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Quantification of Building Carbon Emissions in China a Using Hybrid LCA Model

Guangzu Zhu, Shiqi Wu, Jie Wang, Mengyun Li

College of Civil Engineering, Hefei University of Technology, Hefei, China
Email: 2019170558@mail.hfut.edu.cn

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Abstract

During their life cycle, buildings not only consume a lot of resources and energy, but also produce a large amount of carbon emissions, which have a serious impact on the environment. In the context of global emissions reduction, the trend has been to low carbon buildings. As a major carbon emitting country, it is urgent to promote emission reduction in the construction industry and to establish a model for carbon emissions and calculation in buildings. To this end, this paper collates life cycle carbon emission calculation methods based on life cycle theory and establishes a mixed life cycle carbon emission calculation model for buildings to provide ideas for low carbon buildings in China. A case study of a hospital in Guangming City, Anhui Province is also conducted to verify the feasibility of the model. The results show that the total carbon emission of the hospital is 43283.66 tCO_2eq, with the production phase, construction phase, use and maintenance phase and end-of-life phase accounting for 9.13%, 0.35%, 90.06% and 0.46% of the total carbon emission respectively. An analysis of the factors influencing carbon emissions at each stage is presented, and recommendations are given for corresponding emission reduction measures. The carbon emission calculation model based on the hybrid LCA proposed in this study enables a more comprehensive consideration of carbon emissions in the life cycle of a building, and has implications for the study of building carbon emission calculation.

Keywords

Life Cycle Assessment (LCA), Hybrid LCA, Carbon Emissions, Input-Output Analysis

1. Introduction

In recent years, global climate change has posed a serious threat to people's lives as greenhouse gas emissions led to glacier melting, extreme weather and sea level rise. Reducing greenhouse gas emissions has become a focus for the world, especially China. USEIA (2010) (USEIA, 2010) estimates that global carbon emissions will be 42.7% higher in 2035 than in 2007, surging to 42.4 billion tonnes. The construction sector contributes 23% of global CO_2 emissions, of which nearly 41% is emitted by China (Hong et al., 2015). In response, China has proposed that it will increase its independent national contribution and adopt strong policies and measures, with carbon emissions aiming to peak by 2030 and working towards carbon neutrality by 2060. The Central Economic Work Conference in 2020 listed "achieving carbon peaking and carbon neutrality" as one of the key tasks for 2021 (Wang & Zhang, 2020).

The construction industry has an important impact on the economy, society and the environment. As China's industrialization and urbanization continues to accelerate and its urban and rural population grows, both the scale and number of buildings are growing significantly. The emergence of a large number of new buildings and infrastructures on the one hand, and the large amount of energy consumed to maintain the normal operation of buildings on the other, has resulted in the construction industry consuming large amounts of energy and emitting large amounts of greenhouse gases. According to research, the construction sector accounts for approximately 40% of the country's total carbon emissions, making it one of the most carbon-intensive sectors in China (Zou, 2015). Therefore, the construction industry has a huge potential to reduce emissions and is a key target for future emission reduction tasks.

Research on life cycle assessment (LCA) has been conducted since the 1970s. It was not until the 1990s that Hunt et al. first applied LCA to the construction sector, studying the environmental impact of building materials (Huang et al., 2018). Since then, a large number of studies related to life cycle assessment of buildings have emerged. Research topics include building life cycle environmental impact assessment, green building assessment, low carbon building assessment and the development of tools for building life cycle carbon emission assessment (Atmaca & Atmaca, 2015; Filimonau et al., 2021; Madathil et al., 2021; Xi & Cao, 2022). Life cycle assessment analysis of building projects provides a quantitative perspective on the environmental impact assessment of buildings. Currently, the calculation methods for building life cycle carbon emissions based on basic principles can be divided into: process-based LCA (P-LCA) and input-output LCA (IO-LCA).

P-LCA decomposes the study objectives into sub-processes and combines activity data with relevant emission factors to assess emissions. The method is able to identify the detailed results of the process under study (Onat et al., 2014) and accounts for the majority of research in the field of engineering and construction technology (Fenner et al., 2018; Han et al., 2022; Tabrizikahou & Nowotarski, 2021) and is widely used for the environmental impact analysis of individual buildings (Islam et al., 2015; Seo & Foliente, 2021). However, P-LCA requires the collection of a large amount of basic data and therefore has a high time cost. In addition, many studies simplify the system by ignoring secondary links and indirect emissions and only consider a few major carbon emission processes in the life cycle phase, resulting in incomplete system boundary definitions and inevitable truncation errors (Nassen et al., 2007). The truncation error makes it difficult to assess potential consumption and emissions with system boundary heterogeneity (Lave et al., 1995), reducing the accuracy of the P-LCA.

IO-LCA, which converts monetary values into environmental impacts based on economic input-output tables and material flows, has a more complete system boundary and is more suitable for macro-level analysis of the construction industry (Chang et al., 2016; Wang et al., 2021). Acquaye & Duffy, 2010 assessed emissions from the construction industry in Ireland, including groundworks, structural works, services, finishes and plant operations. Ma et al., 2017 investigated the energy and emissions from the construction and operation of the "Tianjin Tower" based on environmental input-output tables. However, input-output tables provide sectoral averages of emissions, making it difficult to distinguish between carbon emissions from different products in the same sector, and may not be accurate for the life-cycle carbon emissions of a building. In addition, IO-LCA uses idealized assumptions to translate monetary values into corresponding carbon emissions, making it difficult to provide a fully integrated assessment of particular products within economic sectors at the micro level (Majeau-Bettez et al., 2011).

Combining the advantages of P-LCA and IO-LCA, hybrid LCA (H-LCA) has recently been seen as a potential replacement method and is widely used in carbon emission calculations (Praseeda et al., 2015). Depending on the composition structure of hybrid analysis, it can be divided into tiered hybrid (TH), input-output based hybrid (IOH) and integrated hybrid (IH) (Suh & Huppes, 2005). The TH method is the most commonly used hybrid method (Crawford, 2014). It uses a process-based analysis to assess emissions from major processes and an input-output analysis for emissions from other sources. It not only extends the systematic boundaries of the original process analysis, but also ensures the accuracy of the findings. The IOH and IH methods extend the original input-output data by integrating process information on industries, products and related emissions, broadening the system boundary and giving more comprehensive results (Dixit et al., 2013; Suh et al., 2004). However the collection and processing of information can be costly and may lead to additional errors due to imperfect assumptions (Su et al., 2010).

In addition, a large number of studies on building carbon emissions have focused on residential buildings, and relatively little research has been done on carbon emissions from public buildings, especially medical buildings, given the complex and diverse spatial types and building forms of public buildings. Li Hui et al. studied the carbon emissions of reinforced concrete buildings of different building types (residential, hospital, commercial and school). The results show that the life-cycle carbon emissions of hospital buildings are much greater than those of other types of reinforced concrete structures (Li et al., 2019).

Therefore, this paper proposes a building life cycle carbon emission calculation model based on the TH approach and assesses the applicability of the developed calculation model using the Mingguang City Hospital in Anhui Province as an example. The calculation model uses P-LCA as the basis for calculating carbon emissions at each stage of the building life cycle, while using the sectoral full carbon emission factors calculated from the China Input-Output Tables 2012 and the China Energy Statistics Yearbook 2012, IO-LCA is used to quantify building carbon emissions that are ignored by P-LCA or are difficult to quantify, so that P-LCA can be optimized. For example, building accessories such as isolators, interface agents, putty powder and paints and coatings lack carbon emission factors, which cannot be calculated by P-LCA. The calculation model developed in this paper enables the quantification of carbon emissions based on input-output data. Therefore, compared with P-LCA, the building mixed life cycle carbon emission calculation model has more advantages in practical application. The paper is organized as follows: Section 2 introduces the building hybrid life-cycle carbon emission calculation model. Section 3 conducts a case study. The results of the calculations are also analyzed. Discussion and conclusions are presented in section 4.

2. Methodology

Given the limitations of both process analysis and input-output analysis in quantifying the life-cycle carbon emissions of buildings, they do not reflect the level of carbon emissions of buildings well. To address the shortcomings of the current study, this paper proposes a hybrid LCA-based carbon emission calculation model. The model is based on process analysis, and by introducing input-output data, the integrity of the system boundary is ensured, while the accuracy of the research results is improved. In this paper, the application of the hybrid LCA-based carbon emission calculation model is as follows.

1) Clarify the project research boundary;

2) Clarify the selection criteria for energy, building material and machinery carbon emission factors;

3) Carbon emission calculation formulae for each phase.

2.1. Research Purpose and Scope

The system boundary determines which processes are included in the LCA, which is a prerequisite for calculating carbon emissions. The system boundary is generally divided into a temporal scope and a spatial scope (Säynäjoki et al., 2017), which are interlinked. Based on the division of building life cycle stages, this study defines the spatial scope as four stages: production stage, construction stage, use and maintenance stage, and end-of-life stage. The activities involving carbon emissions in each stage specifically include:

1) Production phase: the production and procurement process of building materials.

2) Construction phase: the transportation of building materials from the factory to the construction site and the operation of construction machinery on site.

3) The use and maintenance phase: the energy consumed in the process of maintaining comfortable environmental conditions in buildings, including energy consumed for lighting, water supply, HVAC (heating, cooling and ventilation systems) and equipment use. It also includes the production and procurement of building materials and the transportation of building materials as a result of building repair, maintenance, renovation and replacement work.

4) End-of-life phase: This mainly includes the demolition of buildings, the transportation of waste and the disposal of waste.

The definition of time horizon mainly refers to the time horizon span of the building life cycle. In this paper, the time span for the use and maintenance phase is set at 50 years. The time span of the other phases is determined based on the actual situation of the case project.

Considering the differences in the types of buildings studied, the types of building materials and machinery used in the production phase and the years of construction, a comparison using the sum of the carbon emissions of each stage of the building life cycle would be very different but lacking in comparability. In order to make the carbon emission calculation model established in this paper comparable with domestic and international studies, this paper uses "annual carbon emissions per unit of floor area" as a functional unit to compare carbon emissions at different stages of the building life cycle, and the unit of measurement is tCO2eq/(a.m^2).

2.2. Selection of Carbon Emission Factors

Carbon emission factors include energy emission factors, building material emission factors, transport emission factors and machinery and equipment emission factors. Due to the differences in production methods and energy structures in different countries and regions, there are significant differences in carbon emission factors. Therefore, carbon emission data from foreign countries cannot be directly applied to Chinese construction projects. This paper follows the following priorities in the carbon emission factors chosen:

1) National standards;

2) Established domestic databases;

3) Research data available in the domestic literature;

4) The relationship between national statistical yearbooks, quota standards, various types of inventory data, etc., and the conversion and commutation of the target results.

As China currently does not have a complete carbon emission base database, this paper uses national standards and existing research data from the domestic literature as the source of the carbon emission factors to be used. The Standard for Calculating Carbon Emissions from Buildings (GB/T 51366-2019), as the standard for carbon emissions from buildings in China, provides detailed data on the basis of carbon emission factors.

In addition, this paper constructs a complete carbon emission factor for the input-output sector based on the China Input-Output Tables 2012 and the China Energy Statistics Yearbook 2012 to supplement the missing carbon emission data in the process analysis, the exact process is shown in Figure 1. Table 1 shows the full carbon emission factors for each sector.

Table 1. Complete carbon emission coefficient of input-output sector.

department	Department code	Complete carbon emission factor ($tCO_2e/10^4CNY$)
Coal mining and washing products	S006	2.68
Oil and gas production products	S007	1.93
Ferrous metal ore mining and beneficiation products	S008	2.82
Non ferrous metal ore mining and beneficiation products	S009	2.61
Non metallic ore mining and beneficiation products	S010	2.45
Wood processing and wood, bamboo, rattan, palm and grass products	S034	1.77
Coatings, inks, pigments and similar products	S044	3.19
Special chemical products	S046	3.07
Chemical fiber products	S049	3.00
Rubber products	S050	2.16
Plastic products	S051	2.52
Cement, lime and gypsum	S052	11.55
Gypsum, cement products and similar products	S053	5.89
Brick, tile, stone and other building materials	S054	4.37
Glass and glass products	S055	4.37
Ceramic products	S056	3.41
Steel calendaring products	S060	5.31
Ferroalloy products	S061	5.56
Residential building	S099	3.15
Civil engineering construction	S100	2.90
Building installation	S101	2.90
Architectural decoration, decoration and other architectural services	S102	1.90
Railway Freight Transportation	S103	2.42
Road freight transportation	S104	2.11
Water cargo transportation	S105	2.23
Carriage of cargo by air	S106	2.47

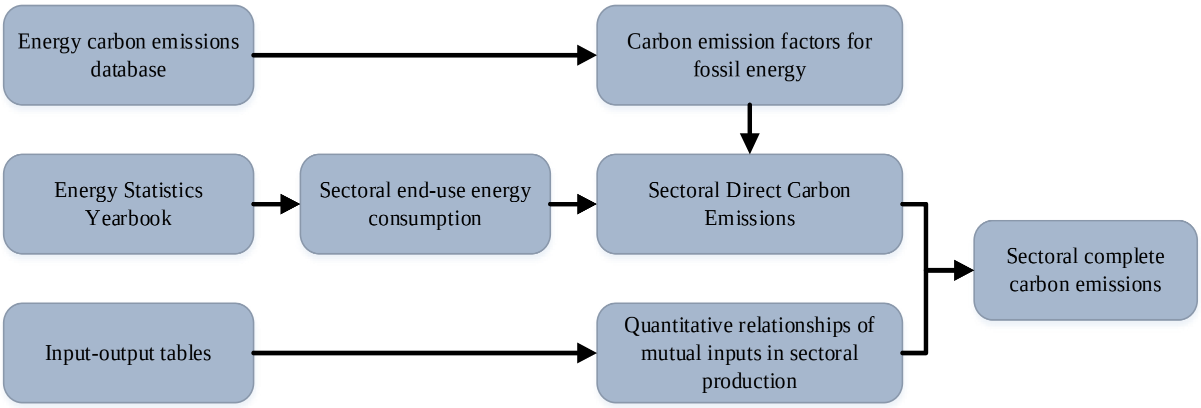

Figure 1. Calculation process of total carbon emission of the sector.

2.3. Calculation Formula of Carbon Emission in Each Stage

2.3.1. Production Stage

The carbon emission in the construction production stage comes from the production process of building materials. The carbon emission factor of main building materials (concrete, steel, brick, etc.) has always been a research hotspot. Therefore, the carbon emission factor of main building materials can be obtained through existing research, and the carbon emission can be calculated by process analysis.

$$CE_m = \sum Q_i \times EF_i \tag{1}$$

where CE_m refer to the carbon emission in the production stage of building materials, Q_i refer to Consumption of building materials *i*, EF_i refer to the carbon emission factor of building material *i*.

Other building materials include various sporadic materials and chemical products, such as solvents, face tiles and other metal products. The carbon emission factor of such building materials is difficult to obtain, but the material price can be found. Therefore, according to the Department of building materials (S044-S095), other building materials use the input output method to calculate carbon emissions.

$$CE_{IO} = \sum CE_{IO,i} = \sum EF_{IO}^{i} \times C_i \tag{2}$$

where $CE_{IO,i}$ refer to the carbon emission of products or services *i*, EF_{IO}^{i} refer to carbon emission of the sector to which the product or service *i*, C_i refer to the cost products or services *i*.

2.3.2. Construction Stage

Carbon emissions during the construction phase consist of two main processes: material transportation and on-site construction machinery operations. The carbon emissions from the two phases are calculated separately and aggregated to obtain the total carbon emissions for that phase. The calculation formula is as follows:

$$CE_C = CE_{trans} + CE_{con} \tag{3}$$

where CE_{trans} refer to carbon emissions from the transport of construction materials, CE_{con} refer to carbon emissions from the operation of building construction machinery.

The carbon emissions from material transportation can be calculated according to the distance travelled and the transportation carbon emission factor according to Equation (4). This method is simple and widely used. However, materials are transported over different distances and by different types of means of transport, which increases the workload. Therefore, it is also possible to estimate carbon emissions directly according to Equation (2), based on the freight costs of various materials and the complete carbon emission factors (S104-S107) for the corresponding transport sector.

$$CE_{trans} = \sum M_i \times D_i \times T_i \quad (4)$$

where M_i refer to the consumption of building materials *i*, D_i refer to the average transportation distance of building materials *i*, T_i refer to the carbon emission factor of unit weight transportation distance under the mode of transportation of building materials *i*.

The carbon emissions from the operation of construction machinery on site come from energy consumption. For small housing construction, there are not many types of machinery invested and can be calculated according to Equation (5) based on the number of machinery shifts and the carbon emission factor per machinery shift. For large housing construction projects, there are many types of machinery invested and the consumption of various machinery is difficult to count. Carbon emissions can be estimated according to Equation (2) based on the cost of machinery invested in the construction and the complete carbon emission factor for the construction sector (S099-S102).

$$CE_{con} = \sum BT_i \times EF_{BT,i} \quad (5)$$

where BT_i refer to the consumption shift of construction machinery *i*, $EF_{BT,i}$ refer to the carbon emission factor per shift of construction machinery *i*.

2.3.3. Use Stage

The building use stage can be divided into operation stage and maintenance stage, so the carbon emission in the use phase consists of these two parts.

$$CE_U = CE_O + CE_m \quad (6)$$

where CE_O refer to carbon emissions from building operation phase, CE_m refer to carbon emissions from building maintenance phase.

The operation phase has the longest cycle time and the carbon emissions during this phase are mainly due to energy consumption for lighting, water supply, HVAC and equipment use. The relevant energy consumption data can be obtained from actual measurements or records, regional averages from statistical studies, calculations based on relevant codes and standards, and estimates using energy simulation software. Actual measured data is highly accurate, but it is a lot of work and is not applicable to buildings that are not yet in use. Regional average data reflect regional averages and are suitable for pre-analysis and policy development. Normative calculated values can be used as a good approximation of building energy consumption and save time in calculation and analysis. The software simulation is suitable for the building design phase and focuses on the building's heating and cooling energy consumption. In this paper, the energy consumption during the operational phase of a project is simulated using the Autodesk Green Building Studio (GBS) software in a case study. The carbon emission in the operation stage is calculated as follows:

$$CE_O = \sum E_i \times EF_{e,i} \tag{7}$$

where E_i refer to the consumption of energy *i*, $EF_{e,i}$ refer to the carbon emission factor of energy *i*.

The carbon emissions during the maintenance phase come from the consumption of building materials in the production and procurement of building materials and the transportation of materials due to the ageing and renewal of building materials or components. Building materials have different lifespans and are renewed differently and need to be calculated separately. The calculation of carbon emissions during the maintenance phase is similar to that of the production and construction phase.

2.3.4. End of Life Stage

The carbon emissions at the end of building life mainly include the carbon emissions generated in the process of building demolition, mechanical equipment construction and construction waste transportation and waste disposal.

$$CE_{EoL} = CE_D + CE_{WT} + CE_W \tag{8}$$

where CE_D refer to carbon emissions from building demolition phase, CE_{WT} refer to carbon emissions from construction waste transportation, CE_W refer to carbon emissions from construction waste disposal.

Theoretically, the calculation method of carbon emission in the building demolition stage is the same as that in the construction stage, but in practical application, there is a lack of relevant data of building demolition, so it is usually estimated according to the demolition process. In this paper, the construction cost of building demolition and the complete carbon emission coefficient of the housing construction department (S099) can also be used to estimate its carbon emission according to formula (2).

Before calculating the carbon emission of waste transportation and disposal, the quantity and type of waste generated after building demolition shall be counted first. For buildings that are not actually demolished, they should be estimated according to relevant standards and specifications (Ouyang, 2016).

In this paper, The Technical Code for Emission Reduction of Construction Waste (Technical Specification for Emission Reduction of Construction Waste, 2011) is used to estimate the quantity and types of waste in the demolition process. The calculation formula is as follows:

$$W_x = A_x \times q_x \tag{9}$$

where W_x refer to quantity of construction waste generated from new projects, A_x refer to total area of new buildings, q_x refer to waste production index of new buildings (see Table 2).

The method of calculating carbon emissions for waste transport is similar to that for material transport. Currently, common waste disposal methods include landfilling, incineration and recycling. Based on the research results in the literature, this paper calculates the carbon emission in the process of waste treatment, and the calculation formula is as follows:

$$CE_m = W_i \times \sum \left(EF_{land,i} \times R_{land,i} + EF_{inc,i} \times R_{inc,i} + EF_{rec,i} \times R_{rec,i} \right) \quad (10)$$

where W_i refer to the quality of waste *i*, $EF_{land,i}$, $EF_{inc,i}$, $EF_{rec,i}$ refer to the carbon emission factors of the *i* waste landfill, incineration and recycling respectively, $R_{land,i}$, $R_{inc,i}$, $R_{rec,i}$ refer to the proportion of the *i* waste landfill, incineration and recycling respectively (see Table 3 and Table 4).

Table 2. Production indicators of demolition construction waste.

Building category	waste production index (kg/m^2)	Classification index of waste production(kg/m^2)	
Public buildings	35	concrete	18.0
		Bricks and blocks	2.2
		mortar	2.1
		Metal	3.0
		wood	6.3

Table 3. Carbon emission factors of construction waste landfill, incineration and recycling.

Types of construction waste	Landfill (kgCO$_2$eq/t)	Incineration (kgCO$_2$eq/t)	Recycling (kgCO$_2$eq/t)
concrete	43.99	-	1.1365
Plastic	514.54	2800	-
wood	424.49	1725	-
Metal	37.82	-	−37.3142
mortar	-	-	0.297
Crushed stone brick	4.2	-	3.7701

Table 4. Proportion of waste landfill, incineration and recycling.

Types of construction waste	Landfill	Incineration	Recycling
concrete	45%	-	55%
Plastic	65%	-	40%
wood	55%	15%	30%
Metal	15%	-	85%
Glass	60%	-	40%
Other garbage and mixed garbage	90%	-	10%

3. Case Study

In this paper, a public hospital in Mingguang, Anhui Province was selected as a case study. The hospital is a public building of reinforced concrete frame structure with an area of 1702 m^2 and a total construction area of 6267 m^2. The exterior of the building is shown in **Figure 2**. The hospital has five floors. As a comprehensive service platform, the lobby on the ground floor can be used for general outpatient services, simple patient treatment, medical billing and other related tasks. The second to fourth floors are the inpatient area, which is the standard living floor for patients. There is a boiling water room, toilets, a nurses' station and 17 wards, which can put down 102 beds. The fifth floor is the equipment floor.

3.1. Data Collection

For this project case, Revit 2016 software was used to build the BIM model with LOD set to 300. and the model was imported into GTJ2018 software to add reinforcement information and obtain a complete bill of quantities in accordance with Chinese standards. For the purpose of the study, the cost data for each phase of the project was quantified using Xindian software (a local pricing software in Anhui). The GBS software was mainly used for the simulation of energy consumption during the operation phase. There are two main reasons for this. On the one hand, the software has good interactivity with Revit 2016 and transfers information via the gbXML file format. On the other hand, the software allows environmental, climatic and other parameters to be set and the updated building performance data can be fed back into the BIM model to enable analysis and optimization of building performance.

3.2. Results Analysis

3.2.1. Carbon Emission in Production Stage

Figure 3 shows the carbon emission proportion distribution of various building materials in the production stage. Among them, commercial concrete, steel and masonry materials contribute the most to the carbon emission, which are 1313.30 tCO_2eq, 1020.28 tCO_2eq and 863.11 tCO_2eq respectively, accounting for 80.88% of the total carbon emission in the production stage. Secondly, cement mortar, building ceramics, architectural coatings and doors and windows have also made important contributions to the total carbon emission in the production stage, producing 275.58 tCO_2eq, 164.16 tCO_2eq, 169.63 tCO_2eq and 86.00 tCO_2eq respectively.

3.2.2. Carbon Emission in Construction Stage

The carbon emission from the transportation of building materials is 97.93 tCO_2eq. In view of the maximum quality of concrete, the carbon emission caused by concrete transportation is the highest, followed by mortar. It can be seen that building materials with heavier self weight will produce higher carbon emissions in the transportation stage.

Figure 2. Effect drawing of hospital.

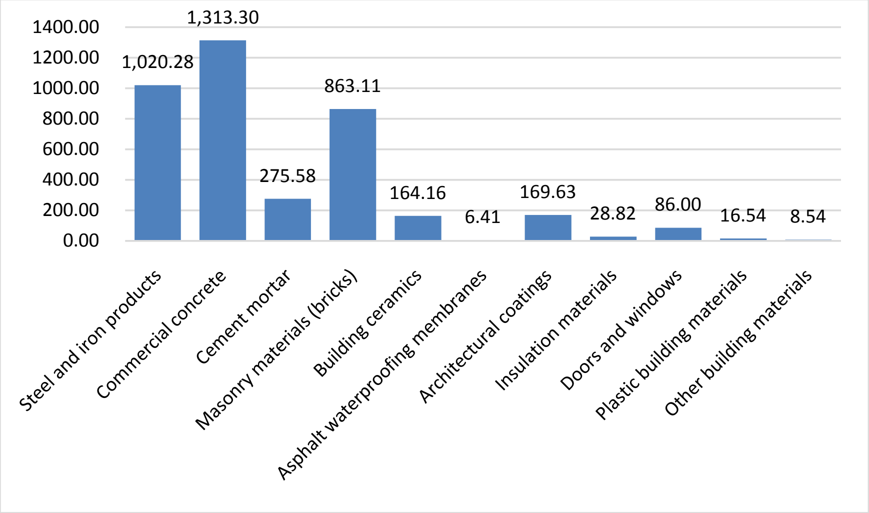

Figure 3. Analysis of carbon emission composition of materials in production stage.

Apart from the carbon emissions from the transportation of materials during the construction phase, most of the carbon emissions are generated by the energy consumed by the mechanical operations and daily offices on the construction site. It is difficult to fully cover all carbon emission processes by traditional process analysis methods.

Therefore, this paper uses the construction cost budget and sectoral carbon emission full factor of the project case to calculate the carbon emissions generated during the construction process. The Xindian software estimated the building construction cost budget to be 176,500 RMB, which corresponds to a sectoral carbon emission full factor of 3.15 $tCO_2eq/10^4CNY$ for residential housing construction. By calculating formula (2), the carbon emissions generated during the construction of this project are calculated to be 55.59 tCO_2eq.

3.2.3. Carbon Emission in Use Stage

This paper uses DBS software for energy consumption analysis. The results show that the annual carbon emissions of the hospital amounted to 777.80 tCO_2eq, of which the carbon emissions due to electricity consumption were higher at 585.69

tCO_2eq, accounting for 75.30%. Based on a 50 years operation period, the total carbon emissions generated by the hospital during the operation period is 38890.00 tCO_2eq. As shown in **Figure 4**, HVAC accounts for 55.44% of the carbon emissions from electricity consuming equipment, followed by lighting, which generates 118.37 tCO_2eq.

As shown in **Figure 5**, among the fuel consuming equipment, HVAC generates 181.77 tCO_2eq or 94.62% per year, while hot water accounts for only 5.38% of the annual carbon emissions from fuel consuming equipment.

In addition, GBS modelled the specific monthly carbon emissions generated by the hospital's electricity and fuel consumption, as shown in **Figure 6**. **Table 5** shows the carbon emissions by season during the operational phase. The most significant carbon emissions are in winter (December to February) with 262.37 tCO_2eq, followed by summer (June to August) with 191.74 tCO_2eq. Considering that Anhui has a mid-latitude monsoon climate, with cold winters and hot summers, heating and hot water generate a lot of energy in winter and air conditioning and cooling consume a lot of electricity in summer, so carbon emissions are high in winter and summer. Fuel consumption is mainly for heating and daily hot water in winter, with a high proportion of heating consumption, which leads to a significant reduction in energy consumption in summer. In addition, daily electricity consumption for lighting and equipment is not seasonal or time-sensitive, so carbon emissions from electricity consumption are relatively stable overall.

Table 5. Composition of carbon emissions in the four seasons of the operational phase.

Seasons	Carbon Emissions from Electricity Consumption	Carbon Emissions from Fuel Consumption	Total carbon emissions (tCO_2eq)
Spring	129.79	36.97	166.76
Summer	147.71	15.45	163.16
Autumn	173.49	4.48	177.97
Winter	190.53	1.21	191.74

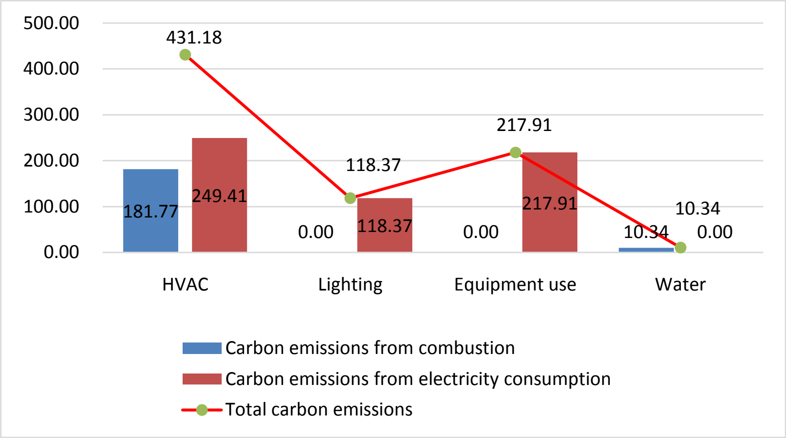

Figure 4. Composition of carbon emissions from facilities in the operational phase.

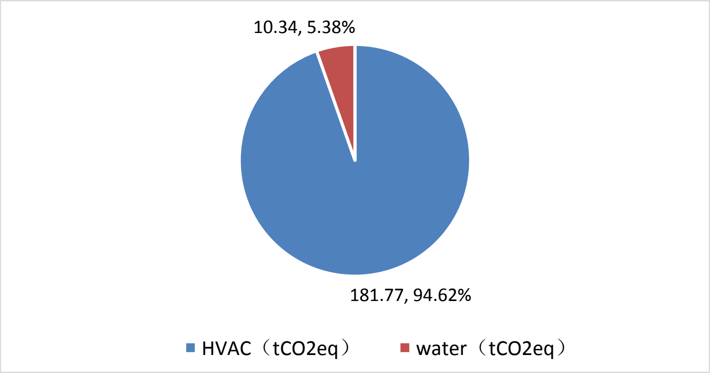

Figure 5. Comparison of fuel consumption for operating equipment.

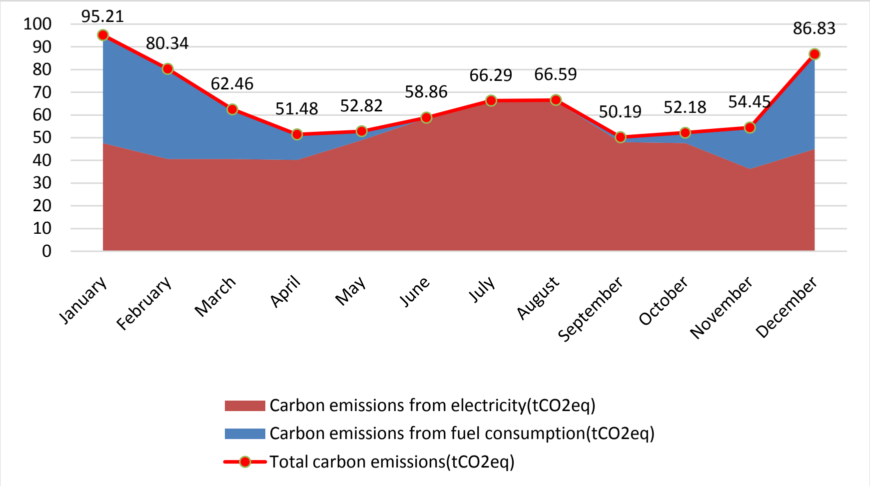

Figure 6. Analysis of monthly carbon emission composition in operation stage.

In this paper, only the repair and replacement of building windows and doors are considered. The carbon emissions mainly come from the production and transportation of replacement building materials and the transportation of construction waste. The carbon emission statistics generated by the production of replacement materials within 50 years of the building are shown in Table 6. Using the input-output approach, the carbon emissions from transport are calculated according to Equation (2) and the carbon emission factors for the “road freight transport and transport support activities” sector, resulting in carbon emissions from transport of 10.60 tCO_2eq. As shown in Figure 7, the total carbon emissions from the maintenance phase are 99.93 tCO_2eq, with 89.33 tCO_2eq or 89.39% of the carbon emissions from construction materials. The carbon emissions caused by material transportation and waste transportation only accounted for 10.61% of the total carbon emissions during the maintenance phase. Among the building materials, the rain shutters are the most emitted, with a carbon emission of 49.17 tCO_2eq. This is mainly due to the fact that rain shutters consist of aluminum alloy, which has a high carbon emission factor. In addition, the number of replacement rain shutters is high.

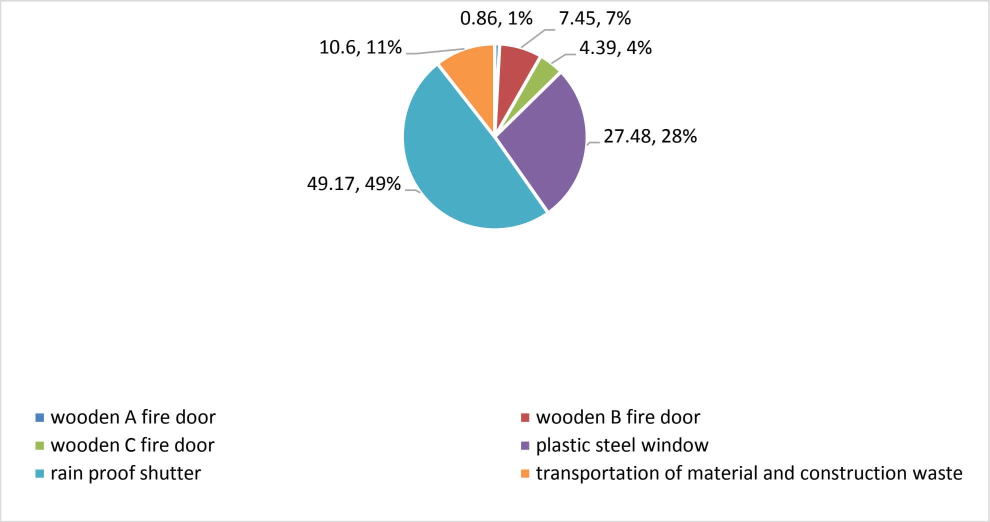

Figure 7. The composition of carbon emissions during the maintenance phase.

Table 6. Carbon emission calculation of material production in maintenance stage.

Building material	Quantity (m^2)	Carbon emission factor ($kgCO_2/m^2$)	Replacement times (50year)	Carbon emissions ($kgCO_2eq$)
Wooden fire door A	9.66	89.05	1	860.22
Wooden fire door B	83.61	89.05	1	7445.47
Wooden fire door C	49.32	89.05	1	4391.95
Plastic steel window	1373.96	20	1	27479.20
Rain proof shutter	386.59	127.20	1	49174.25
Total			89351.09	

3.2.4. Carbon Emission in End-of-Life Stage

As the demolition and disposal phase occurs at the end of the building's useful life, accurate data is not available, so an estimation method can only be used. The results of the calculations are shown in Table 7. The total carbon emissions from the end-of-life phase are 198.44 tCO_2eq, with the main source of carbon emissions being building demolition, which generates 196.46 tCO_2eq, accounting for 98.99% of the total carbon emissions from this phase. The main source of carbon emissions from building demolition came from the mechanical use of concrete element removal and masonry block removal, while handrails, windows, doors and suspended ceilings were removed manually, producing almost no carbon emissions.

According to the results of the production stage, the main building materials in this case are concrete, metal, brick, block and mortar. Therefore, these four building materials are mainly considered for waste disposal. As shown in Figure 8, the total carbon emission in the waste disposal stage is 1.87 tCO_2eq, of which concrete contributes the most, producing 2.30 tCO_2eq. In waste recycling and disposal, only metals reduce carbon emissions by 0.49 tCO_2eq.

3.2.5. Carbon Emission in the Life Cycle of Building

Through the above calculation results, the carbon emissions of the case hospital in the production stage, construction stage, use and maintenance stage and end of life stage can be obtained. According to the building area and the assumed time range of each stage, the annual carbon emissions per unit area of the hospital life cycle can be calculated. The results are shown in Table 8.

As can be seen from the figure, the building life cycle carbon emission of the case hospital is 43283.66 tCO_2eq, and the average annual unit carbon emission is 129.10 kg $CO_2eq/(y·m^2)$. The carbon emission in the use stage is 38979.33 tCO_2eq, accounting for 90.06% of the total carbon emission in the life cycle, and the carbon emission in the production stage is 3952.37 tCO_2eq, accounting for 9.13%; 0.35% and 0.46% in construction stage and end of life stage respectively.

Table 7. Carbon emission calculation at end of life stage.

content	Carbon emission (tCO_2eq)	Proportion
Demolition of construction machinery	196.46	98.99%
Waste transportation	0.11	0.06%
Waste Disposal	1.87	0.94%
Total	198.44	-

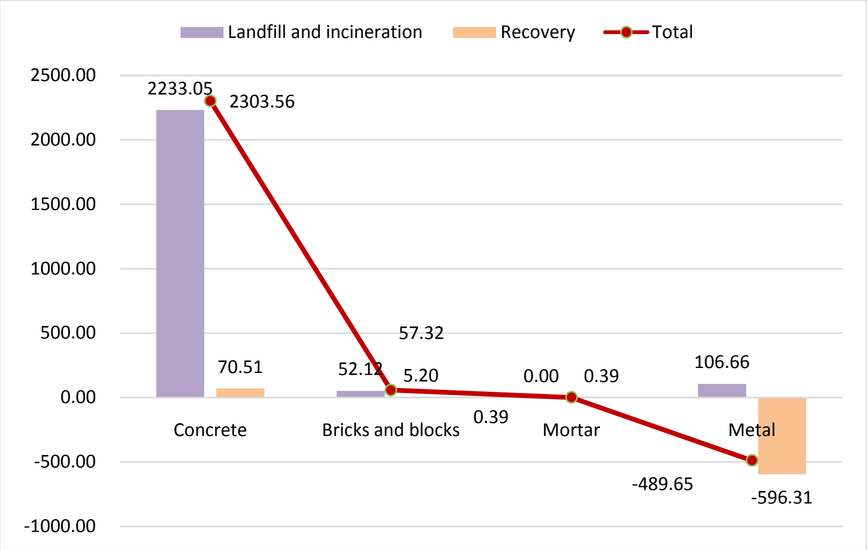

Figure 8. Carbon emission composition analysis of waste disposal.

Table 8. Calculation results of hospital life cycle carbon emission.

Life cycle phase	Total carbon emission (tCO_2eq)	Average annual carbon emission per unit area ($kgCO_2eq/(y·m^2)$)	Percentage (%)
Production stage	3952.37	315.33	9.13
Construction stage	153.52	24.49	0.35
Use phase	38979.33	124.40	90.06
End of life stage	198.44	63.33	0.46
Total	43283.66	129.10	100.00

3.3. Emission Reduction Strategy

The main source of carbon emissions in the production phase is commercial concrete, followed by steel and bricks, so saving the use of these three types of building materials is an effective way to reduce carbon emissions in this phase. On the one hand, the recycling rate of building materials is improved. From a life cycle perspective, by recycling building materials, the life cycle of building materials can be improved and the extraction of raw materials can be reduced, thus reducing the impact on the environment. On the other hand, improve the production process and reduce the carbon emission factor of building materials. The current production process of building materials in China is backward and the management methods are inappropriate, resulting in higher carbon emissions and loss rates during the production of building materials (Zhang et al., 2021). Therefore, there is a need to improve production management and introduce advanced production technologies, which are very effective in reducing carbon emissions. In addition, the performance of construction materials should be improved to increase the service life of building materials, thus reducing the consumption of building materials.

For the transportation of building materials during the construction phase, firstly, the principle of proximity, try to use building materials from local areas. Reduce the carbon emissions during transportation by shortening the transport distance. Secondly, choose energy-saving and environmentally friendly means of transport. Priority is given to vehicles with high load-bearing capacity, low energy consumption, high delivery efficiency as well as low pollution. And for on-site construction, green construction is recommended. Under the basic premise of ensuring quality and safety, resources are saved as much as possible and the impact on the environment is reduced.

The highest carbon emissions are generated from operational energy consumption during the use and maintenance phase, which accounts for 90.06% of the total life cycle carbon emissions of the building. Therefore, emission reduction in this phase is mainly considered in terms of operating equipment. The first is to improve the performance of the equipment. Improve the energy efficiency rating of heating and cooling equipment and daily equipment to save energy and reduce consumption. Secondly improve the use of clean energy and renewable energy. Examples include solar water heaters, photovoltaic power generation systems and ground source heat pump systems. Thirdly improving the energy structure and adjusting the power conversion technology in a timely manner can reduce the consumption of primary energy and lower the carbon emission factor of electricity.

For the end-of-life phase, on the one hand, building demolition solutions are chosen rationally, using a combination of manual and mechanical demolition to improve demolition efficiency while retaining the recyclable properties of the building waste as much as possible. On the other hand, the waste transport scheme is optimized. The construction waste is reasonably classified and processed, reducing the distance and number of times the waste is transported out of the building and reducing the energy consumption of the transporting tools.

4. Discussion and Conclusions

This paper calculates the carbon emission coefficients of China's building related sectors based on Chinese input-output tables and energy statistics, and thus develops a hybrid LCA-based carbon emission calculation model. The model is based on the process analysis method, combining input-output data to make up for the deficiencies of process analysis by using input-output data to supplement data that are not available in the process analysis, and to improve the completeness of the carbon emission calculation. Carbon emissions are calculated for the life cycle of the Guangming City Hospital in Anhui Province in conjunction with an actual building case. The calculation results show that carbon emissions from the operation phase are the highest, accounting for 94.58% of the total building carbon emissions. The carbon emissions in the operation phase mainly come from the electricity consumption in the HVAC. The production phase accounts for 5.01% of carbon emissions, with concrete, steel and brick being the most significant sources of carbon emissions. The construction and end-of-life phases account for only 0.22% and 0.19% of the total carbon emissions. Based on the calculation results, the main influencing factors of carbon emissions are analyzed for different stages and corresponding emission reduction measures are proposed. The feasibility of the hybrid building life-cycle carbon emission calculation model is also demonstrated through case studies, which is of some significance to the study of building carbon emission calculation.

This study also has some limitations, which can be used as a direction for future research or improvement. The building energy simulation in this study uses the prescribed recommended values, which are different from the actual carbon emission situation, and the actual operational energy consumption data of the building can be collected for further study in the future. In addition, this paper is limited to the empirical analysis of a single building and does not examine and compare multiple building types and building groups. Multiple case studies are more conducive to confirming the reliability and feasibility of the constructed calculation model.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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