentage of the heavy structure in the building material producing phase is higher than that of the light structure.

The percentage of carbon emission in the constructing phase and demolishing phase of heavy structure is higher than that of light structure, because the energy consumption of heavy structure is higher than that of light structure in the construction and demolition phase due to the relationship between structure type and material.

The chart on the right shows:

The time and area factors are not considered in the analysis of the chart on the left. If the building material producing phase, constructing phase and building demolishing phase are considered as one year, the carbon emissions per unit building area per year can be calculated. It can be found from the chart on the right:

Comparison of all structure types:

(1) The percentage of carbon emission per unit time in the building material producing phase is the highest;

(2) The percentage of carbon emissions per unit time in the constructing phase and demolishing phase has increased significantly;

Above all, all the carbon emission in the constructing and using phases is the highest. However, the carbon emission per unit time in building materials' producing phase is higher than that in the constructing and using phases. The other two phases (constructing phase and demolishing phase) also have great carbon reduction potential and space, and due to the centralized emission, it has a greater impact on the environment. Therefore, while paying attention to the carbon emission in the constructing and using phases, nor can we ignore the significance of emission reduction in other phases.

Comparison between heavy structure and light structure can be concluded:

(3) The percentage of carbon emission per unit time of light structure (about 25%) is much higher than that of heavy structure (about 5%);

(4) The sum of carbon emissions per unit time of heavy structures in the constructing phase and building demolishing phase is higher than that of light structures;

(5) The percentage of carbon emission per unit time of heavy structures in the constructing phase and building demolishing phase is higher than that in the using phase; The percentage of carbon emission per unit time of light structure in constructing phase and building demolishing phase is lower than that in using phase;;

Carbon emissions per unit building area per year:

(1) Heavy structure > light structure; (2) Reinforced concrete structure > steel structure > light steel structure > wood structure.

5. Conclusion

By using LCA (life cycle evaluation) theory, the building's whole life cycle carbon emission accounting model is established, and the carbon emission of four different structure types and structural materials is calculated. The research shows that the light structure is lower than the heavy structure, and the reinforced concrete structure > steel structure > light steel structure > wood structure. Therefore, under the conditions permitted by the national macro policy, choosing light structure, wood structure buildings with good thermal insulation performance and small heat capacity are one of the effective methods of reducing low-carbon emission in the construction industry.

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References

[1] Chen H. Strengthening carbon reduction work in my country's construction industry. Construction Enterprise Management. 2022;(04):45-46.

[2] Building Energy Conservation Research Center of Tsinghua University. Annual Development Research Report of Building Energy Conservation in China. Beijing: China Building Industry Press; 2020.

[3] Wu Y, Zhang S, Jiang L. The current situation of building carbon emissions in my country and the approach to carbon neutrality in Chongqing Architecture. 2021;20(S1):66-68.

[4] Yang S, Liu J, Yang T, Liu Y, Li M. Research on carbon emission accounting of public buildings in the process of carbon trading. Building Science. 2020;36(S2):326-330.

[5] Kong F, Xiong H, Yan H. Carbon emission analysis of building life cycle based on energy-saving design. Sichuan Architecture. 2022;42(03):59-61.
[6] Feng G, Cui H, Chang S, Huang K, Wang Q. Analysis of carbon emissions and influencing factors of near-zero energy buildings. Progress in Climate Change Research. 2022;18(02):205-214.
[7] Cao X, Miao C, Pan H. Comparative analysis and research on carbon emissions of prefabricated concrete and cast-in-place buildings based on carbon emission model. Building Structure. 2021;51(S2):1233-1237.
[8] Gao Y, Mei S. Analysis on the construction of carbon emission database in the whole life cycle of Chinese wood structure buildings. Architecture Technology. 2020;51(03):260-263.
[9] Cang Y, Luo Z. Research on the accounting method of physical and chemical carbon emissions of building materials in different phases of engineering design. Urban Architecture. 2019;16(26):33-35.
[10] Chen Y, Song C, Xie P, Dai X. Carbon emission analysis of green office buildings. Construction Technology. 2019;(Z1):112-115.