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An Empirical Study on the Impact of Different Structural Systems on Carbon Emissions of Prefabricated Buildings Based on SimaPro

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Abstract

In the context of global emission reduction, the low-carbon sustainable development of the construction industry has become an important research content. With the vigorous development of new industrial technologies, the application of prefabrication technology to buildings had become a mainstream. However, the research on the role of prefabricated technology in reducing building carbon emissions was not yet comprehensive, and the research on the relationship between prefabricated structure types and carbon emissions in the construction stage was not yet thorough. Guided by life cycle assessment (LCA), this paper used the scenario analysis method to set different working conditions for five different structural systems, and used SimaPro software to evaluate the carbon emissions of prefabricated buildings in order to clarify the carbon emissions of prefabricated buildings under different structural systems, and explore their impact mechanisms in depth. Finally, take the existing buildings in China as an empirical study, the results showed that: 1) The carbon emissions produced by the four common prefabricated structural systems were almost the same. Different structures had different requirements for the combination of components. The carbon emissions of individual buildings would be superimposed according to the carbon emission characteristics of various individual components to form the final total carbon emissions. 2) When the building structure system requires more combinations of components, the greater the amount of transportation invested in the transportation process, the more carbon emissions would be caused. In the calculation of all individual building construction stages, the carbon emissions generated by tower cranes almost exceed the sum of the carbon emissions of all mobile machinery. 3) Prefabricated shear wall structures and prefabricated frame-shear wall structures require a large amount of hoisting

of prefabricated shear walls, so the carbon emissions of their mechanical equipment were also the highest.

Keywords

Prefabrication, Different Structural Forms, Carbon Emissions, Scenario Analysis

1. Introduction

In recent years, problems such as global warming, extreme weather, sea level rise, and ecosystem destruction have occurred frequently. The greenhouse effect has seriously threatened the sustainability of the natural environment and human society. According to the first assessment report of the United Nations Intergovernmental Panel on Climate Change (IPCC), the main cause of global warming is the excessive emission of greenhouse gases (GHG) such as CO_2 [1]. In order to reduce greenhouse gas emissions and control the acceleration of global warming, countries have successively introduced measures and policies for energy conservation and emission reduction. For example, the United States officially re-joined the "Paris Agreement" in 2021, and re-launched a strategic sustainable plan to deal with climate change to reduce its dependence on fossil fuels in many ways. At the 75th session of the United Nations General Assembly, it was announced that China would strive to achieve carbon peaking by 2030 and achieve net-zero carbon emissions by 2060.

Achieving the "dual carbon" goal requires multi-industry and multi-level joint efforts. The construction industry is one of the seven major industries that emit GHG. According to the sixth assessment report released by the IPCC in 2021, the construction industry consumes about 40% of the total energy consumption, and the annual greenhouse gas emissions are as high as 29% [2]. In the "Research Report on China's Building Energy Consumption and Carbon Emissions" released by the China Building Energy Conservation Association in December 2022, the total carbon emissions of the entire construction process in the country accounted for 50.9% of the country's carbon emissions in 2020, reaching 5.08 billion tons. From 2005 to 2020, the carbon emissions in the whole process of construction in China increased by 2.3 times, with an average annual growth rate of 5.8%. It can be seen that the greenhouse gas emission reduction measures in the construction field have become an important research content for countries to achieve emission reduction goals and promote the low-carbon sustainable development of the construction industry; among the components of greenhouse gases, CO_2 is the most important component of greenhouse gases More people's attention [3] [4] [5]. And further, it can be known that in the construction industry, housing construction accounts for a large part of the total carbon emissions [6].

For this reason, Japan, the United States, Germany and other countries have successively requested the development of industrialized construction [7] [8]. Prefabrication technology is a technology that changes the traditional cast-in-place production mode, which produces building components through off-site manufacturing facilities, and then completes the construction work through on-site assembly [9] [10] [11]. Prefabricated buildings have the advantages of high production efficiency, short construction period, and good product quality. Prefabrication is produced intensively in a controlled environment. In the process of component manufacturing and production, due to the improvement of the production workshop environment and manufacturing process, the material loss in the processing process has been greatly reduced. At the same time, the large-scale centralized production of components is conducive to the recycling and reuse of waste materials. At the current level of technology utilization, the total waste generation rate of prefabricated construction projects is 25.85% lower than that of non-prefabricated projects, and prefabrication can effectively reduce most types of construction waste [10]. This has very important practical significance for reducing CO_2 emissions. From the perspective of macro performance, prefabricated buildings reduce construction waste and human labor time, and seem to have obvious potential for carbon emission reduction, but there is still insufficient research on the relationship between prefabricated buildings and carbon emission reduction.

Therefore, testing the carbon emission reduction capability of prefabricated buildings has become a topic that must be studied. Although some scholars have studied the life cycle carbon emissions of prefabricated buildings, whether different structures have an impact on the carbon emissions of the building construction stage, and what kind of impact relationship exists is not yet clear, so the impact on prefabricated building structures and carbon emissions Mechanistic studies are crucial. This research mainly includes the following contributions: 1) Established a carbon emission calculation model of prefabricated buildings based on SimaPro software. 2) Based on the scenario analysis method, set up different component combinations of different structural systems, and simulate the impact of different structures on materials. 3) Based on the above theoretical research, combined with typical cases to calculate carbon emissions, and analyze the characteristics of carbon emissions at the life cycle level and mechanical equipment level.

2. Literature Review

2.1. Prefabricated Building Carbon Emissions

The research on carbon emissions of prefabricated buildings can be generally divided into two aspects: 1) The impact of prefabricated buildings on energy consumption: Scholars have studied the ecological damage of prefabricated buildings, the generation of construction waste, and the constraints on the development of the construction industry. In his research on prefabricated buildings, Ferdous pointed out that the construction process caused 32% of energy consumption, 30% of carbon dioxide emissions and 30% - 40% of waste generation [12]; there is an approximately linear correlation between the rate and the average incremental energy use [13]. 2) The impact of prefabricated buildings on greenhouse gas emissions: the operation stage of buildings produces the vast majority of greenhouse gas emissions [14], and many studies are dedicated to proposing advanced emission reduction technologies, policies and measures to reduce greenhouse gas emissions during the operation stage [15] [16]. Tavares assessed the life cycle environmental impact, cost and waste of two different construction systems (prefabrication and conventional) and different structural materials, providing a comprehensive assessment showing that prefabrication can reduce impact, material use, waste and production time to achieve similar operating performance, leading the construction industry towards a more circular path [17]. Generally speaking, the research on carbon emissions under prefabricated buildings mostly focuses on energy consumption and greenhouse gas emissions, but there are few studies on the evaluation of prefabricated horizontal systems and the impact of different structural systems on carbon emissions.

2.2. Carbon Emissions under Different Structural Systems

After the above analysis of the research status on carbon emissions of prefabricated buildings, it can be known that although there have been more and more researches on carbon emissions of prefabricated buildings, there are still few studies that further explore the CO_2 emission reduction mechanism of prefabricated buildings, especially through different structural systems. What factors affect carbon emissions indirectly? There are indeed studies that have focused on structural system aspects, for example [18] by showing that changes in structural system characteristics, including the type of anti-side load system, material and height of the structure, can have a significant impact on the carbon footprint of the structure, as The carbon footprint of each individual design is estimated by considering emissions during material extraction, transport, construction, operation and end-of-life stages.

However, there are generally two problems in the research: 1) The cases of different structural systems exist in many different buildings, and few prefabricated buildings are involved. Although the carbon emission calculation results are accurate, they are not carried out in the same building, so the comparison does not go deep into the system; 2) The actual situation is not considered: in most cases, different structural systems have different working conditions, and the components contained in them The combination and construction process are also different. Buildings will change the number of components and the total amount of materials with different structural systems. Consideration of variations in this mechanism of action is blank.

In summary, the existing research lacks exploration of changes in the relationship between component level, structural system and final carbon emission impact. This study solves this research gap from two aspects: firstly, it uses scenario analysis to set up, and sets up different working conditions according to the specific regulations that affect the number and types of components in the structural system. Secondly, use software to calculate the carbon emissions of the materialization stage of the same building, and observe the differences in carbon emissions at various levels.

3. Method

3.1. Research Framework

In this study, the LCA method was used to calculate the carbon emissions of the prefabricated building construction stage. LCA is a widely used method for assessing the environmental performance of a product throughout its life cycle [19] [20]. An accurate LCA method consists of the following four steps: (I) Objective and Scope Definition; (II) Life Cycle Inventory; (III) Impact Assessment and (IV) Interpretation.

CO_2 emissions are the most common and the most common greenhouse gas emissions. The LCIA method converts the rest of the greenhouse gases into CO_2 equivalents through a conversion factor, which can be effectively used as a measure of greenhouse gas emissions [21]. The IPCC 2013 method is an update and improvement based on the 2007 data of the Intergovernmental Panel on Climate Change (IPCC). The method shows that different global warming potentials (GWP) have a great impact on climate change. Prefabricated buildings usually have a lifespan of 100 years, so it is most reasonable to choose GWP 100.

In this paper, the software tool SimaPro is used to assess the environmental impact of the building system, and the IPCC 2013 GWP 100 assessment results are used. For the setting of different structural system working conditions of the building, the scenario analysis method is selected to realize. Scenario analysis is a systematic method that describes and simulates various scenarios that will appear on the assumption that a certain phenomenon or trend will continue to develop in the future [22]. This article uses the scenario analysis method to help calculate carbon emissions under different structural system scenarios, so as to compare the carbon emission reduction potential under each scenario. The basic ideas for setting up different scenarios are as follows: 1) To analyze the factors that have the greatest impact on the structural system. In this study, through the investigation and actual case of the project, the human factors such as social environment are excluded, and the factors affecting the calculation of the physical and chemical stage such as prefabricated building components, transportation distance of components, and material loss rate are taken into account. 2) Using Glodon and SimaPro software, multiple calculations were performed on single buildings under different conditions under different scenarios, and the impact of changes in various factors on carbon emissions in the materialization stage was analyzed, and an attempt was made to find out the impact mechanism. This study proposes a methodological framework based on the LCA theory, see **Figure 1**.

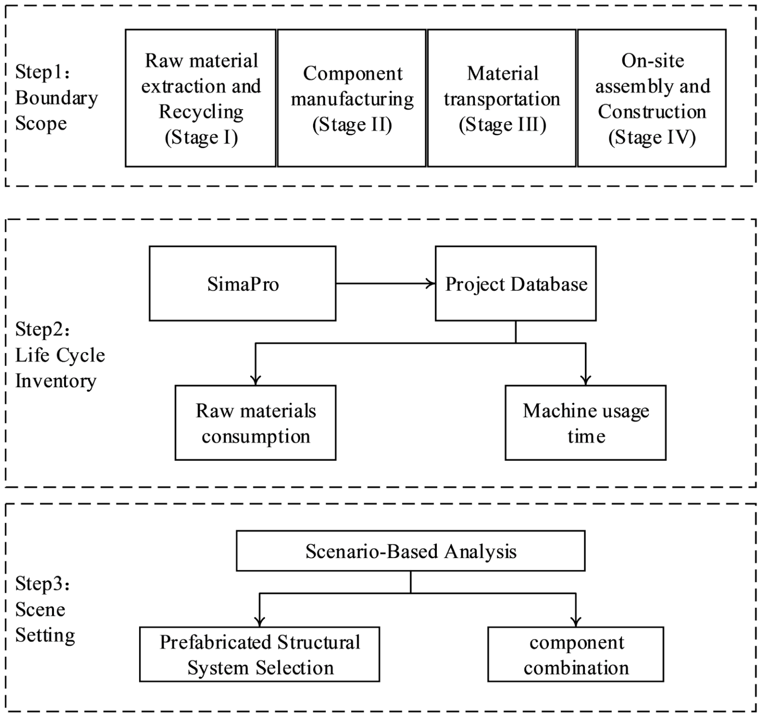

Figure 1. Research framework.

3.2. Research Steps

3.2.1. Carbon Emission Model of Prefabricated Buildings Based on SimaPro

1) Determine the goals and scope

According to the research purpose of the article, the research target of LCA is prefabricated buildings. Compared with traditional buildings that transport raw materials to the construction site for on-site pouring, prefabricated buildings transport raw materials to the prefabrication factory, produce prefabricated components in the prefabrication factory, and then transport the prefabricated components to the construction site for installation. Therefore, the biggest difference between prefabricated buildings and traditional cast-in-place buildings is the stage of materialization. Although the GHG emissions in the materialization stage account for a small proportion in the entire life cycle, due to the existing large number of energy-saving regulations or other policies, 80% - 90% of the life-cycle GHG emissions that occur during operation will increase over time. With the passage of time, it drops sharply [23].

At the same time, the period of the building transformation stage is very short (compared to the total time of the operation stage). Studying the carbon emission mechanism of buildings in the physical and chemical stage and proposing corresponding emission reduction measures can achieve better emission reduction effect in a very short time and complete the goal of carbon neutrality as soon as possible. Therefore, the relative contribution of emissions and impacts of the materialization stage becomes more important and dominant [24]. From the perspective of reducing the amount of carbon emissions generated per unit time in the entire life cycle of a building, the research significance of the materialization stage is greater than that of the operation stage; from the perspective of process emission reduction in building construction stage and component material manufacturing production, the emission reduction capacity is greater than that of raw material resource mining stage. The research goal of the article is the building life cycle assessment under different structural system scenarios, so the scope is the materialization stage of the building, that is, from the cradle-to-site.

According to the goal of the material and product system from the cradle to the field, the carbon emission assessment is divided into four stages: raw material mining and recycling (Stage I), component manufacturing (Stage II), material transportation Stage (Stage III), on-site assembly and construction (Stage IV). A schematic diagram of building construction activities is shown in Figure 2.

2) Life cycle inventory analysis

The main task of the life cycle inventory analysis stage is to collect and record the data required for the assessment to meet the established objectives and scope [19]. The inputs to the system in the prefabricated building stage are raw materials and various energy sources, and the outputs are greenhouse gases and buildings.

3.2.2. Scenario Setting Based on Scenario Analysis

1) Selection of prefabricated structural system

From the component-oriented perspective, whether the vertical components are prefabricated will affect the selection of the initial structural system and construction technology of the prefabricated building, thereby affecting the carbon

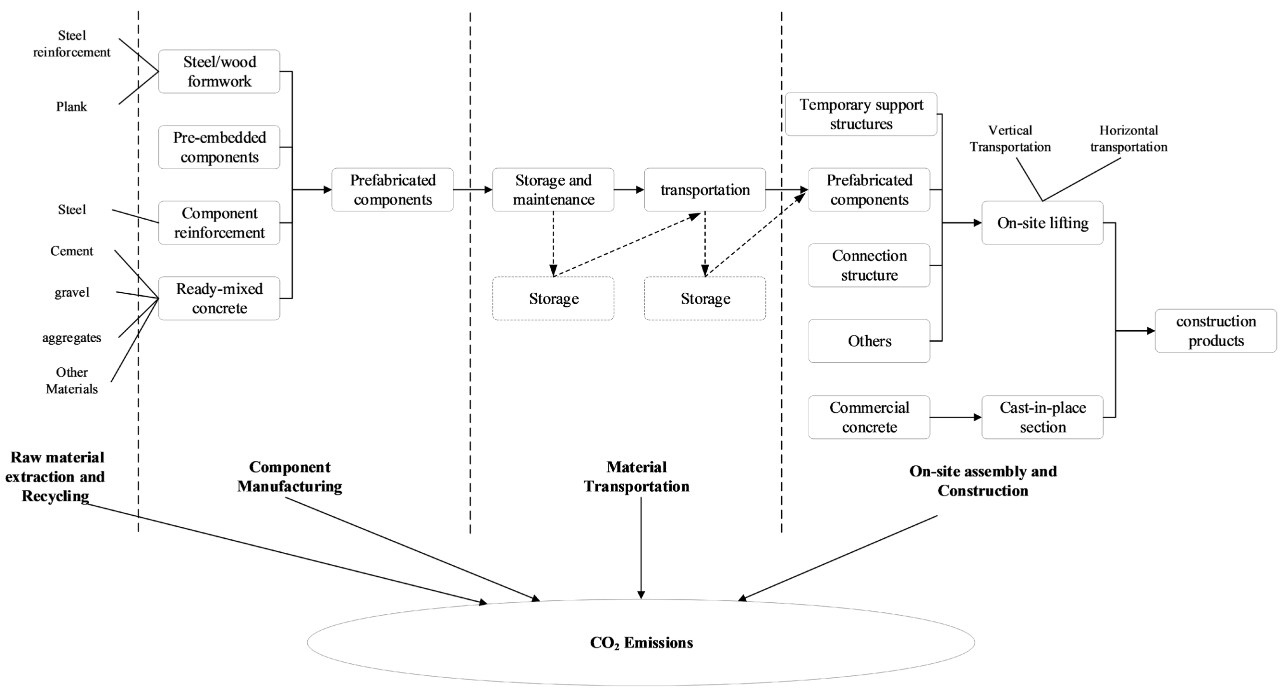

Figure 2. Phasing of carbon emission sources.

emissions in the building construction stage. In order to carry out follow-up calculations reasonably, the research sorted out the relevant theoretical basis and engineering practice [25]. This study concludes that the precast concrete structure system is mainly divided into two systems according to whether the vertical force members are prefabricated or not.

The selection of structures can start from a variety of emphases, and there are completely different structural selection schemes. Different schemes need to be formulated according to different construction formats and purposes. For commercial residential projects with strict cost control, you can choose cast-in-place external hanging structure or shear wall structure to improve the comfort of the residence and control the cost. For projects such as low-income housing apartments with economical and affordable considerations, due to the small indoor area of the building, a frame structure or a frame-shear structure system can be selected. For the high-evaluation projects in the prefabricated building evaluation standards, it is necessary to consider the structure selection under the condition of high prefabrication rate, so it is necessary to select the shear wall system or frame-shear wall system with the most component combinations, and in the envelope structure Use prefabricated elements such as cladding. This is also the most used structure in the field of prefabricated buildings.

2) Combination of components under different structural systems

At the level of component selection and combination, the laminated slab components with the highest degree of reusability should be considered first, and non-structural components such as prefabricated stairs, prefabricated balconies, cornices and prefabricated parapets that can meet the requirements of the facade should be considered secondly. Finally, according to different Due to the limitations of the prefabricated building structure system, configure structural stress components (prefabricated beams, prefabricated shear walls and prefabricated columns). This study summarizes component scenarios under different structural systems, see **Table 1**.

4. Empirical Research on Different Structural Systems

4.1. Case Selection

In this study, strictly refer to the requirements of the "Technical Standards for Precast Concrete Buildings" on the maximum applicable height, in order to meet the setting of all common structural systems on the basic building, a bungalow building with an overall height of less than 40 meters is selected. And because the case is selected as a residential type, the variable load range in the application process is small, and the bearing load is mainly the building's own weight, so it is very suitable as a comparative analysis of different structural systems.

The 4# building in Anhui Province was selected, and the completion date of the building is October 2021. The basic architectural description of the case can be found in **Table 2**. The standard floor plans and elevations of the case are shown in **Figure 3**.

Table 1. Component scenarios under different structural systems.

Structural System Classification	Prefabricated parts							
	Prefabricated external wall	Prefabricated shear wall	Laminated slabs	Prefabricated beam	Prefabricated column	Prefabricated stairs	Prefabricated balconies and overhangs	Prefabricated parapet
In-pouring and external hanging system	●							
Composite shear wall system			△					
Prefabricated Frame Structural System			●	●	○	●	●	●
Prefabricated partial frame-supported shear wall structure system		○	●	○		●	●	●
Prefabricated Shear Wall Structural System		●	●	○		●	●	●
Prefabricated Frame-Shear Wall Structural System		○	●	○	○	●	●	●

● indicates that under this structural system, prefabricated components have been used in the corresponding parts of the building; ○ indicates that under this structural system, part of the corresponding parts of the building adopts prefabricated components; △ indicates that this part of prefabricated components is a prefabricated laminated wall, not a laminated slab.

Table 2. Basic information table of case building.

Content	
Construction area	1952.1 m^2
Building type	Residential building
Floor height	6 floors, floor height 2.9 m
Total building height	23.2 m
Building structure	Concrete-frame structure

Figure 3. Elevation of the case.

The analysis process in this section is to analyze different scenarios by changing the structural system settings of the same single building. In actual construction, there are differences in component connection design, steel anchorage design, stirrup configuration, etc. of different structural systems. Through a large number of structural design cases and literature analysis, this study concluded that for residential buildings with a maximum building height of less than 30m, structural reinforcement requirements can meet the structural performance in general cases, in order to simplify software modeling and calculation workload. In this study, the institutions that have no special provisions in the "Code" are unified in accordance with the "Code for Design of Concrete Structures GB50010" and adopt general structural reinforcement settings.

4.2. Result Analysis and Discussion

The material consumption and mechanical energy consumption used in the basic case and research scenarios of different structural systems are imported into SimaPro, and the five different structural systems are compared horizontally. The carbon emissions obtained in the construction stage of a single building are shown in Figure 4.

Under the background of the basic case selected in this study, all buildings using prefabricated technology have different degrees of carbon emission reduction compared with cast-in-place structures. Among them, the hanging wall structure has the greatest potential to reduce carbon emissions, and its carbon emissions in the materialization stage are only 88% of traditional buildings; the prefabricated frame shear wall structure is the smallest of the four structures selected, and its carbon reduction capacity is about 5% of that of traditional buildings. However, it can be seen from the lower bar chart 5.8 that buildings using prefabricated technology reduce emissions by an average of 10% compared with

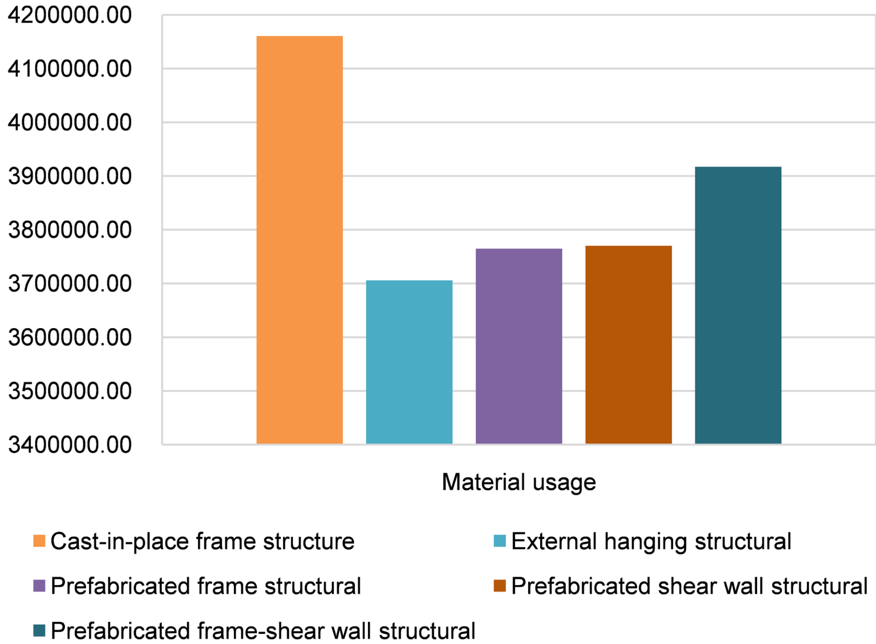

Figure 4. Carbon emissions of different structural types.

cast-in-place buildings. This result proves that prefabricated buildings have good performance in environmental emissions, which is also in line with the current general research conclusions [26].

1) Comparison of prefabrication technology and cast-in-place technology

By exporting the construction process data of each structural system, the following conclusions can be drawn: the carbon emissions generated by building material flow basically determine the fundamentals of carbon emissions in the physical and chemical stage, that is, the carbon emissions generated by materials still play a decisive role in the physical and chemical stage of building. As shown in Figure 5, the carbon emission of material flow is the sum of Stage I and Stage II, which accounts for 97% - 98% of the total carbon emissions in the building construction stage. It can be seen that it is still important to start from the aspects of saving construction material resources and waste of materials in the construction process. This is the most direct and most effective method of reducing carbon emissions in the construction industry. Further analysis shows that the carbon emissions of cast-in-place buildings and external wall panel structures in Stage I account for 80% of the total. The reason is that the above two structures are poured with cast-in-place concrete for the main structure, and the amount of concrete and steel bars used in the main structure accounts for most of the single structure. The latter three kinds of buildings that prefabricate the main structure have a balanced proportion in terms of material carbon emissions, and the materials used for production are averaged to I and II stages, and the whereabouts of building materials are more even.

In addition, the carbon emission of construction machinery other than material flow is also worthy of attention. The carbon emissions of construction

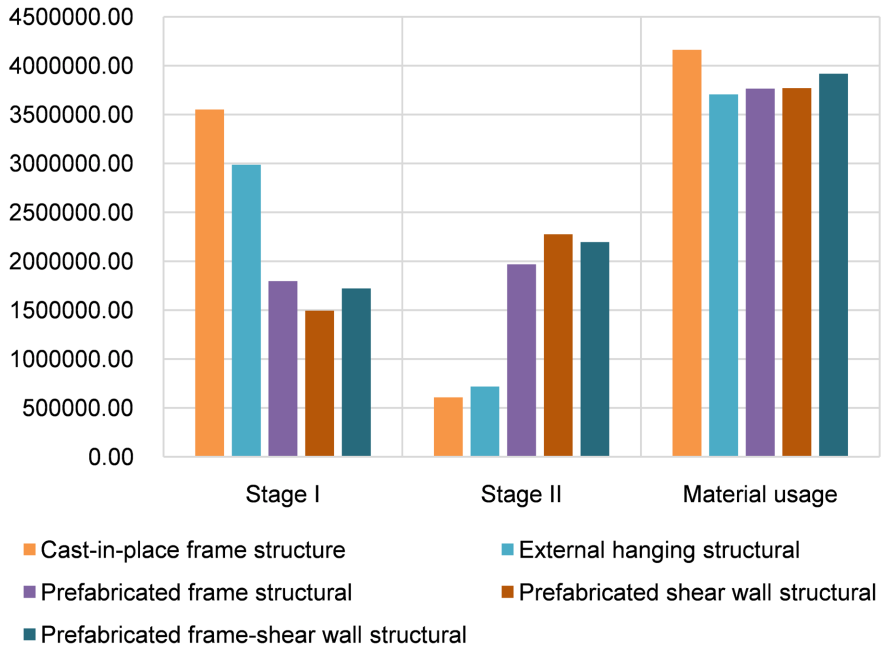

Figure 5. Carbon emissions from material flows of different structural types.

machinery in the materialization stage can be understood as the carbon emissions generated by all the machinery and equipment used for production and construction on site.

Also according to the stage division analysis, the prefabricated shear wall structure in the third stage produces the highest carbon emissions during the component transportation stage, followed by the prefabricated frame-shear wall structure. The specific values are shown in Table 3. The main transportation content is the prefabricated shear wall, self-heavy and large in quantity, it requires a larger load and more transportation layers. The carbon emission of component transportation has obvious characteristics: the more component combinations required by the building structure system, the greater the amount of transportation invested in the transportation process, and the more carbon emissions will be caused. Therefore, component manufacturers should pay attention to the order in which components are shipped out of the warehouse, reasonably arrange transportation vehicles and specifications, and avoid environmental pollution and economic losses caused by large vehicles pulling small goods. The general construction contractor selects local components and building materials as close as conditions permit, and reduces the carbon emissions of Stage III by reducing the transportation distance.

Stage IV is mainly the carbon emissions of energy used by machinery and equipment on the construction site. Compared with traditional cast-in-place buildings, buildings using prefabricated technology have significantly reduced carbon emissions from mechanical equipment. From the comparison in Figure 6 below, it can be seen that the prefabrication technology has shifted material production in the on-site materialization stage to centralized manufacturing,

Table 3. Carbon emissions of different structural members during transportation.

Type	Cast-in-place frame structure	External hanging structural	Prefabricated frame structural	Prefabricated shear wall structural	Prefabricated frame-shear wall structural
Component transportation, YWQ	0	2440.20	0	0	0
Component transportation, PCQ	0	0	0	8433.71	3808.60
Component transportation, PCB	0	0	5654.42	5175.60	5175.60
Component transportation, YLT	0	0	160.12	160.12	160.12
Component transportation, PCL	0	0	2070.98	434.33	2070.98
Component transportation	0.00	2440.20	7885.53	14203.77	11215.30

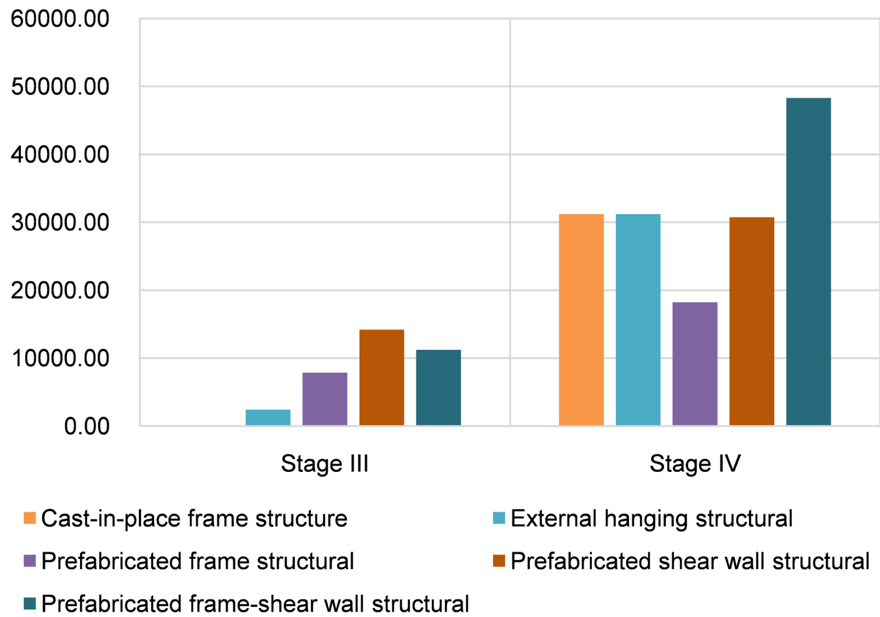

Figure 6. Stage III and IV carbon emissions of different structures.

and its carbon emission characteristics have also changed from rough and unrestrained emissions with strong construction industry attributes to fine design and precise control of emissions with manufacturing attributes. It is also enough to further illustrate that the attributes of the manufacturing industry have a great influence on the substitution effect of the construction site.

2) Comparison between different structural systems of prefabricated buildings

Carbon emissions from four common structures using prefabrication techniques are comparable. Therefore, it is difficult to analyze the characteristics in detail on the "surface", and it is necessary to further consider the carbon emissions at the "point" level, that is, to compare the carbon emissions of the material flow and construction machinery of the four structures. The detailed values are shown in Table 4.

Table 4. Material flow and construction machinery carbon emission of four structures.

Type	External hanging structural	Prefabricated frame structural	Prefabricated shear wall structural	Prefabricated frame-shear wall structural
Material Flow Carbon Emissions	3705865.30	3765017.12	3770135.89	3917257.33
Construction Machinery Carbon Emissions	33651.45	26101.91	44969.64	59511.12

Under the carbon emission of construction machinery, the emission of prefabricated frame building is only 44% of the emission of frame-shear wall. It has very strong carbon emission reduction ability in the carbon emission generated by mechanical equipment, so more in-depth analysis is needed.

Tower cranes are the most powerful fixed machinery in on-site construction. According to the software calculation results shown in **Figure 7**, in the calculation of all single building construction stages, the carbon emissions generated by tower cranes almost exceed the sum of carbon emissions of all mobile machinery. As shown by the broken line in the figure below, the carbon emissions of tower cranes with prefabricated frame-shear structures and shear wall structures are 22,800 kg CO_2-eq and 38,800 kg CO_2-eq, respectively, accounting for 74.4% and 80.6% of all construction machinery carbon emissions. The second largest contributor to on-site mechanical carbon emissions is the construction well crane, which is mainly used for the vertical transportation of small building materials such as blocks, gravel, doors and windows, and waterproof coatings. Under prefabrication technology, the use of construction well cranes has not changed significantly. The reason is that the integration of prefabricated building components and modules is not considered in the various structural scenarios set up, so materials such as doors and Windows still need to be transported by construction well cranes. On the other hand, due to the requirements of the structural form, both of the above two buildings need tower cranes to hoist the prefabricated shear walls, and the hoisting work of a component is completed after the steel structure is anchored and fixed. The working hours of the tower cranes increase accordingly, so is the corresponding construction. The use of well cranes and other mechanical equipment has not been reduced, so this has further contributed to the increase in overall mechanical equipment carbon emissions.

In this study, the mobile construction machinery is mainly classified into steel bar processing and concrete pouring. The characteristic of this type of machinery is that its power is small, the number of users is usually 1 - 2, and the use time is relatively fragmented. The histograms in the figure below represent the carbon emissions of different types of mobile machinery. The external wall building has more demand for such machinery. The prefabrication of the external wall does not involve the main structure, so the construction process is the same as that of the traditional building. Various steel bar processing machines are used for on-site cutting and binding, and then the main structure is formed. Rely on the concrete pump truck to pump the commercial concrete, and then use manual vibration, compaction and other construction techniques to process the concrete. After the main concrete curing reaches the design strength, the prefabricated exterior wall will be hoisted. Its construction is still characterized by traditional rough on-site manufacturing, so a large amount of carbon emissions generated by on-site construction machinery comes from labor and small machinery, and its construction speed largely depends on construction organization and management methods. Buildings involving the prefabrication of the main structure eliminate the need for on-site formwork and concrete pumping processes, so the use of small machinery is transferred to the component factory in large quantities, and industrialized means are used for centralized construction.

Among the overall carbon emissions, the prefabricated frame shear structure is the highest, producing 3.98 × 10^6 kg CO_2-eq, while the external wall panel structure is the lowest, producing 3.74 × 10^6 kg CO_2-eq. Figure 8 demonstrates that the carbon emissions of buildings adopting prefabricated technology are nearly identical.

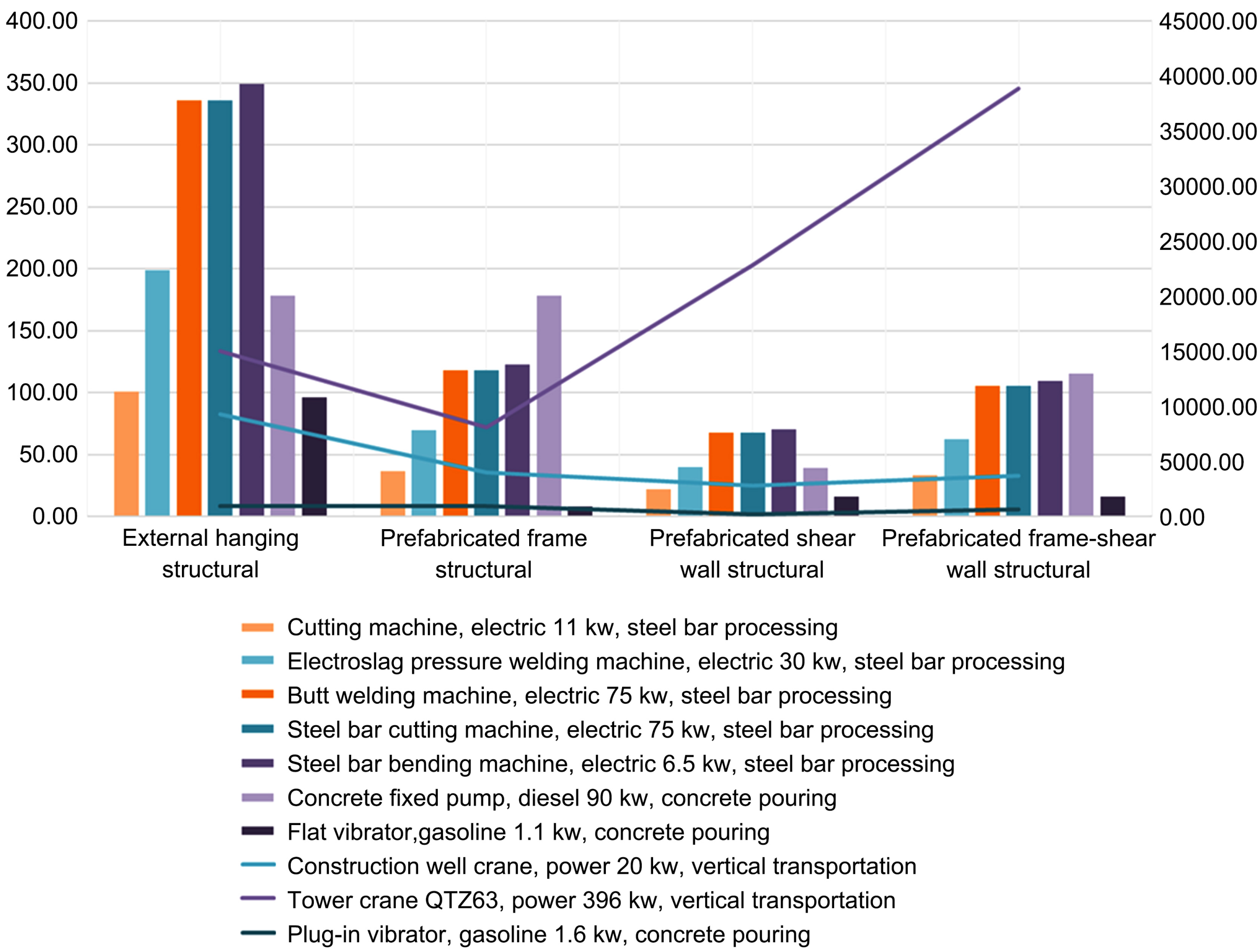

Figure 7. Comparison of carbon emissions of construction machinery and equipment.

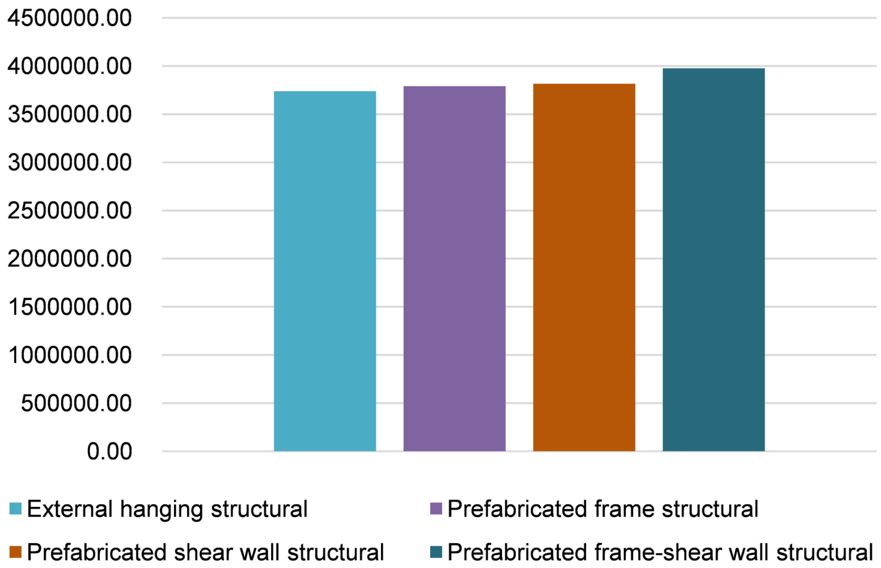

Figure 8. Comparison of carbon emissions of different structure types.

Due to its complex structure and high requirements for steel bar binding technology, shear walls show high carbon emissions in the component factory stage. Putting it into the single structure, in the process of hoisting the shear wall, it is necessary to fully consider the anchorage and concrete pouring between the wall and the beam slab to achieve the lateral stiffness of the structural nodes, and this complex process is reflected in the Among the carbon emissions are the increase in the use of steel materials and the increase in the use of tower cranes. Therefore, prefabricated shear wall structures and prefabricated frame-shear wall structures that use a large number of shear wall components have increased carbon emissions. For this reason, although the use of materials for these two structures is less than that of traditional buildings, the amount of savings is limited, and the use of on-site construction machinery that should be saved most is still at a relatively high level, resulting in insignificant carbon emission reduction effects. However, because the prefabricated frame-shear structure still has tower cranes for hoisting prefabricated beams and prefabricated columns, the carbon emissions are even greater. The external hanging wall panel structure is consistent with other structures in the scene setting, and has a relatively high level of use of laminated plate components, so its carbon emission reduction part mainly depends on the laminated plate, and part of it comes from the effect of the prefabricated external wall on it, so it reflects to Carbon emissions are the least. This further shows that the carbon emission reduction capability of components is still well reflected in individual buildings.

Building construction using prefabrication technology has again been shown to have a good carbon reduction potential, which is in line with most studies [27] [28]. The impact of different structural systems on carbon emissions in the stage of prefabricated materialization is not much different in the cases selected in this study, and the difference in carbon emissions is concentrated within 4%.

The carbon emissions generated by the materialization stages of different structural systems still take the carbon emissions generated by the material flow as the general trend. Different structures have different requirements for the combination of components, and the carbon emissions of individual buildings will be superimposed according to the carbon emission characteristics of various individual components to form the final total carbon emissions. The possible reason for this phenomenon is that because of the scenario calculation of different structural systems in the same single building, a six-storey bungalow building with a small size is selected, which makes the difference in prefabrication technology of each structure not reflected.

5. Conclusions

In this paper, the life cycle assessment theory is used to analyze and compare the carbon emissions of different working conditions caused by different structural systems of prefabricated buildings with similar building scales in China, so as to observe the changes in the environmental impact of the overall building construction stage. It fills the research gap for the changing law of the relationship between the component level, the structural system and the final carbon emission impact.

The carbon emission simulation analysis under different structural system scenarios shows that the carbon emissions generated by the materialization stages of different structural systems are still based on the carbon emissions generated by the material flow as the overall trend. Different structures have different requirements for the combination of components, and the carbon emissions of individual buildings will be superimposed according to the carbon emission characteristics of various individual components to form the final total carbon emissions. Based on the cases in this section, the results obtained are that buildings with different structural systems have different degrees of carbon emission reduction capabilities, compared with 9% - 10% reduction in carbon emissions. But the carbon emissions produced by the four common structures are similar.

The carbon emission of component transportation has obvious characteristics: the more component combinations required by the building structure system, the greater the amount of transportation invested in the transportation process, and the more carbon emissions will be caused. Therefore, component manufacturers should pay attention to the order of components out of the warehouse, and arrange transportation vehicles and specifications reasonably. In the calculation of all individual building construction stages, the carbon emissions generated by tower cranes almost exceed the sum of the carbon emissions of all mobile machinery.

The application of components is not single, and the realization of its building products is the result of different types and quantities of various components. Therefore, the impact of carbon emissions of different types of components and different construction machinery on carbon emissions in the materialization stage is on the single building structure This is a signal to decision makers that they do not need to consider too much the impact of the building's structural system when making program decisions from the perspective of carbon emission reduction.

Conflicts of Interest

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

References

[1] Hulme, M. (2017) Intergovernmental Panel on Climate Change (IPCC). In: Richardson, D., Castree, N., Goodchild, M.F., Kobayashi, A., Liu, W. and Marston, R.A., Eds., *International Encyclopedia of Geography*: *People*, *the Earth*, *Environment and Technology*, Wiley, Hoboken, 1-7. https://doi.org/10.1002/9781118786352.wbieg0254

[2] IPCC (2014) Summary for Policymakers. In: *Climate Change* 2014: *Mitigation of Climate Change*: *Working Group III Contribution to the IPCC Fifth Assessment Report*, Cambridge University Press, Cambridge, 1-30. https://doi.org/10.1017/CBO9781107415416.005

[3] Jefferson, M. (2015) IPCC Fifth Assessment Synthesis Report: "Climate Change 2014: Longer Report": Critical Analysis. *Technological Forecasting & Social Change*, **92**, 362-363. https://doi.org/10.1016/j.techfore.2014.12.002

[4] Wang, X., Duan, Z., Wu, L. and Yang, D. (2015) Estimation of Carbon Dioxide Emission in Highway Construction: A Case Study in Southwest Region of China. *Journal of Cleaner Production*, **103**, 705-714. https://doi.org/10.1016/j.jclepro.2014.10.030

[5] Zhang, Z. and Wang, B. (2016) Research on the Life-Cycle CO_2 Emission of China's Construction Sector. *Energy and Buildings*, **112**, 244-255. https://doi.org/10.1016/j.enbuild.2015.12.026

[6] Sim, J. and Sim, J. (2016) The Air Emission Assessment of a South Korean Traditional Building during Its Life Cycle. *Building and Environment*, **105**, 283-294. https://doi.org/10.1016/j.buildenv.2016.06.007

[7] Liu, M. (2016) The Practice and Experience of Developing Prefabricated Building Abroad. *The Construction of Science and Technology*, No. C1, 40-42.

[8] Wang, Z. (2017) Development Trend of American Prefabricated Building Industry (I). *China Construction Metal Structure*, **10**, 24-31.

[9] Gibb, A.G. (1999) Off-Site Fabrication: Prefabrication, Pre-Assembly and Modularisation. John Wiley & Sons, Hoboken.

[10] Hu, R., Chen, K., Fang, W., Zheng, L. and Xu, J. (2022) The Technology-Environment Relationship Revisited: Evidence from the Impact of Prefabrication on Reducing Construction Waste. *Journal of Cleaner Production*, **341**, Article ID: 130883. https://doi.org/10.1016/j.jclepro.2022.130883

[11] Zhang, X., Skitmore, M. and Peng, Y. (2014) Exploring the Challenges to Industrialized Residential Building in China. *Habitat International*, **41**, 176-184. https://doi.org/10.1016/j.habitatint.2013.08.005

[12] Ferdous, W., Bai, Y., Ngo, T.D., Manalo, A. and Mendis, P. (2019) New Advance-

ments, Challenges and Opportunities of Multi-Storey Modular Buildings—A State-of-the-Art Review. *Engineering Structures*, **183**, 883-893. https://doi.org/10.1016/j.engstruct.2019.01.061

[13] Hong, J., Shen, G.Q., Mao, C., Li, Z. and Li, K. (2016) Life-Cycle Energy Analysis of Prefabricated Building Components: An Input-Output-Based Hybrid Model. *Journal of Cleaner Production*, **112**, 2198-2207. https://doi.org/10.1016/j.jclepro.2015.10.030

[14] Cheng, C.C., Pouffary, S., Svenningsen, N. and Callaway, J.M. (2008) The Kyoto Protocol, The Clean Development Mechanism and the Building and Construction Sector: A Report for the UNEP Sustainable Buildings and Construction Initiative. UNEP, Paris.

[15] Su, X. and Zhang, X. (2010) Environmental Performance Optimization of Window—Wall Ratio for Different Window Type in Hot Summer and Cold Winter Zone in China Based on Life Cycle Assessment. *Energy and Buildings*, **42**, 198-202. https://doi.org/10.1016/j.enbuild.2009.08.015

[16] Zhang, X., Platten, A. and Shen, L. (2011) Green Property Development Practice in China: Costs and Barriers. *Building and Environment*, **46**, 2153-2160. https://doi.org/10.1016/j.buildenv.2011.04.031

[17] Tavares, V., Soares, N., Raposo, N., Marques, P. and Freire, F. (2021) Prefabricated versus Conventional Construction: Comparing Life-Cycle Impacts of Alternative Structural Materials. *Journal of Building Engineering*, **41**, Article ID: 102705. https://doi.org/10.1016/j.jobe.2021.102705

[18] Nadoushani, Z.S.M. and Akbarnezhad, A. (2015) Effects of Structural System on the Life Cycle Carbon Footprint of Buildings. *Energy and Buildings*, **102**, 337-346. https://doi.org/10.1016/j.enbuild.2015.05.044

[19] ISO-14040 (2006) Environmental Management—Life Cycle Assessment—Principles and Framework. International Standard Organization (ISO).

[20] ISO-14044 (2006) Environmental management—Life Cycle Assessment—Requirements and Guidelines. International Standard Organization (ISO).

[21] Birch, E.L. (2014) A Review of "Climate Change 2014: Impacts, Adaptation, and Vulnerability" and "Climate Change 2014: Mitigation of Climate Change": Intergovernmental Panel on Climate Change. *Journal of the American Planning Association*, **80**, 184-185. https://doi.org/10.1080/01944363.2014.954464

[22] Hsia, P., Samuel, J., Gao, J., Kung, D., Toyoshima, Y. and Chen, C. (1994) Formal Approach to Scenario Analysis. *IEEE Software*, **11**, 33-41. https://doi.org/10.1109/52.268953

[23] Guggemos, A.A. and Horvath, A. (2006) Decision-Support Tool for Assessing the Environmental Effects of Constructing Commercial Buildings. *Journal of Architectural Engineering*, **12**, 187-195. https://doi.org/10.1061/(ASCE)1076-0431(2006)12:4(187)

[24] Mao, C., Shen, Q., Shen, L. and Tang, L. (2013) Comparative Study of Greenhouse Gas Emissions between Off-Site Prefabrication and Conventional Construction Methods: Two Case Studies of Residential Projects. *Energy and Buildings*, **66**, 165-176. https://doi.org/10.1016/j.enbuild.2013.07.033

[25] Morris, A.E.J. (1978) Precast Concrete in Architecture: Precast Concrete in Architecture. Whitney Library of Design, New York.

[26] Dong, Y.H. and Ng, S.T. (2015) A Life Cycle Assessment Model for Evaluating the Environmental Impacts of Building Construction in Hong Kong. *Building and Environment*, **89**, 183-191. https://doi.org/10.1016/j.buildenv.2015.02.020

[27] Dong, Y.H., Jaillon, L., Chu, P. and Poon, C.S. (2015) Comparing Carbon Emissions of Precast and Cast-*in-Situ* Construction Methods—A Case Study of High-Rise Private Building. *Construction and Building Materials*, **99**, 39-53. https://doi.org/10.1016/j.conbuildmat.2015.08.145

[28] Teng, Y., Li, K., Pan, W. and Ng, T. (2018) Reducing Building Life Cycle Carbon Emissions through Prefabrication: Evidence from and Gaps in Empirical Studies. *Building and Environment*, **132**, 125-136. https://doi.org/10.1016/j.buildenv.2018.01.026