Quantitative research on embodied carbon emissions in the design stage: a case study from an educational building in China

Ke Liu and Jiawei Leng

School of Architecture and Urban Planning, Suzhou University of Science and Technology, Suzhou, China; Jiangsu Province Key Laboratory of Intelligent Building Energy Efficiency, Suzhou University of Science and Technology, Suzhou, China; School of Architecture, Southeast University, Nanjing, China

ABSTRACT
Achieving low carbon emissions in buildings has a critical impact on controlling global greenhouse gas (GHG) emissions. With the boom in educational buildings, especially those with reinforced concrete structures, carbon emissions from such buildings are brought to the fore. Among building carbon emissions, embodied carbon emissions are closely related to building structure and materials. This paper aims to study the embodied carbon emissions of a Chinese educational building in the design stage with a quantitative method – process-based life cycle assessment, summarizing the carbon emission characteristics of construction materials and proposing corresponding optimization methods. The results indicate that local data of emission factors is preferred for calculating the embodied carbon emissions and the number of construction materials could be obtained through design estimates; that embodied carbon emissions from material manufacturing are much higher than those from material transportation; that steel and concrete are the two most carbon-emitting materials in the reinforced concrete frame structure educational building; and that using local and reused materials are the two main low-carbon optimization measures, with carbon emission reduction contribution rates of 19.7% and 80.3%, respectively, which reused and recycled construction materials should be considered a priority in reducing the embodied carbon emissions of buildings.

CONTACT Jiawei Leng, jw_leng@seu.edu.cn, School of Architecture, Southeast University, Si Pailou Rd. 2# School of Architecture, Southeast University, Nanjing, China

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1. Introduction

Carbon emissions refer to greenhouse gas (GHG) emissions dominated by carbon dioxide (CO$_2$). As large amounts of carbon emissions aggravate climate change, global temperatures continue to increase and human survival and sustainable development are threatened (Intergovernmental Panel on Climate Change (IPCC) 2021). As the nation with the highest carbon emissions worldwide (Yoon, Kim, and Kim 2020), China has announced its ambitious goal to peak carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060 (Xinhua 2020).

To reduce anthropogenic emissions and have any real impact on climate change, it is necessary to reduce emissions from the building sector (La Roche 2012). It has been found that buildings are responsible for approximately one-third of the total direct and indirect energy-related global carbon emissions (Wang et al. 2018). At present, the scale of educational buildings in new construction is rapidly increasing (Tsinghua University Building Energy Research Center (THUBERG) 2018), which results in increasingly prominent carbon emission problems. Life-cycle carbon results from buildings consists of two components: operational carbon (OC) and embodied carbon (EC) (Kang et al. 2015). Currently, various low-carbon strategies focus on controlling operational carbon emissions by saving energy (Azzouz et al. 2017). However, with advances in the field of energy efficiency and stricter requirements for energy efficiency in building codes, the proportion of embodied carbon emissions in the life-cycle carbon of buildings in new projects is on the rise (Plank 2008). In China, between 2001 and 2005, building operational carbon emissions increased by 1.1 billion metric tons, and embodied carbon emissions grew by 1.74 billion metric tons, with an even more significant increase in carbon emissions from construction materials (Peng, Jiang, and Qin 2018).

Carbon emissions occur in all stages of a building's life cycle. Thus, for a broader environmental impact analysis, the life cycle assessment (LCA) of buildings is useful (Roberts, Allen, and Coley 2020; Chau, Leung, and Ng 2015; Lim, Tae, and Roh 2018; Hao et al. 2020). LCA is a process in which the material and energy flows of a system are quantified and evaluated (Ramesh, Prakash, and Shukla 2010). The life cycle stages that are often studied are those associated with the manufacturing and use phases (Bahramian and Yetilmezsoy 2020). In particular, Peng, Jiang, and Qin (2018) compared the life cycle carbon emissions for each stage and showed that the operational stage is the largest contributor to carbon emissions, accounting for approximately 85.4% of total carbon emissions; the construction stage (including raw material procurement, building material production, building material transportation, and construction) contributed 12.6%; and the remaining 2% occurred during the demolition stage. However, it is argued that more energy efficient buildings may indirectly result in more CO$_2$ emissions in other stages related with materials (Abeydeera, Mesthrige, and Samarasinghalage 2019). In some cases, it has been reported that the embodied energy emissions and carbon emissions could exceed the life cycle operational ones (Praseeda, Reddy, and Mani 2016; Dixit et al. 2010). If embodied carbon emissions are neglected further, embodied carbon emissions could reach up to 50% of the total global carbon emissions (Crawford 2011). In previous research, Praseeda, Reddy, and Mani (2016) assessed the embodied energy and carbon emissions of a few residential buildings. Bastos, Batterman, and Freire (2014) presented a life-cycle energy and GHG analysis of three representative residential building types in Lisbon. Embodied carbon emissions were likewise evaluated in an industrialized home in Japan (Ohta 2017). A life cycle inventory analysis model was formulated to calculate the embodied carbon during the life cycle of a residential building (Li et al. 2017). It has also been found that transportation is the main low-carbon influencing mechanism in China’s residential area (Wei and Quan 2021).

Studies have shown that carbon emissions of buildings are analyzed by LCA way frequently, and embodied carbon emissions and operational carbon emissions are the main components of building life-cycle carbon emissions. As researchers have made significant efforts across different areas to understand and mitigate carbon emissions, especially from the operational stage of buildings, the issues of embodied carbon emissions have come to the fore. While there have been studies that focus on embodied carbon emissions, most of them discuss residential buildings and few consider public educational buildings. Although previous studies have made efforts on building embodied carbon reduction and mitigation strategies, they can vary from region to building type, and there is still a lack of research on educational buildings and the accumulation of raw data. To overcome the limitations of previous studies, this study attempted to investigate the embodied carbon emissions of educational buildings and provide related data through an actual project. Specifically, quantitative research on embodied carbon emissions was conducted in the low-carbon design stage of an educational building with reinforced concrete frame structure in southern China. A calculation model was developed using a process-based life cycle assessment approach. Based on the
results, the specific embodied carbon emission characteristics of construction materials were summarized, and the corresponding optimization methods for reducing emissions were proposed. This work could complement and enrich carbon emission research and guide educational buildings to a low-carbon booming development path.

2. Materials and methods

The primary objective of this study is to quantitatively study the embodied carbon emissions of an educational building in the design stage. First, the embodied carbon emission boundary in this study is defined. Second, a process-based life cycle assessment from the perspective of LCA is introduced as a suitable...
approach in the design stage. Third, the corresponding research basis is defined, including the introduction of the project, determination of carbon emission inventories, and data obtention of building material consumption and related transportation. Accordingly, the embodied carbon emissions of the educational building were calculated during the design stage. Finally, the characteristics of the educational building embodied carbon emissions are summarized, two corresponding optimization measures for embodied carbon emission reduction are proposed, and their low-carbon effects are analyzed quantitatively. The study schema is shown in Figure 1.

2.1. The embodied carbon emission boundary of this study

Embodied carbon has been conventionally defined to comprise carbon emissions incurred in various stages, i.e., material extraction, material processing and component fabrication, and construction and assembly of the building’s life cycle. However, it may be extended to include the end-of-life carbon emissions. To clarify the life cycle phases considered, embodied carbon may be reported as “cradle to gate,” “cradle to site,” “cradle to service,” or “cradle to grave” embodied carbon (Akbarnezhad and Xiao 2017). In recent years, with the concept of “green” structural design being gradually accepted, green could also be considered as a structural evaluation standard. From the viewpoint of structure design, an evaluation is conducted by examining two major items: material saving and design optimization (Wang, Liu, and Shen 2021). In terms of embodied carbon emissions, the carbon caused by materials accounts for at least 90% thereof, whereas the effect of the carbon emissions caused by equipment is insignificant (Kang et al. 2015). Generally, buildings of the same structure use similar materials, but their construction approaches may vary according to the site conditions and tools. In order to help architects have a general constraint on the embodied emissions of buildings in the design stage, this paper focuses on the carbon emissions from construction materials reported as “cradle to site,” which account for the largest share of embodied carbon emissions, including carbon emissions from material production and from material transportation (Figure 2).

2.2. Calculation method of embodied carbon emissions: process-based life cycle assessment

The calculation method for LCA mainly includes the measurement method, input-output method, process-based life cycle assessment, and hybrid method (Liu 2021). Considering the design stage of a building project, it is difficult to measure actual data-related emissions, and the input-output method is more appropriate for construction
industry statistics than for phased carbon emission calculations in specific projects. Process-based life cycle assessment is a bottom-up approach that demonstrates carbon emissions from the specific processes of building construction (Zhu et al. 2020). The calculation logic of this method is easy to understand among architects, the calculation is simple and clear, and the carbon emissions of each stage can be independently calculated and analyzed according to specific activities – which is suitable for the design stage. Process-based life cycle assessment is commonly used to identify and quantify the carbon emissions of buildings (Wu et al. 2012; Sandanayake, Zhang, and Setunge 2016; Luo et al. 2019; Zhang et al. 2019), and refers to the calculation of carbon emissions by multiplying the value of economic activities with the corresponding emission factor. This method of analysis is highly encouraged based on the International Organization for Standardization (ISO) standards because of its accuracy and detailed processes (Suh and Huppes 2005). Thus, the basic equation (Intergovernmental Panel on Climate Change (IPCC) 2006) is (1):

\[ Emission = AD \times EF \]  

(1)

where \( AD \) is human activity data and \( EF \) is the emission factor. Specifically, economic activity is often broken down by process flow, and the carbon emissions of each process are expressed as the product of carbon emission factors and the volume of activity at each stage. The total carbon emissions of the entire economic activity process are derived from the sum of the carbon emissions of each segment. Therefore, the equation is (2):

\[ C_{\text{total}} = \sum_{i=1}^{n} (e_i \times Q_i) \]  

(2)

where \( C_{\text{total}} \) is the total carbon emissions throughout all processes; \( e_i \) is the carbon emission factor of phase \( i \); \( Q_i \) is the volume of activity in phase \( i \); and \( i \) is the number of phases/categories. In terms of the embodied carbon emissions of buildings, the calculations should include two phases: the carbon emissions of construction materials in production and the carbon emissions of construction materials in transport. The equations follow:

\[ C_{\text{embodied}} = C_p + C_t \]  

(3)

\[ C_p = \sum_{i=1}^{n} M_i \times F_i \]  

(4)

\[ C_t = \sum_{i=1}^{n} M_i D_i T_i \]  

(5)

where \( C_{\text{embodied}} \) is the embodied carbon emissions; \( C_p \) is the carbon emissions of construction materials in production; \( C_t \) is the carbon emissions of construction materials in transportation; \( M_i \) is the consumption of type \( i \) construction materials; \( F_i \) is the carbon emission factor of type \( i \) construction materials; \( D_i \) is the average transportation distance of type \( i \) construction materials; \( T_i \) is the carbon emission factor of transport distance per unit weight under transport mode of type \( i \) construction materials.

### 2.3. Acquisition and determination of data sources

#### 2.3.1. Case introduction

The present case is an educational training center with a partially earth-covered space in Jiangsu Province, southern China (Figure 1). The total construction area of the project is approximately 1,300 m\(^2\), the total land area is approximately 6,800 m\(^2\), and the building height is 23.9 m, with six floors above ground and one floor underground. The structure divides the entire building into two main parts: the cladding podium section, which is a reinforced concrete frame structure; and the upper standard floor section, which is a steel frame. The two parts of the building are connected vertically by a core at each end, while a large vertical space of approximately 33.9 m in height acts as an atrium throughout the building. The structural form determines that the main materials of construction are concrete and steel (Figure 3).

#### 2.3.2. Amount of construction materials and transport distance

A building project needs various construction materials, and it is difficult to consider all of the materials used in the embodied carbon emissions calculation. Carbon emissions can be calculated for

| Table 1. Inventory of main construction materials in the educational building. |
|-----------------|-----------------|-----|-----------------|
| Type of material | Name of material | Unit | Consumption     |
| Steel           | Large shape steel | t   | 1,430.60       |
|                 | Small and medium shape steel | t   | 309.84       |
|                 | Rebar (Comprehensive) | t   | 1,708.88       |
|                 | Steel truss plate (120 mm) | m\(^2\) | 4,945.58 |
|                 | Steel of curtain wall | t   | 240.00         |
| Sand and gravel | Medium (coarse) sand | t   | 5,059.56       |
|                 | Gravel | t   | 4,242.32       |
| Cement         | Cement (Comprehensive) | t   | 593.72         |
| Glass          | Plate glass | t   | 203.11         |
| Concrete       | C30 concrete | t   | 10,858.80       |
|                 | C35 concrete | t   | 9,683.33       |
|                 | C40 concrete | t   | 3,390.16       |
|                 | Concrete solid brick | t   | 4,907.44       |
| Window frame   | Heat-insulating bridged aluminum window frame | m\(^2\) | 414.76 |
| Curtain wall   | Ultra-high performance concrete (UHPC) | t | 780.00       |
|                 | Aluminum of curtain wall | t | 50.00       |
major construction materials that are large in amount, and construction materials with high carbon emissions can be used to calculate their total emissions (Luo et al. 2019). The benchmark for "main" construction materials is that the total weight of the selected materials is not less than 95% of the total weight of construction materials in the building, such as cement, concrete, steel, etc. (Ministry of Housing and Urban-Rural Development of the People’s Republic of China 2019a). The design estimate is essential to achieve the consumption of the main construction materials in the early stages of a project. Thus, the main construction materials were grouped into different categories, as shown in Table 1. It should be noted that construction materials are often produced outside of the site, and the different transportation modes of construction materials produce different carbon emissions. It is difficult to obtain the actual transport distance of construction materials during the design stage. Thus, it can be assumed that the default transport distance of concrete is 40 km, and that of other construction materials is 500 km (Ministry of Housing and Urban-Rural Development of the People’s Republic of China 2019b).

### 2.3.3. Carbon emission factors of the main construction materials and transportation modes

The accuracy of the carbon emission factor affected the calculation results. It was found that there are different degrees of error in the calculation results of the energy and carbon emissions contained in construction materials for different construction material databases in China and abroad, with the larger errors even reaching approximately 30% (Peng 2012). As the energy structures and energy efficiency vary greatly among countries, the carbon emission factors of different countries also have a large difference, which cannot be directly quoted from foreign data (Lin 2017). More localized emission factors make the evaluation results closer to reality (Ge, Luo, and Lu 2017). Therefore, the selection of emission factors is based on the principle of local priority. Based on Chinese local standards and literature (Ministry of Housing and Urban-Rural Development of the People’s Republic of China 2019a; Centre for Science et al., 2017; Ling et al.

| Type of material | Name of material | Unit | Carbon emission factor |
|------------------|------------------|------|------------------------|
| **Steel**        | Large shape steel | tCO₂e/t | 2.380 |
|                  | Small and medium shape steel | tCO₂e/t | 2.338 |
|                  | Rebar (Comprehensive) | tCO₂e/t | 2.340 |
|                  | Steel truss plate (120 mm) | tCO₂e/t | 2.000 |
|                  | Steel of curtain wall | tCO₂e/t | 2.000 |
| **Sand and gravel** | Medium (coarse) sand | tCO₂e/t | 0.003 |
| **Cement**       | Cement (Comprehensive) | tCO₂e/t | 0.800 |
| **Glass**        | Plate glass | tCO₂e/t | 1.130 |
| **Concrete**     | C30 concrete | tCO₂e/t | 0.099 |
|                  | C35 concrete | tCO₂e/t | 0.113 |
|                  | C40 concrete | tCO₂e/t | 0.122 |
|                  | Concrete solid brick | tCO₂e/t | 0.160 |
| **Window frame** | Heat-insulating bridged aluminum window frame (100% native aluminum profile) | tCO₂e/m² | 2.54 |
| **Curtain wall** | Ultra-high performance concrete (UHPC) | tCO₂e/t | 0.268 |
|                  | Aluminum of curtain wall | tCO₂e/t | 9.500 |

**Table 2. Carbon emission factors of main construction materials.**

| Type of material | Name of material | C₀(tCO₂) | C₁(tCO₂) | C₂(tCO₂) | Embedded (tCO₂) |
|------------------|------------------|----------|----------|----------|-----------------|
| **Steel**        | Large shape steel | 3,404.83 | 92.27    | 3,497.1  | 4297.1          |
|                  | Small and medium shape steel | 724.25 | 19.98    | 744.23   | 744.23          |
|                  | Rebar (Comprehensive) | 3,998.78 | 110.22   | 4,109.00 | 4109.00         |
|                  | Steel truss plate (120 mm) | 127.29 | 4.11     | 131.40   | 131.40          |
|                  | Steel of curtain wall | 480.00 | 15.48    | 495.48   | 495.48          |
| **Sand and gravel** | Medium (coarse) sand | 12.70 | 326.34   | 339.04   | 339.04          |
|                  | Gravel | 9.25 | 273.63   | 282.88   | 282.88          |
| **Cement**       | Cement (Comprehensive) | 474.98 | 38.30    | 513.28   | 513.28          |
| **Glass**        | Glass (Comprehensive) | 229.51 | 13.10    | 242.61   | 242.61          |
| **Concrete**     | C30 concrete | 1,077.82 | 56.03    | 1,133.85 | 1133.85         |
|                  | C35 concrete | 1,096.39 | 49.97    | 1,146.36 | 1146.36         |
|                  | C40 concrete | 436.46 | 18.53    | 454.99   | 454.99          |
|                  | Concrete solid brick | 641.19 | 258.48   | 899.67   | 899.67          |
| **Window frame** | Heat-insulating bridged aluminum window frame (100% native aluminum profile) | 105.35 | 0.22     | 105.57   | 105.57          |
| **Curtain wall** | Ultra-high performance concrete (UHPC) | 209.04 | 50.31    | 259.35   | 259.35          |
|                  | Aluminum of curtain wall | 475.00 | 3.23     | 478.23   | 478.23          |
| **Total**        |                  | 13,502.84 | 1,330.19 | 14,833.03 | 14833.03       |

**Table 3. Embodied carbon emissions of the project (tCO₂).**

![](https://example.com/image.png) **Figure 4. Shares of embodied carbon emissions (Cembodied).**
the carbon emission factors of the main construction materials of the project are listed in Table 2. Based on experience, heavy-duty diesel wagon transport (18 t load) was selected as the transportation mode of the educational building project, which is 0.129 [kgCO₂e/(t·km)].

3. Results

The embodied carbon emissions of the actual educational building, which amounted to 14,833.03 tCO₂, were calculated using the process-based method in the design stage. The carbon emissions of the main
construction materials in production were 13,502.84 tCO$_2$ and the ones in transportation were 1,330.19 tCO$_2$. The specific results of the calculations are listed in Table 3.

Table 3 shows that insofar as the embodied carbon emissions, the carbon emissions in the production stage of construction materials accounted for the majority and were much higher than the carbon emissions in the transportation stage of construction materials (Figure 4). The carbon emissions of different construction materials are quite different and are affected by the influence of consumption, unit carbon emission intensity, transportation mode, and distance. Figure 5 shows that the carbon emissions of steel are the largest, accounting for 60.52% of total embodied carbon emissions, followed by concrete (24.51%) and sand and gravel (4.19%). In terms of the proportion of construction material consumption (Figure 6), the top three types of construction materials were concrete (65.71%), sand and gravel (21.72%), and steel (8.76%). This means that the construction materials that are used the most do not necessarily have the highest carbon emissions. Figure 7 shows that in addition to sand and gravel, the carbon emissions from the construction materials production phase are far higher than the transportation phase carbon emissions, and priority should be given by saving construction material dosage and improving low-carbon production technology to reduce production phase carbon emissions. Carbon emissions from the transport phase of sand and gravel are higher than those from the production phase, and a low-carbon strategy should be considered initially for the use of proximity mining.

4. Discussion

Further LCA research of the educational training center shows that embodied carbon emissions account for 51% of the life-cycle carbon emissions of buildings, which is the largest proportion. However, there is a large potential to reduce emissions during the use and transportation stages of construction materials. Specifically, low-carbon optimization measures – which are done by increasing the reuse and recycling of materials and choosing local production – may be implemented.

4.1. Reuse and recycling of construction materials

The carbon emission attributes of reused and recycled materials are different from those of original materials. Steel and aluminum are two highly recyclable materials that have the potential to mitigate CO$_2$ emissions (Zhu et al. 2020). Standard size steel sections, such as shape steels, are construction materials that can be both directly reused and recycled back into the furnace (Ministry of Housing and Urban-Rural Development of the People’s Republic of China 2019a). The CO$_2$ emissions from

| Material type         | Emissions of original materials (tCO$_2$) | Emissions of reused and recycled materials (tCO$_2$) | Emission reductions (tCO$_2$) |
|-----------------------|------------------------------------------|---------------------------------------------------|-------------------------------|
| Large shape steel     | 3,404.83                                 | 1,361.93                                           | 2,042.90                     |
| Small and medium shape steel | 724.25                                   | 289.70                                             | 434.55                       |
| Aluminum window frame | 105.35                                   | 80.46                                              | 24.89                        |
| Aluminum of curtain wall | 475.00                                   | 28.50                                              | 446.50                       |
| **Total**             | **4,709.43**                             | **1,760.59**                                       | **2,948.84**                |

Table 4. Changes in carbon emissions in the production of shape steel and aluminum.

| Material type         | Emissions in default distance (tCO$_2$) | Emissions in local distance (tCO$_2$) | Emission reductions (tCO$_2$) |
|-----------------------|------------------------------------------|--------------------------------------|-------------------------------|
| Steel                 | Large shape steel                        | 92.27                                | 36.91                         | 55.36                        |
|                       | Small and medium shape steel             | 19.98                                | 7.99                          | 11.99                        |
|                       | Rebar (Comprehensive)                   | 310.22                               | 44.09                         | 66.13                        |
|                       | Steel truss plate (120 mm)               | 4.11                                 | 1.64                          | 2.47                         |
|                       | Steel of curtain wall                   | 15.48                                | 6.19                          | 9.29                         |
| Sand and gravel       | Medium (coarse) sand                    | 326.34                               | 130.54                        | 195.80                       |
|                       | Gravel                                  | 273.63                               | 109.45                        | 164.18                       |
| Cement                | Cement (Comprehensive)                  | 38.30                                | 15.32                         | 22.98                        |
| Glass                 | Plate glass                             | 5.36                                 | 2.14                          | 3.22                         |
|                       | Glass of curtain wall                   | 7.74                                 | 3.10                          | 4.64                         |
| Concrete              | C30 concrete                            | 56.03                                | 56.03                         | 0                            |
|                       | C35 concrete                            | 49.97                                | 49.97                         | 0                            |
|                       | C40 concrete                            | 18.53                                | 18.53                         | 0                            |
|                       | Concrete solid brick                    | 258.48                               | 103.39                        | 155.09                       |
| Window frame          | Heat-insulating bridged aluminum window frame | 0.22                             | 0.09                          | 0.13                         |
| Curtain wall          | Aluminum of curtain wall                | 3.23                                 | 1.29                          | 1.94                         |
|                       | Ultra-high performance concrete (UHPC)  | 50.31                                | 20.12                         | 30.19                        |
| **Total**             |                                          | **1,330.19**                         | **606.79**                    | **723.40**                   |

Table 5. Changes in carbon emissions in the transportation of main construction materials.
the reprocessing of recycled steel in China are 20–50% of the emissions from original steel, which can be calculated as 40%. The CO₂ emissions from recycled aluminum production account for 5–8% of original aluminum, which can be calculated as 6% (Nie, Qin, and Jiang 2012). According to the standard (Ministry of Housing and Urban-Rural Development of the People’s Republic of China 2019a), the carbon emission factor of the aluminum window frame (The utilization ratio of original aluminum and recycled aluminum is 7:3) was 0.194tCO₂/m², which was lower than that of the aluminum window frame (100% native aluminum profile). Usually, the carbon emission reduction effect of material reuse is discussed in the process of demolition, while measures to reduce the embodied carbon emissions are considered at the beginning of construction material selection in the design stage – wherein the reused and recycled metal materials are from the end-of-life stage of other buildings. Under ideal conditions, only considering the use of reused and recycled shape steel and aluminum, the carbon emissions from the production phase of construction materials are reduced by 2,948.84 tCO₂ (Table 4).

4.2. Local construction materials

Since the current purchase distance of construction materials is the default value, construction materials produced locally can be considered as far as possible for the actual purchase of construction materials. The weight of construction materials produced within 500 km of the project should account for more than 60% of the total weight of construction materials (Ministry of Housing and Urban-Rural Development of the People’s Republic of China 2019b2019a). Assuming that the distances of construction materials other than concrete are all 200 km away, and under the condition of constant transportation mode, then the reductions of carbon emissions in the transportation stage of construction materials are 723.40tCO₂ (Table 5).

4.3. Optimization effect

By choosing locally produced construction materials and increasing the use of reused and recycled construction materials, the embodied carbon emissions could be reduced by 3,672.18tCO₂ compared with the original plan. Table 6 shows that increasing the use of reused and recycled construction materials has a higher contribution rate of carbon emission reduction than choosing local production. The contribution rates of the two low-carbon strategies were 80.30% and 19.70%, respectively. Thus, it is suggested that reused and recycled construction materials should be considered a priority in reducing the embodied carbon emissions of buildings.

5. Conclusions

The findings of this study regarding the embodied carbon emissions of an educational building with a reinforced concrete frame structure in the design are as follows;

(a) The content and scope of embodied carbon emissions are similar to, but different from, the embodied carbon emissions in buildings. In the embodied carbon emissions (total 14,833.03 tCO₂), carbon emissions from the production of construction materials are much higher than those from transportation – amounting to 13,502.84 tCO₂ and 1,330.19 tCO₂, respectively.

(b) In the project, the emissions from steel and concrete accounted for the two largest shares of embodied carbon emissions, which are 60.52% and 24.51%, respectively. The use of steel and concrete should be given priority in the design stage of educational buildings of the reinforced concrete frame structure.

(c) Increasing the use of reused and recycled construction materials and choosing locally produced construction materials are two effective measures of reducing embodied carbon emissions. The contribution rates of the two low-carbon strategies are 80.30% and 19.70%, respectively, with the advantages of reused and recycled construction materials being more significant.

This paper provides theoretical and methodological guidance for the quantitative analysis of embodied carbon emissions in an educational building design stage, and low-carbon optimization measures were proposed and compared. These low-carbon optimization approaches are worth promoting, and the contribution of this paper is considerable – providing real data on embodied carbon emissions from an educational building perspective. The quantitative results show that there is obvious potential for emission reduction in the use of construction materials.

| Optimization measure | Emission reductions (tCO₂) | Contribution rate to emission reduction |
|-----------------------|---------------------------|----------------------------------------|
| Local materials        | 723.40                    | 19.70%                                 |
| Use of reused and recycled materials | 2,948.84 | 80.30%                                 |
| Total of embodied carbon emissions | 3,672.24 | 100%                                   |
Acknowledgments

The author gratefully acknowledges the editors and referees for their positive and constructive comments in the review process.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by National Key R&D programs of China [Grant numbers 2020YFD1100405, 2020YFD1100400, 2020YFC2006602], the National Natural Science Foundation of China [No. 52178009, No. 62072324], Open programs of Jiangsu Province Key Laboratory of Intelligent Building Energy Efficiency [BEE202101].

Illustration credits

All Figures and Tables were made by the authors and research team.

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