Assessing the life cycle CO_2 emissions of reinforced concrete structures: Four cases from China

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Assessing the Life Cycle CO_2 emissions of Reinforced Concrete Structures: Four Cases from China

Abstract

The large amount of carbon dioxide (CO_2) emissions from Chinese buildings has caused widespread concern among researchers around the world. A more comprehensive study is needed based on an international perspective as the standards and methods used for estimating emissions have not yet been integrated with international standards. It is necessary to quantify the life cycle emissions from reinforced concrete structures through a variety of actual engineering data and a multi-case empirical study to establish their standard value, in order to promote the rapid development of low-carbon buildings in China.

Internationally, reinforced concrete structures are often grouped under six types: schools, hospitals, aerospace, commercial, residential, and prisons. This study examines residential, hospitals, commercial and schools as examples for multiple case studies. Life cycle cost analysis (LCA) principles, multi-case analysis and quantitative studies are combined to assemble a CO_2 emission assessment model in *SimaPro* to evaluate the CO_2 emission over the life cycle of a representative sample of reinforced concrete structures in China with the aim of developing proposals for energy-saving emission reductions.

The results indicate that steel contributes 40% to 53% to global warming and 40% to 80% of the total environmental emissions during the *construction phase* of the buildings analyzed, with energy saving in the *building materials production phase*, especially steel production. The amount of CO_2 emissions is generally 30% more in *the use and maintenance phase* than the construction phase, reaching even 300% for hospital buildings. By contrast, CO_2 emissions during the *demolition phase* are relatively small, accounting for only 3% to 12% of the building’s life cycle. In terms of building type, the life-cycle CO_2 emissions of hospital buildings are much larger than other types of reinforced concrete structures, reaching 3390 kg CO_2 eq/m^2.

Keywords: **Building carbon emissions; Energy conservation; LCA; Impact Assessment; *SimaPro*; Case research**.

1 Introduction

The construction industry is the largest energy consumer in the world economy, accounting for over 1/3 of final energy used. It is responsible for approximately 30% of global carbon dioxide (CO_2) emissions[1], making it a potential key area for large-scale CO_2 emission reduction [2]. Various studies show that an accurate measurement of the life cycle CO_2 emissions from buildings is needed for regulating energy conservation in the construction industry [3], with countries such as the United States, Germany, and the United Kingdom having established a variety of building-level CO_2 emission databases and related computing systems [4].

Reinforced concrete structures are the most important and common architectural form in modern architecture, and account for more than 60% of the total building stock in China [5]. They are also the main source of building CO_2 emissions. However, there is no standard method of calculation in China to determine the amount involved. Although the Department of Standard Quota, Ministry of Housing and Urban-Rural Development issued its *Seeking Opinion on National Standard for Calculating Building Carbon Emissions (Draft for Seeking Comment) (Building Standard Construction Seeking [2017] No. 38)*, it is still at a preliminary stage [6].

Moreover, research into environmental impact assessment (EIA) of reinforced concrete construction faces various problems, not only in China but, internationally [7]. In summary, (a) although dedicated frameworks have been developed for buildings LCA since the 1990s by Peuportier [8], there are still very few studies attempting to develop a standard approach to systematically estimating the CO_2 emissions of reinforced concrete structures. (b) There has been insufficient research into environmental emissions studies. While Peuportier [9] considered environmental impacts in the assessment of residential buildings, providing us with research references, most current environmental emissions research lacks completeness and focuses solely on the impact of building emissions on global warming without examining such other environmental impacts as SO_2 emissions and ozone layer destruction [10]. (c) China's construction sector was divided into 13 building sub-sectors by Chang et al.[11], to calculate building embodied emissions and water footprints. Nevertheless, current research comparing the environmental emissions of various types of reinforced concrete structures does not adopt a life cycle perspective.

As a response to the above problems, this study aims to provide a systematic assessment of total life cycle environmental impact of reinforced concrete structures in China. The life cycle costs analysis (LCA) principle is quantitatively expressed using the *SimaPro* software and the *Building for Environmental and Economic Sustainability (BEES)* method. Environmental impacts is considered in terms of not only CO_2 emissions but also other categories of environmental impact such as, acidification and eutrophication, at various phases of four types of reinforced concrete structures over their life cycle. By comparing the CO_2 emission estimates at each project phase of the building types, the key Environmental impact categories affecting CO_2 emissions are identified. The findings will help to develop an effective energy saving and emission reduction plan throughout the construction life cycle. The paper concludes with some policy suggestions to provide practical guidance for the healthy and rapid development of low-carbon buildings in China, and potentially in other countries.

2 Literature Review

2.1 Building CO_2 Emissions

It has been identified that CO_2 emissions is a key environmental indicator threatening the Earth's ecology and climate. At present, many studies have researched building CO_2 emissions, generally focusing on four aspects: (a) green technology; (b) CO_2 emission policy; (c) building materials and construction; and (d) building LCA.

(a) *Green technology*: Green technology has attracted increasing research interests in engineering, environment science, and energy areas. Since environment concern has become a global issue, green technology provides potential solutions[12]. Further, it has a positive impact on CO_2 reduction. Green technology is considered the best response to climate change, and its application in buildings has been widely promoted in many countries, especially China [13-16]. For example, green technologies are utilized to evaluate service life and life cycle CO_2 emission reductions and to develop a low carbon durability design for apartment buildings in South Korea [14]. China also issued a series of green technology application standards and additional regulations. In 2012, the Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD) published opinions concerning the acceleration of the development of green technology application of buildings in China [15]. In 2013, the MOHURD and National Development and Reform Commission of the People's Republic of China jointly issued a green building action plan, after which the application of green technology in building officially commenced [16].

(b) *Carbon emissions policy*: In order to reduce CO_2 emissions and maintain the sustainable development of an economy, governments have promulgated a variety of policies. There is a close relationship between carbon trading-prices, carbon tax policies, etc. and carbon emissions [17, 18]. Lu et al. [19] also assess the effectiveness of building emissions policy by calculating the amount of building CO_2 emissions and provide a new scientific basis for the development of carbon emission policy for the construction industry from the perspective of decomposition.

(c) *Building materials and building construction*: Choi et al. [20] propose a resizing approach to reducing the amount of material used during the design phase to reduce the cost and CO_2 dioxide emissions of high-rise buildings. Nevertheless, there are many other uncertainties that affect the CO_2 emissions from high-rise buildings [21-24]. Lee et al. [25], for example, found that using new composite precast concrete structures to replace *in situ* reinforced concrete can achieve a 5.5% reduction in CO_2 emissions. In addition, the overall CO_2 emissions of buildings can be reduced by increasing the proportion of wood building materials used [26-29].

(d) *LCA*: In recent years, LCA methods are often incorporated into such building construction decisions as in selecting environmental-friendly materials and products, and assessing and optimizing the construction process [30-36]. LCA assessment covers the construction, maintenance, and demolition phases of buildings [37, 38], and adopting LCA to assess buildings can identify the most important factor that affects environmental emissions over the building’s life cycle [39-41]. LCA studies show that the life-cycle energy consumption of low-energy buildings is much less than traditional buildings [41, 42]. These studies focus on life-cycle energy consumption. However, the environmental impact of buildings goes beyond embodied and operational energy to include such other aspects as resource and mineral extraction, and the use of fossil fuels [43]. Chang et al.[44] adopt a highly aggregated Input-Output (I-O) model for building embodied energy and emission quantification. Monahan and Powell [45] and Hammond and Jones [46] have studied the energy and CO_2 emissions associated with the construction phase, while Hacker et al. [47] and the NHBC Foundation [48] study the CO_2 emissions during the construction and *operating* phases. In the LCA process, the terminal phase of the life cycle is usually considered to be the most difficult phase, with many studies of the terminal life cycle scene [49-51]. WRAP [52] adopt a simplified approach in assuming that 70% of the material is reused at the end of the life cycle and 30% sent to landfill, which is a conservative demolition value based on the current recovery rate in the construction industry.

2.2 Method of estimating building CO_2 emissions

Many studies over the years have developed various tools to assess the life-cycle CO_2 emissions of buildings [53-58]. For example, Huang et al. [59] and Nayoon Lee et al. [60] develop a comprehensive life cycle model to support the partition assessment of the CO_2 footprint; Azzouz et al. [61] emphasize the importance of LCA in early building design decisions; Hong Xian et al. [62] propose a simulation and optimization method based on a simulation model to reduce the CO_2 emissions of on-site construction; Chang et al.[11] employ a disaggregated I-O LCI model for specific calculations of building embodied emissions and water footprints in China; while the methodology and procedure of the disaggregated I-O LCI model development are illustrated by Chang et al. [63]; Schmidt et al. [64] facilitate establishing a low-carbon and reasonably-priced building environment by creating a framework incorporating LCC and lifecycle GHG assessment; and Jaehun & Jehan [65] develop a mathematical model to determine the optimal number of apartment units. In addition, BIM technology also provides a model for exploring the CO_2 emissions of buildings [66, 67].

These analyses contain many differences in their inventory analysis and conditional assumptions, and lack a unified method of calculation and evaluation criteria. Few studies in the world have conducted comparative analyses of the total life-cycle CO_2 emissions of different types of reinforced concrete structures. In addition, studies that mainly focus on the in-use phase and calculation of CO_2 emissions for the life cycle of buildings are scarce [68]. Furthermore, on a global scale, the large-scale use of reinforced concrete structures requires the establishment of a systematic CO_2 emission model that can accurately measure the life cycle CO_2 emissions of various types of reinforced concrete structures[69]. Especially in China, it is necessary to develop a suitable model for estimating CO_2 emissions and to conduct a comparative analysis of multiple types of structures to better guide low-carbon and green construction of reinforced concrete structures [70].

3 Research Method

This study aims to systematically estimate the CO_2 emissions of different types of reinforced concrete structures. This involves the use of multiple case studies combined with quantitative research methods.

3.1 Multiple case studies

The case study method is used to illustrate the problem through one or more selected cases, with the use of collected data to analyze the logical relationships between events. Multiple case studies help provide a more comprehensive understanding and reflect the different aspects of cases, making the approach a more rigorous, scientific, and theoretically validated research method[71]. In doing this, a comprehensive analysis is carried out for each case as an independent whole. The results are then integrated for a cross-case analysis of the four cases as a unified abstraction, and induction of the cases then provides a more incisive descriptions and stronger explanations. The case study of this paper comprise of three steps: (a) selection of cases; (b) classification of cases; and (c) the application of cases.

(a) *Selection of cases*. China is a big country with a vast number of reinforced concrete structures, so it is important to analyze projects that are representative of a large number of actual engineering cases for the research results to be more reliable and universal. In this respect, data were collected from a number of actual building cases from various provinces in China, from which representative cases were selected.

(b) *Classification of cases*. Internationally, reinforced concrete structures are often divided into six types[72]: schools, hospitals, aerospace, commercial, residential, and prisons. Due to the confidentiality issue of aerospace and prison construction data, only four types, i.e. housing, hospitals, businesses and schools were selected for the multiple case studies.

(c) *Application of cases*. After steps (a) and (b), the study elaborates on the last selected case, and illustrates the representativeness of the case and its source. The main material data for the reinforced concrete structural area building unit, and the energy data consumed during the construction process, were manually extracted from the list of case data and entered into *SimaPro* to build a CO_2 emission model, measure the model, and assess the environmental impact involved.

3.2 Quantitative research with *SimaPro*

The principles of LCA is taken as the guiding ideology, and the *BEES* method in the *SimaPro* software is selected to conduct a quantitative study of the research case.

SimaPro was first developed in the University of Leiden in the Netherlands in 1990. It can analyze and compare EIAs by using characterization, research and normalization, and weighting methods. The final analysis results are widely accepted, with many studies in the fields of machinery, food, products, and construction, having adopted the *SimaPro* software and the software's database. Of the many EIA construction industry applications, Steele et al. [73], for example, use *SimaPro* software to conduct the EIA of a bridge project, to provide suggestions concerning how to solve the environmental problems involved. Giri and Reddy [74] use the *SimaPro 8.0* software in finding that an MSE wall is more environmentally sustainable than a cantilever wall. Yay [75] establish a municipal solid waste management system through the *SimaPro* database. Danielle et al. [76] use the *SimaPro* software to analyze the sensitivity of the environmental performance of three different wall types. Starostka-Patyk [77] point out the usefulness of *SimaPro* in a company's decision-making process for designing new (and handling defective) products with an example of an IT solution; while Krish et al. [78] use *SimaPro* to conduct an economic assessment of the technology's breakeven and viability during a project. Some studies in China also use the *SimaPro* software to evaluate the life cycle of construction projects [79, 80].

The categories of environmental impact commonly encountered in *BEES* of the *SimaPro* software include Global warming, Acidification, Eutrophication, Ecotoxicity, Smog, Natural resource depletion, Habitat alteration, and Ozone depletion. The analysis results have high efficiency and reliability when using the *SimaPro* software along with its *BEES* to calculate the CO_2 emissions of reinforced concrete structure in a life cycle.

The *BEES* method was developed by the NIST (National Institute of Standards and Technology) Engineering Laboratory, which includes actual environmental and economic performance data for 230 building products[81]. *BEES* measures the environmental performance of building products using the life-cycle assessment approach specified in the ISO 14040 series of standards. All stages in the life of a product are analyzed, comprising raw material acquisition, manufacture, transportation, installation, use, and recycling and waste management [82].

The *Ecoinvent* database is used here. This contains LCI data from various sectors, such as energy production, transport, building materials, production of chemicals, metal production, and fruit and vegetables. The entire database consists of over 10,000 interlinked datasets, each of which describes a life-cycle inventory at the process level.

Based on the above method and database, the system boundary for the study is defined (Fig. 1). First, the functional unit is defined as 1 m^2 effective building area. Second, in order to ensure the feasibility and objectivity of the research, the lifetime of the reinforced concrete structure is assumed 50 years. In addition, it is assumed that the material transportation distance is 20 km. Building construction electricity is 10-14 kWh/m^2, and 16.25 kWh/m^2 for building demolition. Finally, the waste disposal scenario is assumed the municipal solid waste scenario (treatment of municipal solid waste, landfill).

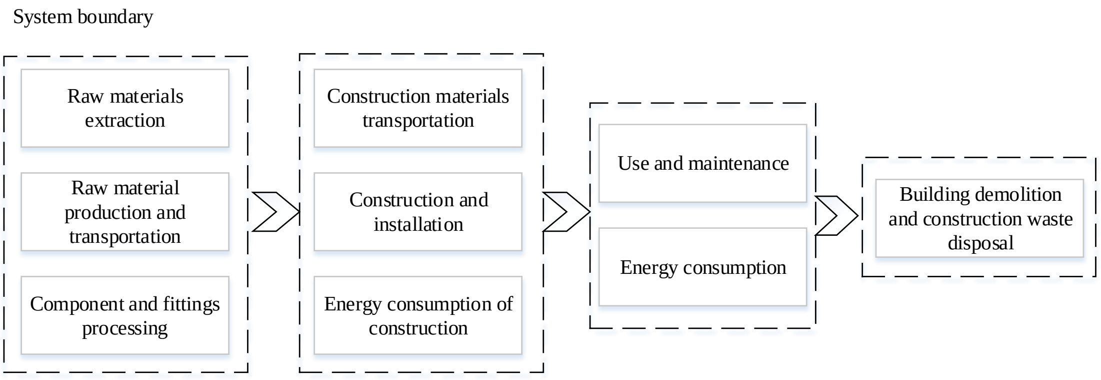


Fig. 1. System boundary of the reinforced concrete structures LCA

After assembling the CO_2 emission models in *SimaPro* for the four types of reinforced concrete structures, the CO_2 emissions is quantitatively analyzed for the life cycle of the construction, use and maintenance, and demolition phases of each reinforced concrete structure. Finally, a comparison of the four cases is undertaken, from which proposals are made for energy saving and emission reduction plans for each phase of the structures' life cycle. The methodology framework for the study is shown in Fig. 2

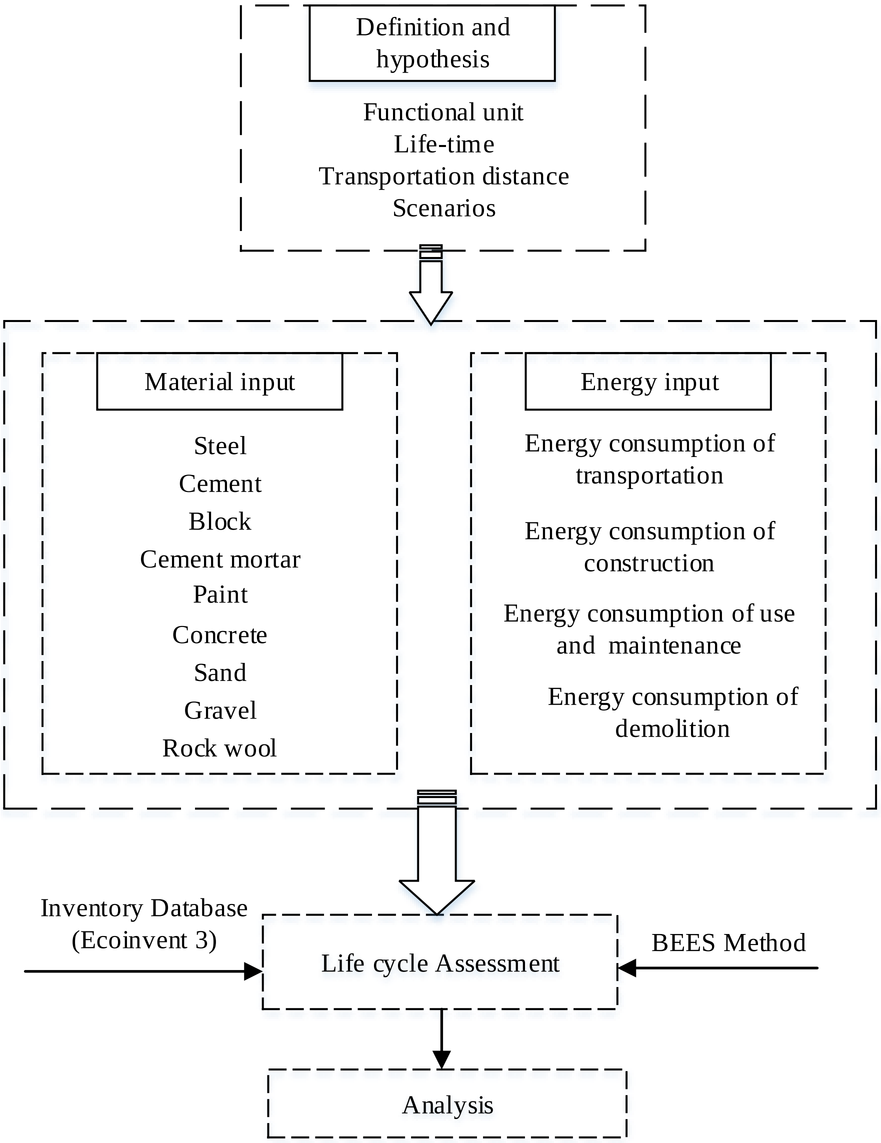


Fig. 2 Methodology framework

4 Multiple Cases Studied

This section describes the selection of four types of reinforced concrete structures; namely, residential, hospital, commercial, and school buildings, to conduct multiple case studies and using the *SimaPro* software for CO_2 emission assessments. Each type of data extracted from the actual construction projects is shown in Appendix. After collecting the data, the comparative analysis, and building evaluation process Charts and Tables are shown in the Appendix.

4.1 Case collection

Case 1: Residential building

This residential project is a reinforced concrete structure complex in a commercial residential district of Shaanxi Province. It comprises six high-rise residential buildings and an underground garage. It has 8 degrees of seismic fortification intensity, with a total construction area of 86,059 m^2, of which 24,880 m^2 is underground; and 55,569 m^2 and 5,610 m^2 above ground for residential and commercial use respectively. Various pollution prevention and control measures were adopted during the project's construction, such as water environment protection, air environment protection, and noise reduction measures. High-rise residential buildings are quite representative of urban residential buildings in China and are likely to dominate in the future too.

The quantities of primary materials per unit area of the building are shown in Table 1.

Table 1. Main materials of the residential building per functional unit area (/m^2)

Material	**Unit**	**Value**
Steel	kg	210.44
Concrete	m^3	1.73
Block	kg	67.42
Cement mortar	kg	166.70
Paint	kg	0.01

Case 2: Hospital building

This hospital project is located in Guangdong Province. It is a 7-storey building, of which the second and third floors are canteens. The fourth floor is the duty room for the nutrition department. The first floor and the fifth to sixth floors are warehouses, storage rooms, and security equipment libraries. The seventh floor contains oxygen working rooms and facilities equipment. The building has a total construction area of 1601 m^2 and 8 degrees of seismic fortification intensity. The building has many functions such as treatment, diet, residence, and storage, and well reflects the basic functions and characteristics of the hospital project type. Table 2 gives the building's main materials.

Table 2. Main materials of the hospital building per functional unit area (/m^2)

Material	**Unit**	**Value**
Concrete	m^3	0.488
Portland cement	kg	113
Steel	kg	95
Block	kg	224
Sand	kg	389
Cement mortar	kg	159
Paint	kg	7

Case 3: Commercial building

The commercial project is an office building of a construction company in Guangdong Province. This is a 36-story building with a total construction area of 192,181m^2. It has a frame structure with an independent foundation. Its design life is 50 years, with 7 degrees of seismic fortification intensity. It has a fire resistance level of one. It is a representative commercial building, being typical of its kind in China. The main materials are listed in Table 3.

Table 3. Main materials of the commercial building per functional unit area (/m^2)

Material	Unit	Value
Block	kg	27.01
Concrete	m^3	0.661
Steel	kg	95.00
Rock wool	kg	0.055
Cement mortar	kg	32.23
Paint	kg	0.225
Gravel	kg	2.170

Case 4: School building

This school project type is from the teaching building construction project of a college in Zhejiang Province. The project has five floors above ground and no basement. There are nine common classrooms, three combined classrooms, teaching, and research rooms, a drinking room, and electricity distribution rooms on the first floor. There are nine common classrooms, teaching and research rooms, drinking room, distribution rooms on the second and fourth floor; and the fifth floor has 12 common classrooms and power distribution rooms. The total construction area is 4,981 m^2 with 8 degrees of seismic fortification intensity. It has a frame structure, and a flat roof with no day lighting. Its rooms well reflect the basic functions and characteristics of this project type. Its main materials are listed in Table 4.

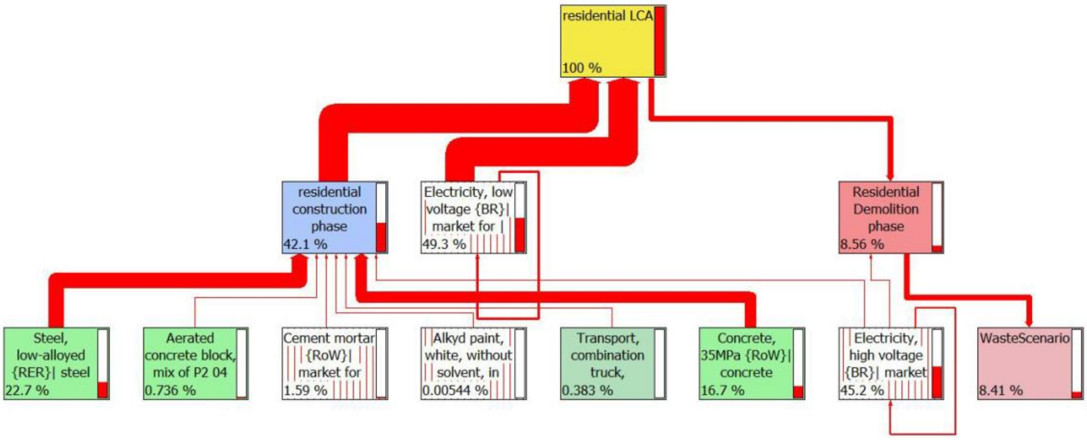
Table 4. Main materials of the school building per functional unit area (/m^2)

Material	**Unit**	**Value**
Steel	kg	53.53
Concrete	m^3	0.503
Block	kg	233.99
Paint	kg	4.27
Cement mortar	kg	120.09

4.2 Results

Case 1: EIA of the Residential Building

From the software analysis and calculations according to the assembly model, the network structure of the environmental emissions of the residential building life cycle is shown in Fig. 3. The network structure provides a diagrammatic illustration of the contribution of the materials' environmental emissions to environmental impact in each phase.



Note: Residential construction phase 42.1% − the construction phase accounts for 42.1% of the environmental emissions to the environmental impact of the residential building life cycle.

Electricity, low voltage 49.3% − the use and maintenance phase accounts for 49.3% of the environmental emissions to the environmental impact of the residential building life cycle. Etc.

Fig. 3. Network structure of the environmental emissions of the residential building life cycle

As Fig. 3 indicates, the residential building produced 42.1% of environmental emissions during the construction, 49.3% in the use and maintenance phase, and only 8.56% in the demolition phase. Of the eight categories of environmental impact considered, global warming is primarily affected by CO_2 emissions. The results show that the construction phase contributes the most to global warming (reached to 60%) during the life cycle. Table 5 summarizes the carbon emissions of the residential building in the construction phase.

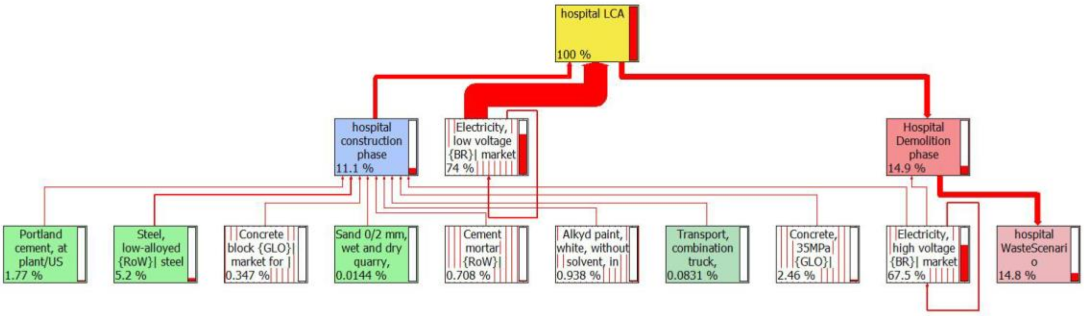
Table 5. The carbon emissions of the residential building in the construction phase

Materials & related processes	Carbon emissions /kg CO_2 eq	Percentage
Steel	613.43	49.242%
Block	31.29	2.512%
Cement mortar	44.44	3.568%
Paint	0.05	0.004%
construction electricity	2.04	0.164%
Transportation	10.11	0.812%
Concrete	544.37	43.699%
Summary	1246	100%

The CO_2 emission during the construction phases is 1246 kg CO_2 eq, accounting for 60.5% of the building's life cycle emissions followed by the use and maintenance phase (702 kg CO_2 eq, accounting for 34.1%) and the demolition phase (111 kg CO_2 eq, accounting for 5.38%). The CO_2 emission per construction unit is 2059 kg CO_2 eq / m^2 throughout the entire residential life cycle.

Case 2: EIA of the Hospital Building

The network structure of the environmental emissions in the life cycle of the hospital building is provided in Fig. 4, which shows its environmental emissions to be the most during the use and maintenance phase (74%), the demolition phase (14.9%), and the construction phase (11.1%).



Note: Hospital construction phase 11.1% — the construction phase accounts for 11.1% of the environmental emissions to the environmental impact of the hospital building life cycle.

Electricity, low voltage 74% — the use and maintenance phase accounts for 74% of the environmental emissions to the environmental impact of the hospital building life cycle. Etc.

Fig. 4. Network structure of the environmental emissions of the hospital building life cycle

Table 6 summarizes the carbon emissions of hospital building in the construction phase.

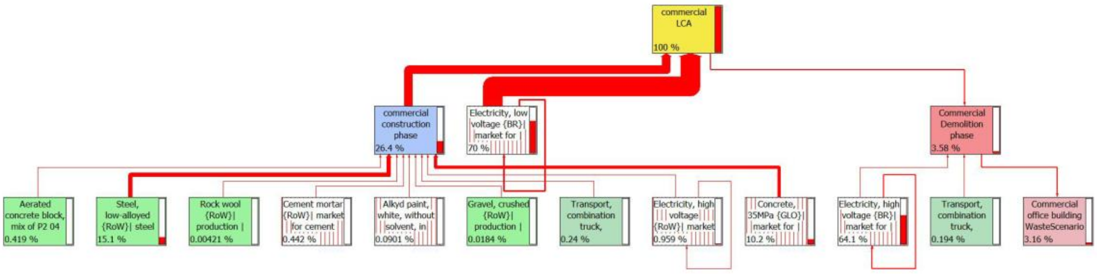
Table 6. The carbon emissions of hospital building in the construction phase

Materials & related processes	Carbon emissions /kg CO_2 eq	Percentage
Concrete	168	23.614%
Cement	154	21.646%
Steel	285	40.059%
Block	20.8	2.924%
Sand	0.947	0.133%
Cement mortar	42.5	5.974%
Paint	33.7	4.737%
Construction electricity	1.67	0.235%
Transportation	4.83	0.679%
Summary	711	100%

The amount of CO_2 emissions during the use and maintenance phase is 2,260 kg CO_2 eq, accounting for 66.9%, followed by the construction phase (711 kg CO_2 eq, at 21%), and demolition phase (410 kg CO_2 eq, at 12.1%). The emissions per construction unit throughout the life cycle of the hospital building are 3,390 kg CO_2 eq/m^2.

Case 3: EIA of the Commercial Building

The network structure of the environmental emission in the life cycle of the commercial building is shown in Fig. 5.



Note: Commercial construction phase 26.4% — the construction phase accounts for 26.4% of the environmental emissions to the environmental impact of the commercial building life cycle.

Electricity, low voltage 70% — the use and maintenance phase accounts for 70% of the environmental emissions to the environmental impact of the commercial building life cycle. Etc.

Fig. 5. Network structure of the environmental emissions of the commercial building life cycle

As Fig. 5 indicates, the environmental emissions of the commercial building occur mainly during the use and maintenance phase, accounting for 70% of its life cycle emissions, followed by the construction phase (26.4%) and demolition phase (3.58%). Table 7 shows the carbon emissions at the construction phase of the commercial building.

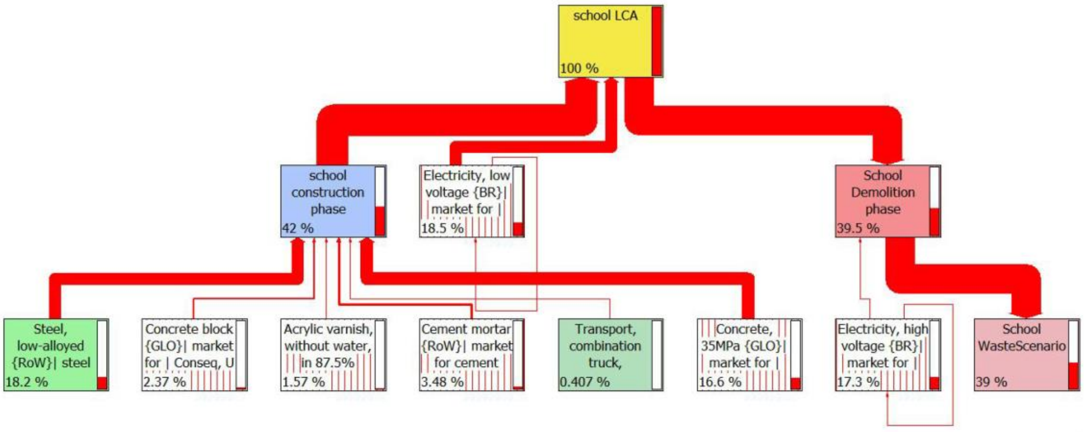
Table 7. The carbon emissions of the commercial office building in the construction phase

Materials & related processes	Carbon emissions /kg CO_2 eq	Percentage
Block	12.54	2.3%
Concrete	226.73	41.5%
Steel	286.18	52.4%
Rock wool	0.074	0.014%
Cement mortar	8.59	1.6%
Paint	1.03	0.189%
Gravel	0.022	0.004%
Transportation	4.574	0.838%
Electricity	5.997	1.1%
Summary	546	100%

The CO_2 emissions during the use and maintenance phase is 702 kg CO_2 eq, accounting for 54.75%, followed by the construction phase (546 kg CO_2 eq, at 42.54%) and demolition phase (35 kg CO_2 eq, at 2.70%). The CO_2 emissions per construction unit during the entire life cycle of the commercial building are 1283 kg CO_2 eq/m^2.

Case 4: EIA of the School Building

The network structure of the environmental emissions in the life cycle of the school building is shown in Fig. 6, which indicates they are most during the construction phase (42%), followed by the demolition phase (39.5%) and use and maintenance phase (18.5%).



Note: School construction phase 42% — the construction phase accounts for 42% of the environmental emissions to the environmental impact of the school building life cycle.

Electricity, low voltage 18.5% — the use and maintenance phase accounts for 18.5% of the environmental emissions to the environmental impact of the school building life cycle. Etc.

Fig. 6. Network structure of the environmental emission of school building life cycle

The carbon emissions of the school building in the construction phase are summarized in Table 8.

Table 8. The carbon emissions of the school building in the construction phase

Materials & related processes	Carbon emissions /kg CO_2 eq	Percentage
Steel	161	40.089%
Block	21.8	5.428%
Paint	10.2	2.540%
Cement mortar	32	7.968%
Concrete	173	43.077%
Transportation	3.61	0.899%
Summary	401	100%

The CO_2 emissions during the construction phase are 401 kg CO_2 eq, accounting for 61.4%; followed by the demolition phase (166 kg CO_2 eq at 25.3%) and the use and maintenance phase (86.4 kg CO_2 eq, at 13.2%). The CO_2 emissions per construction unit throughout the life cycle of the school building are 653 kg CO_2 eq/m^2.

5 Discussion

In terms of estimated CO_2 eq emissions per unit of construction area, the hospital, residential, commercial, and school buildings produce 3390 kg, 2059 kg, 1440 kg and 653 kg respectively over their full life cycle (Xining et al.'s [83] result for China residential buildings is similar at 2993 kg). The results highlight the importance of building type in determining its amount of life cycle emissions.

Table 9. Emissions of the four types of reinforced concrete structure in each life cycle phase（kg CO_2 eq）

Phase	Residential building	Hospital building	Commercial building	School building
Construction phase	1246	711	546	401
Use and maintenance phase	702	2260	702	86.4
Demolition phase	111	410	35	166

As shown in Table 9, energy consumption during the construction phase is the most in the life cycle of the residential and school buildings, while it is the most in the use and maintenance phase for the hospital and commercial buildings. Therefore, the life cycle phase is a key aspect for energy conservation. The results contrast with Kumanayake et al.'s [84] 629.6 kg CO_2 eq. in the construction phase of Sri Lanka commercial buildings, and Zhixing et al.'s [85] 326.75 kg CO_2 eq. in the construction phase of 78 China commercial buildings, leaving our results between these two, which to some extent supports their validity.

The CO_2 emissions of hospital buildings are concentrated in its use and maintenance phase, which is due to a large amount of medical equipment used after the hospital buildings are put into operation[86, 87]. In order to support the operation of equipment, energy consumption of building increases greatly, thus increasing the CO_2 emissions of hospital buildings, and making it far more than the other three types of buildings. Therefore, reduction of CO_2 emissions in hospital buildings can start with introducing advanced and low-energy equipment.

In general, CO_2 emissions during the use and maintenance phase accounts for 34% to 67% of the CO_2 emissions in a life cycle, of which the school in use and maintenance phase accounts for relatively less. Although the larger contribution rate for the use and maintenance phase is related to its 50-year cycle, resulting in a relatively large final absolute impact. Hence, the energy conservation at this phase is especially important. During this phase, it is most important to ensure that the functions of buildings are brought into full play, with their safety needs, suitability, and durability guaranteed[88]. Structural maintenance and reinforcement are particularly important and should be based on scientific detection and identification. It is necessary to adopt reasonable maintenance reinforcement measures, or improve the safety and durability of the structure through structural transformation [89]. While satisfying the normal function of the building, it is necessary to ensure the energy-saving and environmental protection of the building and extend its useful life.

Table 5. Rate of construction phase CO_2 emissions of the four reinforced concrete structure types by material

Material	**Residential building**	**Hospital building**	**Commercial building**	**School building**
Steel	49.20%	40.10%	52.4%	40.20%
Cement	-	21.60%	-	-
Block	2.51%	2.93%	2.3%	5.43%
Cement mortar	3.57%	5.98%	1.6%	7.98%
Paint	0.004%	4.74%	0.19%	2.54%
Construction electricity	0.16%	0.24%	1.1%	-
Transportation	0.81%	0.68%	0.84%	0.90%
Concrete	43.70%	23.60%	41.5%	43.00%

Note: "-" indicates that there is no item.

The detailed contributions of materials to *construction phase* CO_2 emissions of the four types of structures are shown in Table 10, indicating that steel contributes the most construction phase emissions, followed by concrete, cement mortar, blocks, paint, and other building materials. It can be seen that the highest carbon emissions during the construction phase of the residential building are due to the large amount of steel and concrete used per functional unit area. The results are mutually supportive of the results of Chang et al. [11], who found that the some types of buildings have larger carbon footprints because of their heavy structural designs, involving the intensive use of such high-emission building materials as steel and cement. Therefore, a "Carbon emission reduction" program for this phase would need to start from the production of steel and concrete, implementing clean, green production, and using advanced technology and equipment to optimize its structure and mix to help reduce resource consumption[90]. The contribution of steel to global warming is 40%-53%, and to the entire environment emissions is as high as 40%-80%.

Energy conservation in the production phase of building materials, especially that of steel, also plays an important part in conserving energy over the building life cycle. Therefore, in addition to optimizing the structure and equipment to obtain energy savings in the production phase of steel, it is also necessary to protect the steel against rust, which can guarantee or even extend the natural life of the steel. This is especially the case during the in-use phase of the building, when cracks in the concrete protective layer can expose the steel directly to the air, increasing the corrosion rate of the steel, which will inevitably reduce the building’s useful life [91]. The situation is even more severe in coastal areas[92]. Therefore, it is necessary to maintain the steel so it can play a full role in strengthening the whole structure[93]. In addition, the corrosion resistance of the steel can be enhanced by the incorporation of limestone powder to improve the interaction of the cement-based material in the concrete with the steel[94] by helping the resistance of the concrete to chloride penetration[95], thereby reducing the degree of corrosion and depth of carbonation.

6 Conclusion

As the main modern architectural form, reinforced concrete structures are a major source of CO_2 emissions. This paper uses the principle of LCA as the theoretical guiding ideology, and measures building CO_2 emissions through the innovative and systematic use of multiple case studies (school, hospital, commercial, and residential buildings) combined with quantitative research methods. In addition, the study evaluated the multiple environmental impacts of reinforced concrete structures, including global warming, acidification, eutrophication, eco-toxicity, smog, consumption of natural resources, habitat change, and ozone depletion. Moreover, the analytical models used for calculating the life cycle environmental emissions of reinforced concrete structures provides suggestions for energy conservation and identifies the key phases and fields of energy conservation to better assist the formulation of energy conservation policies and promote coordination between regulatory authorities[96, 97].

Overall, the total CO_2 emissions per unit is approximatley 30% higher in the four buildings' use/maintenance phase (3750.4 kg CO_2 eq) than the construction phase (2904 kg CO_2 eq), indicating the need to pay attention to post-occupancy energy use and energy conservation of buildings in order to reduce their huge energy consumption and CO_2 emissions. Steel and concrete are the main building materials contributing most to environmental emissions during the construction phase and need to be the focus of energy conservation to reduce construction CO_2 emissions. In terms of building type, hospital and school building have the highest and lowest CO_2 emissions per unit respectively, with the most construction and use/maintenance phase CO_2 emissions being by the residential building and hospital respectively.

For the government, as a smart regulator, the implication for practice is the need to develop CO_2 emission standards to promote technological advancement. As a long-term strategic planner and incubator, the government must promote building innovation and the development of low-carbon buildings by providing a friendly and innovative environment for promoting the use of new technologies, processes, and business models for energy conservation and emission reduction through tailored vocational training programs and effective programs in vocational schools and higher education development programs. As a forward-looking project owner, the government could also consider the maximization benefits obtained by the owners from the project's full life cycle, taking into account all the costs and benefits involved and the flexibility of the reuse of potential assets.

Finally, it should be pointed out that the study involves only four reinforced concrete structure cases to carry out the analysis, and therefore the findings suffer from a lack of generalizability. Although using *SimaPro* to calculate the CO_2 emissions of buildings in China is still not perfect, the findings are nevertheless of great significance because of the lack of alternative methods. In addition, due to the material diversity and complexity of the specific buildings, the study could not analyze more building materials and their energy consumption processes. Thus, future research with other types of reinforced concrete structures needs to be conducted for a complete CO_2 emission analysis of reinforced concrete structures.

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