

# Carbon emissions of cast-in-place and prefabricated buildings: a comparative analysis and carbon reduction strategy

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**Abstract:** Prefabricated buildings are increasingly advocated for their benefits, which include a shortened construction period, cost-efficiency, and enhanced resource utilization. However, the comparison between prefabricated and cast-in-place buildings on life-cycle carbon emissions is still insufficient. This study assesses and analyses the life cycle carbon emission of both types of structures and achieves carbon reduction strategies at various life cycle stages from actual cases. The analysis reveals that for both modular and cast-in-place buildings, the materials contributing the most to carbon emissions are concrete blocks, concrete, steel rebar, formwork, and wall plaster. In addition, the formwork in prefabricated buildings constitutes nearly half of the total carbon emissions during the construction stage compared to cast-in-place structures. In the maintenance phase, cast-in-place buildings are more low-carbon than prefabricated buildings because the insulation can be replaced. During the dismantling stage, carbon emissions from prefabricated buildings are approximately 11.31% lower than those from cast-in-place structures. The study also introduces several carbon reduction measures, for example, substantial emission reductions can be attained by substituting ordinary Portland cement with new dry process cement, employing RRAC concrete over regular concrete, utilizing lightweight aggregate concrete blocks instead of aerated concrete blocks, and opting for recycled steel. Regarding the operational phase, the implementation of solar photovoltaic panels on building rooftops has been proven to effectively curtail carbon emissions.

## 1 Introduction

The construction industry is one of the three major energy-consuming industries, alongside industry and transport[1]. In China, energy usage in buildings accounts for about 25% of the total energy consumption of society. When incorporating related factors such as the production and transportation of building materials, the cumulative energy consumption associated with the construction industry reaches an estimated 46.7%[2] and the carbon emissions it produces account for about 40% of the total carbon emissions[3], which is one of the key industries for energy conservation and emission reduction[4]. Amidst rapid urbanization, the aggregate number of structures is on an uptrend, and as residents' living standards persistently ascend, both the absolute and relative quantities of carbon emissions from buildings are projected to surge significantly. With the rapid development of urbanization, the total number of buildings is increasing, and the living standard of residents continues to improve. The absolute value and relative proportion of building carbon emissions will rise rapidly.

The potential for carbon reduction in the building sector is immense. According to a consultancy report by the Chinese Academy of Sciences, buildings can achieve energy savings of 30-70% by implementing prudent energy-saving designs and applying scientific operation and management[5]. As such, the calculation and analysis of carbon emissions within the construction

industry hold significant importance for energy conservation and emission reduction across society[6].

In recent years, prefabricated buildings have gained prominence due to their rapid construction speed, high productivity, and abbreviated construction timelines. Notably, Sweden and Japan are international leaders in this domain, with prefabricated structures comprising 20% and 16% of housing construction, respectively[7]. Concurrently, numerous scholars have engaged in research on the energy-saving, emission-reduction performance, and carbon-reduction measures specific to prefabricated buildings. For instance, Shasha Chang[8] discovered that the carbon emissions from prefabricated buildings are approximately 20% lower than those of traditional structures throughout their entire lifecycle. Similarly, Zhou[9] advocated for the acceleration of research and development and innovation in prefabricated building technologies, alongside the advancement of new environmentally friendly materials, through studies on the carbon emissions of prefabricated structures.

While there is a substantial body of research on methods for quantifying carbon emissions in the construction industry, there is a comparative paucity of studies examining the lifecycle carbon emissions of prefabricated buildings versus cast-in-place structures. Therefore, this paper aims to compare and analyze the carbon emission characteristics of aims to compare and analyze the carbon emission profiles of prefabricated and cast-in-place buildings at various stages of their entire

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lifecycle, specific research ideas are shown in Figure 1. This analysis is grounded in a specific case study, with the ultimate goal of proposing viable strategies for

carbon reduction at various stages of the whole life cycle based on a specific real case and presents reasonable carbon reduction strategies.

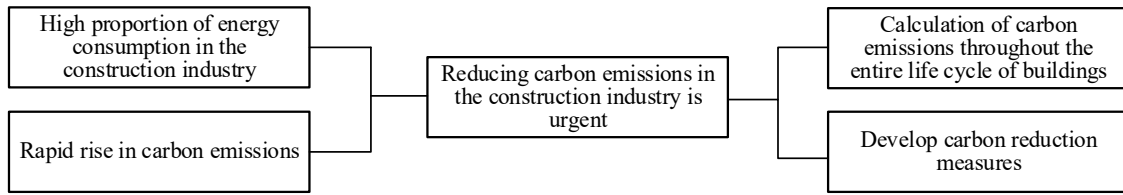


Fig. 1. Background and research ideas.

## 2 Computational theory

### 2.1 Selection of calculation methods

Common methodologies for calculating carbon emissions from buildings include the carbon emission factor method, measured data method, and input-output method. The carbon emission factor method involves multiplying established activity data by a carbon emission factor to determine the carbon emissions of the target entity. This method is straightforward, user-friendly, and characterized by a brief time cycle[10]. The measured data method entails using nationally or industrially recognized instruments to measure the flow, concentration, and flow rate of greenhouse gases emitted by the target and its surroundings[11]. While the precision of this method is high, yielding data that is both accurate and reflective of actual conditions, it necessitates an extensive time commitment and substantial labor costs. Additionally, it imposes stringent demands on the measuring instruments, equipment, and environmental conditions during the measurement process. Conversely, the input-output method operates on the principle that the aggregate of all resources and energy inputs in a target's production process should equate to the total output of GHG emissions. This approach is exclusively applicable for macro-level calculations[12].

In this study, a detailed account of each stage and sub-stage carbon emission is imperative when performing calculations. Considering the requirements for time, labor, and material resources, we have opted for the carbon emission factor method to compute the carbon emissions associated with the building.

### 2.2 Computational framework

The whole life cycle carbon emission of a building takes into account four stages, namely the construction stage, operation stage, maintenance stage and demolition and recycling stage, so the whole life cycle carbon emission of a building is the sum of the carbon emissions of the four steps.

$$LCCE = CE_{con} + C_M + CE_{main} + CE_{dem} \quad (1)$$

LCCE—Whole Life Cycle Carbon Emissions of Buildings

$CE_{con}$ —Carbon emissions during the construction stage

$C_M$ —Carbon emissions during the operational stage

$CE_{main}$ —Carbon emissions during the maintenance stage

$CE_{dem}$ —Carbon emissions during the dismantling and recycling stage

#### 2.2.1 Construction stage

In the construction stage, the carbon emission is calculated based on the bill of quantities. The fixed consumption of labor, materials and machines required to complete each item of the bill of quantities is found through the national, provincial or industrial specifications. Then, After the calculation of all the inventory carbon emissions are summed up, the total carbon emissions of the building phase can be obtained. The formulas are as follows:

$$CE_{con} = \sum CEC_i \times Q_i + \sum CEC_j \times Q_j \quad (2)$$

$$CE_{con} = \sum p CE_{lab} + \sum q CE_{mat} + r CE_{mech} \quad (3)$$

$CEC_i$ —unit carbon emission coefficient of subdivision project

$CEC_j$ —unit carbon emission coefficient of measure engineering

$Q_{ij}$ —quantity of subdivision project

$CE_{lab}$ ,  $CE_{mat}$ ,  $CE_{mech}$ —Carbon emission factors corresponding to labour, material and equipment

$p, q, r$ —Consumption corresponding to time, materials and equipment

#### 2.2.2 Operational stage

The carbon emissions during the operation stage mainly come from HVAC, lighting, hot water, elevators, etc. The main forms of energy consumed are electricity and natural gas. According to the Standard for Calculating Carbon Emissions of Buildings in China (GBT51366-2019), the carbon emissions of the buildings during the operation stage are calculated as follows:

$$C_M = \frac{\sum_{i=1}^n (E_i EF_i) y}{A} \quad (4)$$

$E_i$ —Annual energy consumption in buildings (unit/a)

$EF_i$ —Carbon emission factors of energy

$y$ —Building design life

$A$ —building area( $m^2$ )

#### 2.2.3 Maintenance stage

The specific content in the maintenance stage includes replacing structures such as doors and windows, external insulation layers, etc. The carbon emissions generated in

the maintenance stage are divided into two parts. One is the carbon emissions generated in dismantling the old structure; The other is the carbon emissions generated by the production, transportation and installation of new components.

### 2.2.4 Demolition and recycling phase

In the demolition stage, mechanical and manual demolition is adopted, and the carbon emission in the demolition stage is equal to the amount of waste generated multiplied by the corresponding demolition quota consumption and carbon emission factors. Construction waste recycling is the reuse of building materials and energy, which helps to reduce the carbon emission of the whole life cycle of the building. Its calculation is based on the specific material recovery rate and the corresponding carbon emission factor.

## 3 Case study

### 3.1 Case description

In this case, two similar appearance buildings are located in the same residential area, using cast-in-place and prefabricated structures, the design lifespan during the operation stage is 50 years. Their specific parameters are showed in Table 1, and the elevation drawing is shown in Figure 2.

**Table 1.** Basic project parameters.

Construction process	Cast-in-place Building	Prefabricated Building
Story	10	10
Length (m)	73.3	15.5
Width(m)	15.5	13.7
Building area(m <sup>2</sup> )	11361.5	10042.1
Building height(m)	26.4	23.2
Structure type	Shear wall	Assembled monolithic shear wall



**Fig. 2.** Elevation of cast-in-place building and prefabricated Building.

### 3.2 Carbon emissions of cast-in-place and prefabricated buildings in whole life cycle

As illustrated in Table 2, the carbon emissions produced by prefabricated buildings throughout their entire life cycle are markedly lower than those of traditional cast-in-place buildings. The data indicate that, regardless of the construction method employed, the operational phase

of a building invariably contributes the most significant share of carbon emissions in its entire life cycle, exceeding 70%. Furthermore, the construction phase also accounts for a substantial portion of carbon emissions, constituting more than 20%. This underscores the importance of focusing on both these stages when strategizing for effective carbon reduction in building projects.

**Table 2.** Carbon Emissions of Cast-in-Place and Prefabricated Buildings.

Stages	Prefabricated building		Cast-in-place buildings		Carbon Emission reduction (%)
	Carbon footprint (tCO <sub>2</sub> -eq)	Share of carbon emissions (%)	Carbon footprint (tCO <sub>2</sub> -eq)	Share of carbon emissions (%)	
Construction stage	3679.11	23.60	4199.75	24.6	12.40
Operational stage	11946.84	76.64	12707.33	74.43	5.98
Maintenance stage	123.81	0.79	68.05	0.4	-81.94
Demolition and Recycling stage	-160.68	-1.03	96.98	0.57	265.68
Sum	15589.08	100	17072.11	100	8.69

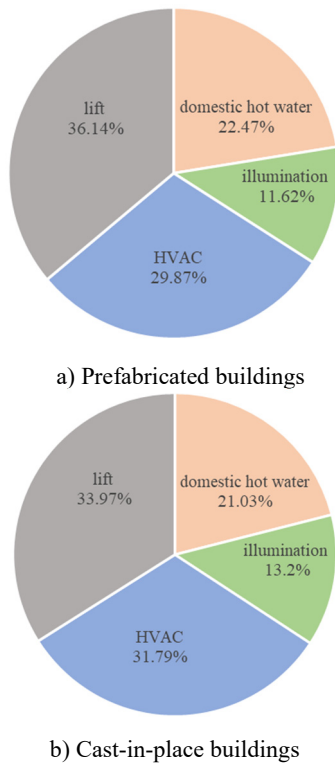
#### 3.2.1 Construction stage

Materials generate over 95% of carbon emissions during construction, followed by machinery and labor. The top five materials contributing the highest carbon emissions, applicable to both prefabricated and cast-in-place structures, have been identified as concrete blocks, concrete, reinforcing steel, formwork, and wall plaster. In the case of cast-in-place buildings, the combined carbon emissions from reinforcing steel and concrete constitute 63.48% of the total emissions during the construction stage. This implies that over half of the carbon emissions in this stage are attributed to reinforcing steel and concrete, a critical consideration for project designers when devising optimal design. For prefabricated buildings, the carbon emissions from steel and concrete in the construction stage are also considerable, nearing 40% and representing a significant source of emissions.

Beyond reinforcing steel and concrete, the carbon emissions from aerated concrete blocks and wall plastering are also noteworthy. Furthermore, formwork in prefabricated buildings comprises nearly half of the carbon emissions in the construction stage when contrasted with cast-in-place buildings. This discrepancy is due to the construction techniques employed in prefabricated buildings. Since formwork can be reused multiple times, it has the potential to significantly curtail carbon emissions.

### 3.2.2 Operational stage

The primary contributors to carbon emissions during the operational phase are HVAC (heating, ventilation, and air conditioning), lighting, domestic hot water, and elevators. As depicted in Figure 3, there is minimal variance in the proportion of carbon emissions between prefabricated buildings and cast-in-place buildings. This difference is primarily attributable to floor area, which results in divergent energy demands for HVAC and lighting, thereby affecting the total carbon emissions in the operational phase. During the operation phase, due to the necessity of using elevators, domestic hot water, and lighting, it is impossible to control them. Therefore, the development of carbon reduction strategies should focus on HVAC.



**Fig. 3.** Carbon emission comparison of two buildings in operation stage.

### 3.2.3 Maintenance stage

Regarding carbon emissions in the maintenance phase, cast-in-place buildings exhibit superior performance, particularly concerning insulation replacement. This advantage is largely due to the more monolithic structure of cast-in-place buildings, which necessitates less insulation replacement material, thereby reducing carbon emissions. In addition, the integral construction of these buildings minimizes the need for extensive materials and associated processes, typically required in structures with more complex assemblies, ultimately contributing to a lower carbon footprint during maintenance activities.

### 3.2.4 Demolition and recycling stage

When comparing the carbon emissions from the dismantling and recycling stage of prefabricated building to those of cast-in-place building using a consistent

calculation method, it's evident that prefabricated buildings decrease carbon emissions by approximately 11.31% relative to cast-in-place buildings. This reduction is substantial, underscoring the significant carbon-curbing impact of prefabricated construction methods during the dismantling stage. This finding highlights the environmental benefits of prefabrication, particularly in the context of sustainable building practices and the broader imperative of reducing greenhouse gas emissions in the construction sector.

## 4 Carbon reduction strategies

Irrespective of the construction methodology employed, most carbon emissions in a building's entire life cycle are predominantly allocated to the construction and operation stages. These stages collectively contribute the most substantial carbon footprint and should be the primary focus for emissions reduction initiatives within the building sector.

### 4.1 Construction stage

**Table 3.** Carbon emissions change after the material replacement.

Material replacement	Prefabricated building		Cast-in-place construction	
	Carbon reduction (tCO <sub>2</sub> -eq)	Carbon reduction ratio(%)	Carbon reduction (tCO <sub>2</sub> -eq)	Carbon reduction ratio(%)
Concrete RRAC	188.26	5.12	217.05	5.17
Dry cement	43.68	1.18	53.48	1.27
lightweight Aggregate concrete blocks	116.48	6.46	314.3	7.48
Renewable steel	461.74	12.55	877.82	20.90

In the construction phase, materials contribute most significantly to carbon emissions. In its exploration of carbon reduction strategies, this study focuses on substituting materials that are major contributors to carbon emissions in the given case—specifically, concrete, steel reinforcement, blocks, and cement. Table 3 illustrates the impact of these substitutions, showcasing the subsequent changes in carbon emissions during the construction stage following the implementation of these replacements.

This approach underscores the potential environmental benefits of opting for alternative materials with lower carbon footprints in construction. Both assembled and cast-in-place buildings can achieve good carbon reduction by replacing materials with higher carbon emissions.

### 4.2 Operational stage

In the entire life cycle of a building, the operational phase accounts for the highest carbon emissions, with

electricity usage playing a crucial role during this stage. Installing an extensive array of photovoltaic (PV) panels on building roofs allows for the conversion of solar energy into electricity and heat for secondary use, or using other renewable energy solutions, epitomizing the true essence of sustainable development in buildings. According to Yining Zou[13], incorporating solar PV panels on a building's roof can markedly diminish the building's whole life cycle carbon emissions, potentially reducing operational phase emissions by approximately 9.85%. Applying these data to this case, adding solar PV panels to prefabricated buildings could reduce about 7.55% of whole life cycle carbon emissions. Conversely, integrating solar PV panels could reduce around 7.33% of whole life cycle carbon emissions for cast-in-place buildings. Consequently, installing solar PV panels is an effective strategy for curtailing carbon emissions during a building's operational phase, irrespective of whether the structure is prefabricated or cast-in-place.

## 5 Conclusion

This paper introduces a comprehensive set of quantitative methods for assessing the whole life cycle carbon emissions of buildings. Utilizing a real case, it compares and analyzes the characteristics of carbon emissions throughout the life cycles of prefabricated and cast-in-place building. The key findings are as follows.

(1) Viewed holistically, prefabricated buildings' life cycle carbon emissions are significantly lower than those of traditional cast-in-place structures. For both prefabricated and traditional cast-in-place buildings, the construction and operational stages combined contribute to over 99% of the whole life cycle carbon emissions. Therefore, carbon reduction strategies should primarily target these stages.

(2) Concerning the construction stage, materials' carbon emissions constitute more than 95% of the total emissions for both prefabricated and cast-in-place buildings. The five materials contributing the most are concrete blocks, concrete, steel reinforcement, formwork, and wall plaster. Notably, the carbon emissions from formwork in prefabricated buildings account for nearly half of the construction stage's emissions compared to cast-in-place structures.

(3) During maintenance, cast-in-place buildings have a lower carbon footprint than prefabricated buildings, primarily due to the lesser need for insulation replacement.

(4) In the dismantling and recycling stage, prefabricated buildings, owing to their superior structural integrity and higher recyclability, achieve a carbon reduction of approximately 11.31% compared to cast-in-place buildings.

Furthermore, this paper suggests practical carbon reduction strategies tailored to the specific emission characteristics of buildings. In the construction phase, significant carbon emission reductions can be achieved by substituting ordinary silicate cement with dry cement, replacing standard concrete with RRAC (recycled raw aggregate concrete), switching from traditional steam aerated concrete blocks to lightweight aggregate

concrete blocks, and using renewable steel instead of ordinary steel. In the operational phase, where carbon emissions are primarily driven by energy consumption (such as electricity), the installation of solar photovoltaic panels on rooftops can decrease operational carbon emissions, providing valuable guidance for decision-makers in formulating effective carbon reduction strategies.

The research presented in this article, while comprehensive, acknowledges certain limitations. To elaborate, the variability in carbon emission factors across different regions and projects poses a challenge and necessitates a nuanced approach to estimating carbon emissions. The factors utilized in this study may not be universally applicable. Future research could benefit from developing adaptable models for these variances, potentially incorporating dynamic carbon emission factors reflective of specific geographical and project contexts.

Furthermore, this study does not encompass updates in furniture and electrical appliances during the maintenance phase, a limitation stemming from the scope of our research. The life cycle assessment of buildings must consider the environmental impact of periodic updates, including furniture and electrical appliances. These elements contribute significantly to the carbon footprint during the maintenance phase.

Lastly, advancing technologies and evolving regulatory environments continually shape the landscape of carbon emissions in the building sector. Emerging sustainable materials, energy-efficient appliances, the interplay between building design, occupant behavior and environmental impact, and regulatory changes offer new opportunities and challenges for reducing carbon footprints. Future research should aim to integrate these developments into life cycle assessments, providing a more comprehensive and up-to-date perspective on sustainable building practices.

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