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Measuring and reducing the embodied carbon in high-rise buildings through innovative modular construction

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Abstract: The construction industry is a significant contributor to carbon emissions, with its life cycle emissions posing significant environmental challenges. Despite its increasing importance, embodied carbon (EC) generated from the construction process is often ignored. Modular construction (MC), characterized by a combination of off-site manufacturing and on-site assembly, has been recognized for its potential to contribute to environmental benefits. However, there is still a lack of systematic explanation of urban high-rise MC. This study aims to identify whether and to what extent high-rise MC can achieve EC reductions and lay the foundation for effective carbon reductions in the construction industry. To achieve this, the study develops a multi-level EC measurement framework for assessing EC during the construction process, using a real case to quantify the EC and determine carbon reduction performance. The innovation is a more comprehensive understanding of the boundaries of EC, as MC includes the amount of superstructure work and decoration integration. The results show that although the MC will increase EC from the transportation stage due to heavier modules, it achieves a net reduction in total EC by reducing on-site machinery energy consumption and waste rates. In conclusion, this study contributes to a better understanding of the EC emissions associated with high-rise MC, offering a valuable measurement framework for global regions evaluating the EC impacts of high-rise MC in similar contexts.

Key words: Embodied carbon, process-based Life Cycle Assessment, modular building, high-rise building, concrete building

1. INTRODUCTION

Climate change has become a global priority, and carbon dioxide (CO2) emissions are particularly important as a key driver of this change (Pörtner et al., 2022). Among the many industries generating emissions, the construction industry plays a pivotal role in mitigating the climate crisis. According to statistics released by the World Green Building Council, the construction industry accounts for 39% of global carbon emissions related to energy consumption. Therefore, effectively reducing carbon emissions in the construction industry is especially crucial and urgent to reach the goal of carbon neutrality (Bureau, 2017; Chapa, 2019). Moreover, there is a demand driving much of the research around the quantitative measurement of carbon emissions from buildings and strategies to reduce them. The composition of a building's carbon emissions includes both the operational carbon generated by energy consumption during its operational stage - such as heating, ventilation, and air conditioning (HVAC) systems, domestic hot water, lighting and elevators - as well as the EC emissions from the extraction of raw materials, manufacturing and assembly processes. The later covers the entire life cycle of carbon emissions from the production and use of construction materials to their eventual disposal at the end of life. Since buildings have longer lifespans than other products, their operational carbon tends to be more significant. Numerous studies have examined the operational carbon of buildings, and proposed strategies for adopting new and renewable energy sources and achieving zero-carbon buildings. As the operational efficiency of buildings improves and operational carbon emissions are reduced, life cycle EC is becoming an increasingly significant part of total carbon emissions (Chau et al., 2015; Teng et al., 2018). According to the World Green Building Council (WorldGBC), all new buildings, infrastructure and renovation projects need to reduce their EC by 40% before 2030, and strive to achieve net zero EC emissions by 2050.

More recent academic discussions have recognized MC as a mode with the potential to reduce buildings' lifecycle carbon emissions. With its characteristics of prefabricated components in the factory and fast on-site assembly, the approach is considered to speed up and minimize resource wastage in construction, as well as enhance construction productivity. Some studies conducted in recent years have mostly quantified prefabricated buildings and analyzed the performance of EC using a process-based life cycle assessment method (Teng and Pan, 2019). Some studies on modular buildings have continued the boundary delineation and calculation of traditional and prefabricated buildings, without considering the integration characteristics of modular buildings (Quale et al., 2012; Pervez et al., 2021). More importantly, such existing studies on modular buildings have divergent findings on whether and to what extent carbon emissions can be reduced (Mao et al., 2013; Kamali and Hewage, 2016).

In addition, the relevant research generally focuses on low and medium-rise modular buildings constructed with wood or steel modules. There is a lack of research on the carbon emission measurement and detailed analysis of high-rise concrete modular buildings. This study aims to fill the gap in the systematic analysis of carbon emissions of high-rise concrete modular buildings in urbanized environments. To achieve this aim, the study develops a multi-level EC measurement framework and validates it empirically with a case study. The results obtained are discussed, and the key findings are summarized at the conclusion of the study.

2. LITERATURE REVIEW

As for research methods, similar studies have preferred a bottom-up analytical system that accurately captures data on building carbon emissions by subdividing the complex construction process into a series of staged tasks, which then facilitate the execution of classified calculations. Consequently, the methodology of process-based life cycle assessment is commonly used to capture the carbon emissions of the construction process. For example, Cole (1999) divided the whole life cycle carbon emissions of the building into three stages, including planning and design, construction, as well as operation and use. Some studies also defined their research boundaries as a four-stage, including the material production stage, the construction stage, the operation stage, and the demolition stage, and calculated the carbon emissions accordingly (Aye et al., 2012; Gustavsson et al., 2010). Gerilla et al. (2007) and Bribián et al. (2011) established a five-stage model, defined as building material production, construction, use, demolition, and disposal of used materials. Besides, there are also some studies that specifically analyze for a certain stage. Al-Hussein et al. (2009) focused on the construction stages of modular and traditional buildings with a comparison of their carbon dioxide equivalents but material-related EC was not taken into account. While Kawecki (2010) measured the carbon emissions during the manufacturing and installation processes in the factory, the EC related to materials and transportation was not considered. The above indicates that the boundary delineation and calculation methods of different studies are not uniform, and the existing studies involving modular buildings mostly regard module production as a process like the production of components, instead of deeply investigating the characteristics of modular buildings with integrated renovation.

In the research subject, numerous research results focused on modular buildings with steel and wood structures, while there are relatively limited studies on the carbon emissions of concrete modular buildings. Monahan and Powell (2011) compared the energy consumption of low-rise wood-framed modular houses with conventional houses in the material extraction, transportation, manufacturing, and construction stages and found that modular houses can save as much as 34% to 51% of energy consumption. Tavares et al. (2019) assessed the cradle-to-site EC emissions of a one-bedroom modular house, concluding the wood-frame module had the lowest carbon emissions among the steel and concrete modules. Pervez et al. (2021) compared the lifecycle carbon emissions of single-story steel-framed apartments using MC and traditional methods, respectively, and showed the MC method can reduce carbon emissions by up to 46.9%. Concrete modular buildings are less efficient in reducing carbon emissions than wood and steel buildings. Omar et al. (2014) showed a 26.3% reduction in EC emissions for low-rise concrete residential modular buildings compared to conventional buildings, while Wen et al. (2015) found only a 13.4% reduction in EC. However, most of these studies were based on low and medium-rise buildings constructed with steel and wood, and there is still a lack of effective carbon emission quantification methods for concrete modular high-rise buildings.

3. METHODOLOGY

3.1. Multi-level measurement framework for embodied carbon of modular construction

This paper systematically examines the EC emissions of concrete modular buildings through a process-based life cycle assessment method by developing a multi-level EC measurement framework similar to that used to quantify prefabricated construction projects (Teng and Pan, 2019), and interprets the EC results in both the temporal and spatial dimensions. The temporal dimension combines the characteristics and life cycle stages of modular buildings, which are defined as the production, modularization, transportation, and construction stages. One of the most significant features of modular buildings is the integration of decoration, which includes structural systems and interior finishes. Therefore, the spatial dimension contains the EC emissions at the material, component, module, and building levels. The research boundary of this paper is limited to the stages from the extraction of materials to the completion of the construction, which is the "cradle to the end of construction" of the life cycle. The carbon emissions of the building are closely related to the material inputs and energy consumption of the construction activities. Therefore, after defining the boundary, the carbon flows are tracked based on the construction activities in each stage as a prerequisite for the quantitative measurement and analysis of carbon emissions. A corresponding inventory list of carbon emission sources will then be created, thus reducing the risk of incorrect carbon emissions data from circular calculations. The overall framework of the methodology of this paper is shown in Figure 1.

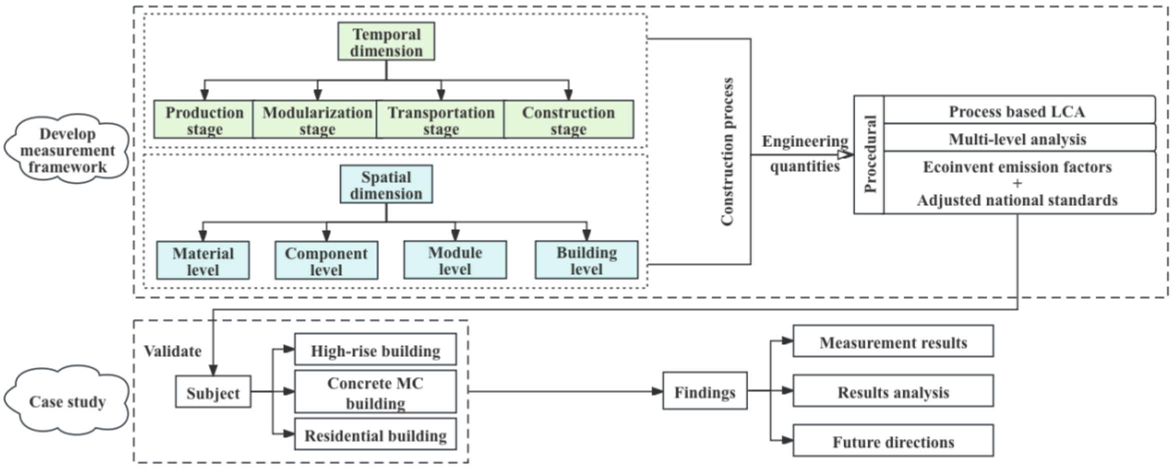

Figure 1. The overall framework of methodology in this paper

3.2. Measurement model for embodied carbon of modular construction

The measurement model guides the subsequent analysis as the core method for converting carbon emissions from construction activities identified within the boundaries into uniformly quantifiable data. Carbon emissions in this paper refer not only to carbon dioxide emissions in the narrow context but also to the environmental impacts of other greenhouse gases (GHGs) except carbon dioxide as defined in the IPCC Guidelines for National Greenhouse Gas Inventories. Since different greenhouse gases have different environmental impacts, the Global Warming Potential (GWP) is used to convert each greenhouse gas into carbon dioxide equivalent (CO_{2e}) for presenting. For comparability and practical significance of the results obtained from carbon emissions measurements, this paper combines the PAS2050 and ISO carbon emissions evaluation standards as the basis for the carbon emissions measurement model.

$$(\textit{Production stage})\ \ EC_p = EQ_i \times CEF_i + EQ_i \times TD_{it} \times CEF_{it}$$

Where EC_p represents the total embodied carbon emissions in the Production stage. EQ_i represents the quantities of material i in the project and is expressed in units of kg or m^3. CEF_i is the corresponding emission factor to produce each unit of material i as described above and is expressed in units of $kgCO_{2e}/kg$ or $kgCO_{2e}/m^3$. TD_{it} is the distance that material i is transported from the extraction site to the manufacturing plant. CEF_{it} is the carbon emission factor of the corresponding transport vehicle used to transport material i and is expressed in units of $kgCO_{2e}/tkm$.

$$(\textit{Modularization stage})\ \ EC_m = EQ_{ri} \times CEF_{ri}$$

Where EC_m indicates the total embodied carbon emissions during the Modularization stage. EQ_{ri} means the quantities of resources r, such as fossil fuels, consumed in the manufacturing process of the component or module i, and uses kWh or MJ as the unit. CEF_{ri} is the carbon emission factor corresponding to the consumption of resources in the above process and uses $kgCO_{2e}/kWh$ or $kgCO_{2e}/MJ$ as units.

$$(\textit{Transportation stage})\ EC_t = EQ_q \times TD_{qt} \times CEF_{qt}$$

Where EC_t means the total embodied carbon emission in the Transportation stage. EQ_q indicates the weight of the module or prefabricated component q and uses kg as the unit. TD_{qt} is the distance of transporting q and uses km as the unit. CEF_{qt} is the carbon emission factor of the transport vehicle used for transporting q and uses $kgCO_{2e}/\ tkm$ as the unit.

$$(Construction\ stage)\ EC_c = EQ_c \times CEF_c$$

Where EC_c shows the total embodied carbon emissions of the Construction stage. EQ_c represents the on-site consumption of resource c and uses the unit kWh or MJ. CEF_c is the corresponding carbon emission factor and uses $kgCO_{2e}/kWh$ or $kgCO_{2e}/MJ$ as the unit.

3.3. Case study of adapting the developed framework

The first high-rise concrete modular construction (MC) project in mainland China is selected as a case study for empirical analysis in this study to validate the effectiveness of the proposed carbon emission measurement framework. The case project consists of five high-rise buildings, three of which are 28 stories and the other two 29 stories, with a gross floor area of 173,491.60 square meters. The project was constructed in 350 days and consists of 6,028 concrete modules. For the quantitative analysis of the carbon emissions for the project, emission factors provided by the Ecoinvent database and national standards with adjustments based on carbon-related parameters used in the local construction industry were used for the measurements. Quantity data was obtained based on the bill of quantities, architectural and structural drawings, and other relevant engineering documents. Additionally, specific geographic location data for the transportation of the project was confirmed through site surveys and in-depth interviews with the project management team. The basic information and primary emission-related inventories of the selected case are presented in Table 1 and Table 2. The typical floors layout for the selected case project is also shown in the following Figure 2.

Table 1. The basic information of the MC case

Category	Detail
Location	Shenzhen, China
Project type	Residential building
Superstructure stories	Three buildings with 28 floors and two buildings with 29 floors
Number of modules	6028
GFA-project (m^2)	173491.60
GFA-typical floor (m^2)	120465.19
Construction period	350 days
Structure	Concrete MC with cast-in-place shear wall

Table 2. Primary emission-related inventories used in this paper

Type	Category	Item	Amount	Unit	Quantity data source	Emission factor source
Materials	MC module	Concrete, C30	65593.24	t	Records, Project documents, Drawings, SimaPro, Site survey	SimaPro Ecoinvent
		Concrete, C60	9008.74	t		
		Reinforcement, HPB300	78.51	t		
		Reinforcement, HRB400	4567.76	t		
		Concrete, C30	673.39	t		
		Reinforcement, HRB400	55.03	t		
		Concrete, C25	7.35	t		
		Concrete, C30	79420.46	t		
		Concrete, C40	17110.11	t		
		Concrete, C50	17110.11	t		
		Concrete, C60	10471.54	t		
		Reinforcement, HRB400	6167.63	t		
		Concrete, C15	5495	t		
		Concrete, C30	216.6	t		
		Concrete, C35	78283.67	t		
		Decoration	42208.98	t		
Transport	Transport	Transport, lorry 16-32t	12	km		
Machinery	On-site machinery	Electricity	532015	kWh		National standard

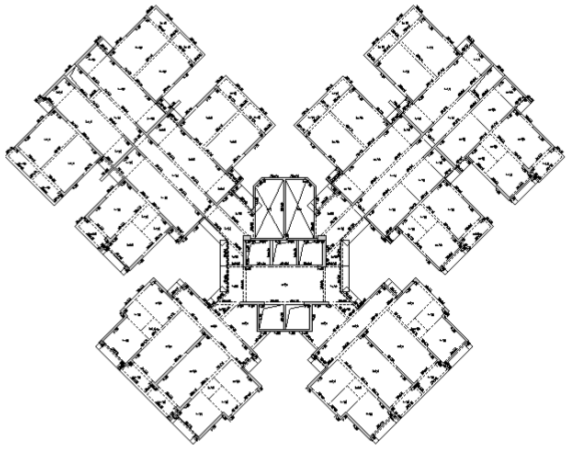

Figure 2. The typical floors' layout plan of the MC case building

4. RESULTS

4.1. Embodied carbon emissions of the modular building case in the temporal dimension

The detailed reporting of the EC emissions of the selected case project in both temporal and spatial dimensions was conducted by integrating the relevant data with the carbon accounting standards in international standards, relying on the previously constructed measurement framework. In the temporal dimension, more than 96% of the EC emissions of the whole building (about 94,507t) originated from the material production and modularization stages. Specifically, the material production stage contributes 63.21% of the EC emissions, while the modularization stage contributes 32.99%. In contrast, the transportation and construction stages accounted for a relatively low with 2.67% and 1.14% of EC emissions, respectively. Although modular buildings are assumed to increase EC emissions in the transportation stage due to their heavier weight compared to traditional buildings, the distance between the factory and the construction site is only about 12 kilometers in this case study, resulting in a non-significant proportion of EC emissions in the transportation stage. The low percentage of EC emissions in the construction stage is due to the nature of the modular building, which allows many processes originally conducted on-site to be moved to a controlled factory environment. Figures 3 and 4 show the EC in the spatial dimension of the MC case project, and the proportion of EC in the standard and non-typical floors, respectively.

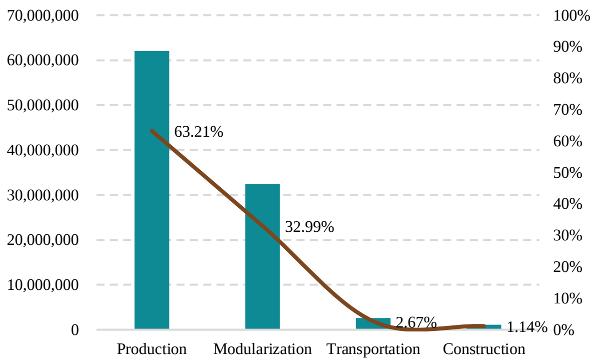

Figure 3. EC of MC case in different life cycle stages

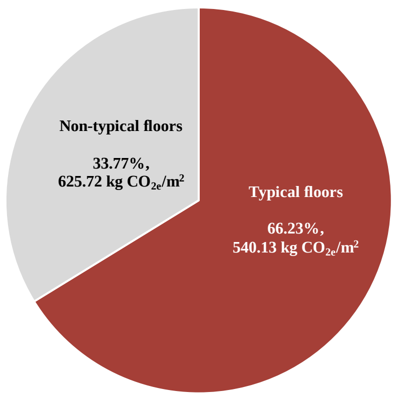

Figure 4. EC emissions of the typical floors and others

4.2. Embodied carbon emissions of the modular building case in the spatial dimension

Following the measurement framework established earlier, the spatial dimension will be reported sequentially by material, component (internal partition wall and stairs), module and building. Since the MC method is mainly used for typical floors of buildings except for substructures, the ground floor and the top floor, this paper presents the EC emission of the typical floors in the spatial analysis, particularly in order to reveal the potential impacts of the MC method on the EC emission in a more precise way. For the detailed emissions proportions of each level, Figure 5 shows the temporal and spatial analysis of the selected case project. At the material level, the EC emissions of materials used in the case project are 62097t, including the EC emissions generated in the typical floors, which is 30450t. The non-typical floors, mainly based on the concrete cast-in-place method, produced EC emissions from materials used about 31647t, amongst which the substructure works produced about 28705t of carbon emissions. In proportion, the concrete cast-in-place method produces a larger percentage of overall carbon emissions, with more than 39% for concrete and more than 26% for reinforcement. At the component level, the EC emissions from individual internal partition walls and staircases are about 1.694t and 0.56t, respectively. At the module level, the carbon emissions of all modules including decoration are 35001t, where the EC emissions of a single module with finishes range from 1.838t to 9.583t depending on its design, and the average carbon emissions of a single module with finishes is 5.805t. Regarding the emissions shares of each module type, Module2, Module1, and Module1a have the largest emissions, accounting for about 21.42%, 18.12%, and 11.41%, respectively. At the building level, the average EC emissions per square meter of the case building were 566.29 kg CO_{2e}/m^2. Within this, the EC generated during the production of materials and modules accounted for 96.19% of the total EC. In comparison, the energy used by equipment and vehicles accounted for only 3.81% of the total emissions. Considering only the typical floors, the average EC emission per square meter of the case building is 540.13 kg CO_{2e}/m^2, while the average EC emission per square meter of the remaining parts using concrete cast-in-place construction method, which includes the substructure, the ground floor and the roof, is 625.72 kg CO_{2e}/m^2. Although the typical floors are mainly constructed with the MC method, in consideration of the structural stability of high-rise buildings, a certain proportion of concrete cast-in-place is still required for the main structure of the building, and the carbon emission of this part is also counted in the statistics of the typical floors. Figure 6 combines the temporal and spatial dimensions to visualize the transformation and distribution of embodied carbon from origin to end use. The figure presents the flow of embodied carbon in the formation process of different components and modules. Taking Module1 as an example, the final allocation of embodied carbon covers the process of modularization, transportation, and construction.

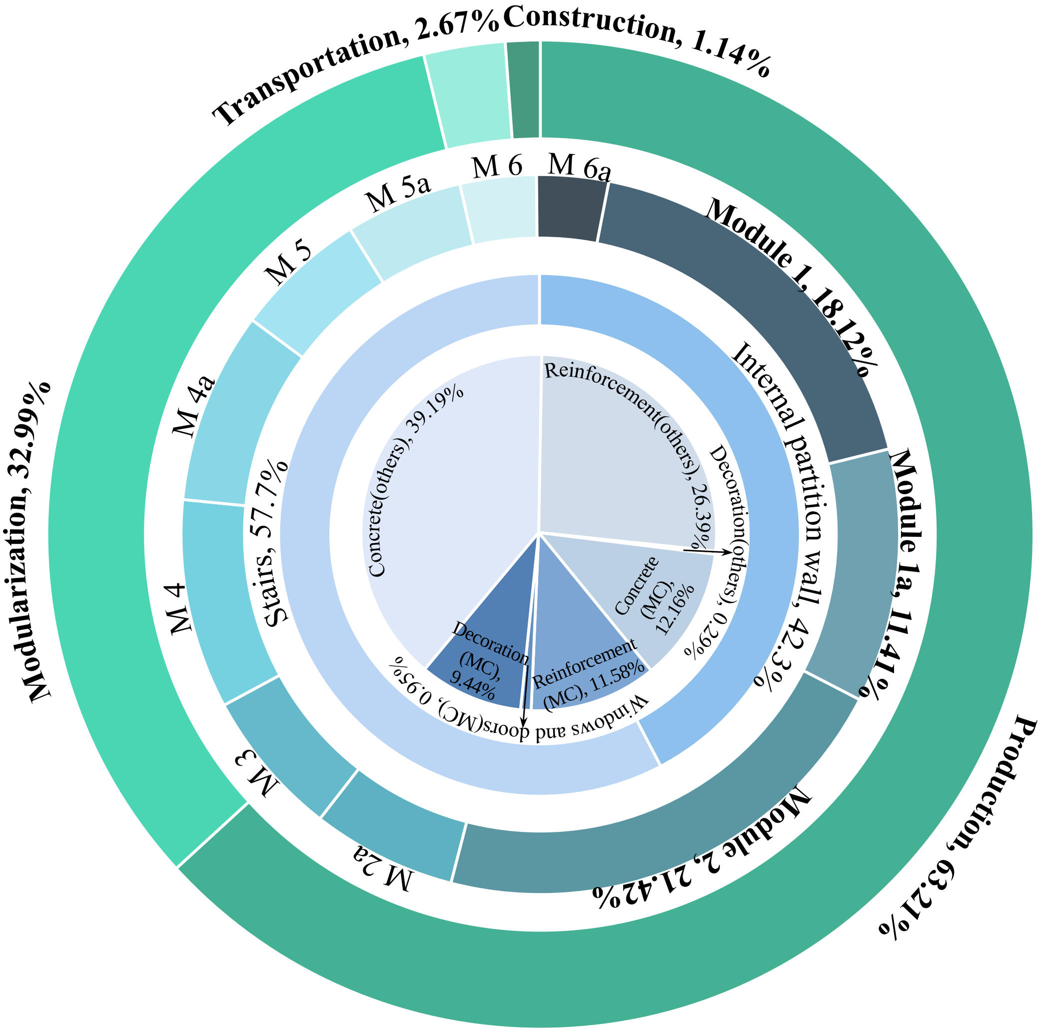

Figure 5. EC of MC case in temporal and spatial dimension

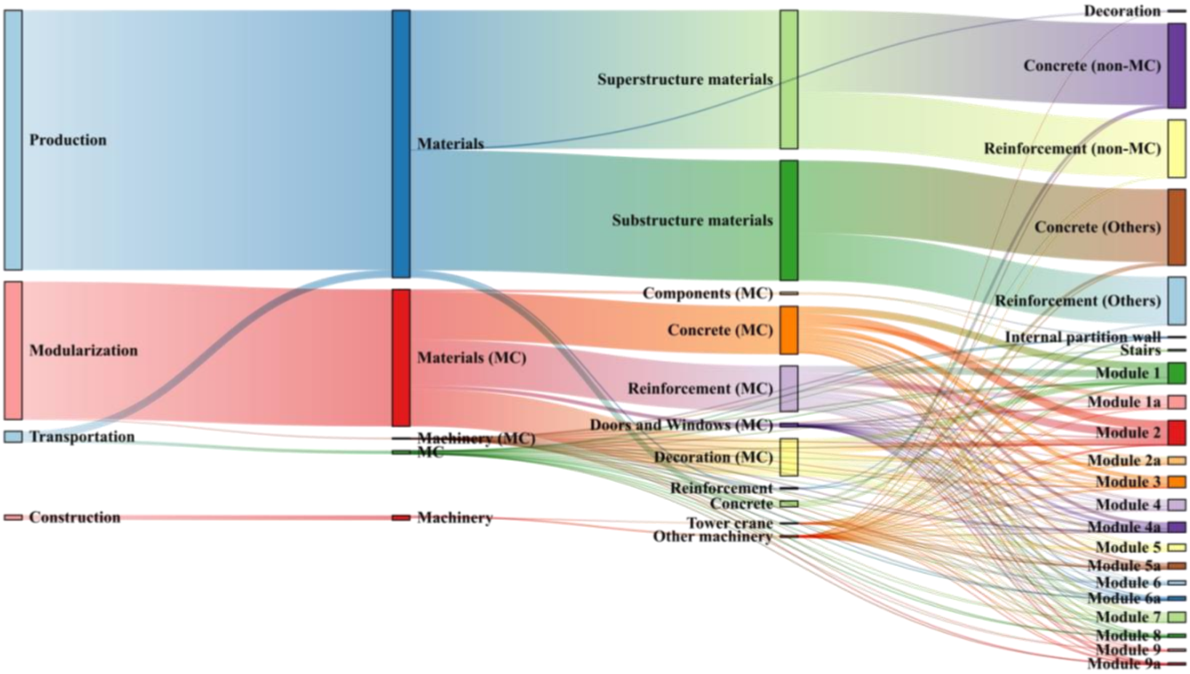

Figure 6. Temporal and spatial distribution of EC flows

5. DISCUSSION AND CONCLUSION

As an environment-friendly and innovative construction method, most studies on modular buildings focused on low and medium-rise buildings with steel and wood structures. This paper innovatively selects the first high-rise concrete MC project in mainland China as the research subject with the aim of assessing its potential and effectiveness in reducing EC emissions. This paper proposes a novel multi-level measurement framework for EC, which measures and analyzes the EC emissions of different life cycle stages and multi-level modularization from both temporal and spatial dimensions. The developed measurement framework for both temporal and spatial dimensions reveals that the average EC emission of the case building is 566.29 kg CO_{2e}/m^2, and especially on the typical floors with the MC method, the average EC emission is reduced to 540.13 kg CO_{2e}/m^2. While the average EC emissions of other non-typical floors constructed with cast-in-place concrete rise to 625.72 kg CO_{2e}/m^2. These data provide essential data support for subsequent carbon reduction studies. The results of this study are consistent with the existing findings of Teng (2020) on the range of EC emissions (336-836 kg CO_{2e}/m^2) for concrete-framed residential buildings. However, the observed carbon reductions are relatively limited compared to the non-MC part of the case project and data from other literature. It is important to note that this study does not include the EC emissions of labor in the statistics. Since a significant advantage of MC is the reduction in labor use and the increase in labor efficiency, the carbon emission savings in labor may be more significant. Also, material wastage during the production process was not considered in the study, and since the components and modules of the MC are produced in standardized factories, it is estimated that the actual carbon reduction will be more obvious. Traditional views argue that the transportation stage may contribute more EC emissions, but due to the short transport distances of the case project in the empirical study, significantly more carbon emissions from the transport process are not observed. Future studies should consider the impact of labor emissions and explore the correlation between transport weight, transport distance, and factory location to evaluate the carbon reduction potential of MC more comprehensively.

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