Joint CSCE Construction Specialty & CRC Conference 2025
Conférence conjointe spécialisée en construction de la SCGC et CRC-2025

Montreal, Quebec
July 28-31, 2025 / *28-31 juillet 2025*

Optimizing Embodied Carbon Emissions in the Life Cycle of Modular Construction to Achieve Carbon Reduction

Xiaohan Wu [1], Yue Teng [1*], Geoffrey Qiping Shen [1], and Chung-lam Ng[2]

[1] Department of Building and Real Estate, The Hong Kong Polytechnic University, Hong Kong, China
[2] Department of Data and Systems Engineering, The University of Hong Kong, Hong Kong, China
[*] yue.teng@polyu.edu.hk (corresponding author)

ABSTRACT: As a principal contributor to global carbon emissions, the construction industry's role in mitigating the adverse effects of climate change is indispensable. Modular construction has emerged as a promising solution to mitigate carbon emissions within this industry. Despite numerous technical strategies proposed for carbon reduction, a gap exists in systematically assessing the life cycle perspectives to balance construction quality, economic benefits, and carbon emission reduction. This study aims to fill this research gap by examining strategies to optimize resource allocation and process design in the modular construction life cycle, thereby minimizing carbon emissions. Firstly, a quantitative objective function to minimize carbon emissions is proposed, focusing on key stages, including material production, modularization, transportation, and on-site installation. Critical decision variables affecting carbon emissions are identified, especially allocating materials and modules between suppliers and factories to meet quality requirements. Subsequently, a mathematical model of single-objective optimization is developed, which is formalized as a mixed-integer linear programming (MILP) model. In this model, total cost and quality standards are incorporated as constraints rather than separate objective functions. The quality constraints are redesigned to use binary variables indicating whether quality requirements are met, ensuring that only qualified suppliers and factories are selected. Suitable optimization algorithms are employed, ensuring computational practicability and real-world applicability. Results demonstrate significant carbon reduction can be achieved through optimized design and management without compromising quality or exceeding cost constraints. The findings of this study have deep implications for advancing sustainable practices in the construction industry.

1. INTRODUCTION

Global climate change has become a major challenge that needs to be urgently addressed. The latest assessment report from the Intergovernmental Panel on Climate Change (IPCC) showed that without effective emission reduction measures, the global average temperature will exceed the control threshold of 1.5°C above pre-industrial levels by the end of this century (IPCC, 2023). As one of the largest energy-consuming industries, the construction industry plays a significant role in global emission reduction (Chen et al., 2023). Carbon emissions from the construction industry cover the whole life cycle. It is estimated that the construction industry accounts for 36% of global energy consumption and 40% of carbon emissions (CIC, 2020). Notably, carbon emissions during the operation stage have shown a downward trend due to the development of energy-saving technologies and the wider use of renewable energy in the construction industry (Huisingh et al., 2015). The proportion of embodied carbon emissions continues to rise. According to WorldGBC, carbon emissions from the materials production and construction process account for 11%

of the total lifecycle carbon emissions of a building, and this proportion can be as high as 50% or more in energy-efficient buildings (WorldGBC, 2019). Currently, 149 countries around the world have set net-zero emission targets, and emissions reduction actions in the construction industry play an important role in achieving this goal (Ma et al., 2024). Nonetheless, traditional construction methods face challenges of efficiency and cost-effectiveness when achieving environmental goals (Hauashdh et al., 2024).

Modular construction is a new construction mode that is driving the transformation of the construction industry towards industrialization (Li et al., 2020). By transferring traditional on-site construction to a controlled factory environment, this mode standardizes construction production processes and industrializes the fabrication of building components (Wu et al., 2025). The production of building components in a controlled factory environment uses standardized and automated processes, which improves production accuracy and efficiency while reducing resource consumption and environmental impact (Wen et al., 2024). Some studies found that modular construction could reduce construction waste (Zhang and Pan, 2021), shorten the construction period (Generalova et al., 2016), and reduce carbon emissions compared to traditional construction modes (Pervez et al., 2021). This industrialized production mode provides a potential path for the low-carbon transformation of the construction industry, and it demonstrates a clear advantage in reducing embodied carbon emissions. The environmental benefits of modular construction depend heavily on effectively managing its life cycle carbon emissions (Kamali and Hewage, 2016; Greer and Horvath, 2023). To fully realize the emission reduction potential of modular construction, a systematic analysis and optimization of its life cycle carbon emissions is required, especially considering the low-carbon design changes resulting from resource allocation and the adoption of innovative production processes, such as employing low-carbon materials. In high-density cities, such optimization needs to consider multiple factors, including site constraints, energy efficiency, transport route planning, material selection, waste management, and building operational performance (Yang et al., 2018). Therefore, analyzing and optimizing the carbon emissions of modular construction from cradle to end-of-construction stage is of great significance for achieving a low-carbon transformation and sustainable development in the construction industry. In particular, optimizing the standardized and efficient construction stages based on industrialized production processes can significantly reduce overall carbon emissions.

Optimizing the carbon emissions from the life cycle of modular construction is crucial for sustainable development and global greenhouse gas emission reduction goals in the construction industry (Teng et al., 2018). The life cycle of modular construction covers material production, modularization, transportation, installation, operation and maintenance, and the final demolition and recycling (Kamali and Hewage, 2016). To ensure the usability of the robust data, which reflect the critical industrialized production processes that distinguish modular construction from traditional construction, this paper limits the boundary from cradle to end-of-construction, including material production, modularization, transportation, and on-site installation. Each stage has a significant impact on the overall carbon emissions, so minimizing the carbon emissions in the life cycle through systematic resource allocation and process design has become the focus of current research and practice (Hariyani et al., 2024).

Existing research has focused on the following issues. The first is material selection and resource optimization. Carbon emissions during the material production stage can be reduced by exploring the use of low-carbon or renewable materials (Zheng et al., 2023), such as low-carbon concrete with mineral admixtures and high-strength steel (Aye et al., 2012). For example, Chen et al. (2022) examined the efficiency of reducing the embodied carbon for various low-carbon concretes to assess the carbon reduction of modular concrete high-rise residential buildings. Wang et al. (2023) discussed quantitative methods for materials selection and supplier evaluation, and established a multi-criteria decision-making model based on carbon footprint to solve problems related to resource allocation. The second is design and process optimization. By optimizing module design and production processes, production efficiency can be improved, thereby reducing material waste and energy consumption during transportation (Banihashemi et al., 2018). Liu et al. (2022) investigated the production scheduling and route optimization of modular components, and proposed a mixed-integer programming model considering time constraints to optimize the process design. The third is related to the optimization of production and logistics. Some studies have adopted green manufacturing technologies and optimized transport routes to reduce energy consumption and carbon emissions (Wang et al., 2019; Pimenov et al., 2022).

However, existing studies focus on a single dimension of the building life cycle and lack a systematic analysis of modular construction, especially for high-rise steel modular construction. Further, there is a lack of a systematic approach that considers construction quality, economic benefits, and carbon reduction targets, making it difficult to fully apply optimization results in practical engineering. Accordingly, this paper fills this research gap by proposing an optimization model that minimizes the life cycle carbon emissions of modular construction while also considering cost and quality requirements as constraints. By establishing a mixed-integer linear programming (MILP) model, which effectively handles discrete and continuous decision variables, this paper comprehensively evaluates and analyzes the interactions and synergistic emission reduction potential between the different stages of high-rise steel frame modular construction. This study provides an optimization framework for the modular construction industry from cradle to end-of-construction that balances the objective function and multiple constraints, promoting the low-carbon sustainable development of the construction industry.

2. METHODOLOGY

2.1 Developing the Carbon Optimization Model

This study develops a mixed-integer linear programming (MILP) model to minimize carbon emissions from cradle to end-of-construction in modular construction. The optimization model focuses on four main stages: material production, modularization, transportation, and on-site installation. The model comprehensively considers the quality requirements of suppliers and factories, cost constraints, and the optimal combination of different low-carbon measures in material production, modularization, transportation, and on-site installation. The linear objective function and constraints in the model facilitate the modeling of linear relationships such as carbon emissions and costs, while the integer and binary variables indicate the selection of suppliers and factories and the quality requirements.

2.1.1 Hypothesis

This paper focuses on the core variables and relationships by simplifying and making assumptions about the real situation as appropriate to ensure the rationality and operability of the optimization model. The following assumptions are therefore made:

[1] The quality requirements of all raw material suppliers and module manufacturers are available and based on relevant quality certifications, audits, or historical assessments.
[2] Costs and carbon emissions are linearly related to the quantities produced and transported.
[3] All transport routes are available, and transport distances are known and accurate.
[4] The production capacities of all suppliers and factories are determined, and capacity restrictions are considered in the model.

2.1.2 Model parameters and variables

Table 1: Notation and meaning for parameters in this study

Notation	Meaning
K	Set of raw material types, indexed by $k \in K$.
M	Set of raw material suppliers, indexed by $m \in M$.
H	Set of the module types, indexed by $h \in H$.
F	Set of module production factories, indexed by $f \in F$.
S	Set of construction sites, indexed by $s \in S$.
D_s^h	Demand for module h at construction site s.
Q_k^h	Quantity of raw material k required to produce one module h (kg).
w_k^{mat}	Quantity of raw material needed for single module k (kg).
w_h^{mod}	Weight of each module h (kg).

$d_{xm,f}$	Transportation distance from raw material supplier m to factory f (kilometers).
$d_{yf,s}$	Transportation distance from factory f to construction site s (kilometers).
$E_{k,m}^{\text{mat}}$	Carbon emission factor for producing one unit of raw material k by supplier m (kg CO_{2e}/kg).
$E_{h,f}^{\text{mod}}$	Carbon emission factor of equipment used in the production of each module h at factory f (kg CO_{2e}/unit).
E^{ins}	Carbon emission factor of equipment used for installing each module (kg CO_{2e}/unit).
E^{tr}	Carbon emission factor per ton-kilometer of transportation (kg CO_{2e}/ton·km).
$c_{k,m}^{\text{mat}}$	Cost of purchasing one unit of raw material k from supplier m (currency units/kg).
$c_{h,f}^{\text{mod}}$	Cost of producing each module h at factory f (currency units/unit).
c^{ins}	Installation cost each module (currency units/unit).
c^{tr}	Transportation cost per ton-kilometer (currency units/ton·km).
Budget	Total budget allocated for the project (currency units).
$\text{Cap}_{k,m}^{\text{mat}}$	Capacity of supplier m for raw material k (kg).
$\text{Cap}_{h,f}^{\text{mod}}$	Production capacity of factory f for each module h (units).

Table 2: Notation and meaning for quality compliance parameters in this study

Notation	Meaning
M	A positive constant used in constraints.
$\text{Qual}_{k,m}^{\text{mat}}$	Quality compliance indicator for raw material k from supplier m; equals 1 if compliant, 0 otherwise.
$\text{Qual}_{h,f}^{\text{mod}}$	Quality compliance indicator for each module h from factory f; equals 1 if compliant, 0 otherwise.

2.1.2.1 Decision variables

$x_{m,f}^{k} \geq 0$: Quantity of raw material k transported from supplier m to factory f (kg).
$y_{f,s}^{h} \geq 0$: Quantity of the module h transported from factory f to construction site s (units).
$z_{k,m}^{\text{mat}} \in \{0,1\}$: Binary variable indicating whether raw material k from supplier m is selected (1 if selected, 0 otherwise).
$z_{h,f}^{\text{mod}} \in \{0,1\}$: Binary variable indicating whether the module h from factory f is selected (1 if selected, 0 otherwise).

2.1.2.2 Objective function

The objective function of minimizing total carbon emissions consists of following four parts:

$$\begin{aligned}\min EC = & \underbrace{\sum_{k\in K} \sum_{m\in M} \sum_{f\in F} E_{k,m}^{\text{mat}} \cdot x_{m,f}^{k}}_{\text{Production emissions}} \\ & + \underbrace{\sum_{h\in H} \sum_{f\in F} \sum_{s\in S} E_{h,f}^{\text{mod}} \cdot y_{f,s}^{h}}_{\text{Modularization emissions}} \\ & + \underbrace{E^{\text{tr}}\left(\sum_{k\in K} \sum_{m\in M} \sum_{f\in F} d_{xm,f} \cdot w_{k}^{\text{mat}} \cdot x_{m,f}^{k} + \sum_{h\in H} \sum_{f\in F} \sum_{s\in S} d_{yf,s} \cdot w_{h}^{\text{mod}} \cdot y_{f,s}^{h}\right)}_{\text{Transportation emissions}} \\ & + \underbrace{E^{\text{ins}} \cdot \sum_{h\in H} \sum_{f\in F} \sum_{s\in S} y_{f,s}^{h}}_{\text{Installation emissions}}\end{aligned}$$

2.1.3 Constraints

[1] Demand satisfaction: ensure that the demand for every module type at each construction site is met,

$$\sum_{f\in F} y_{f,s}^{h} \geq D_{s}^{h}, \forall h \in H, \forall s \in S$$

[2] Material balance: ensure that factories receive sufficient raw materials to produce the required modules,

$$\sum_{m\in M} x_{m,f}^{k} \geq \sum_{h\in H} Q_{k}^{h} \cdot \sum_{s\in S} y_{f,s}^{h}, \forall k \in K, \forall f \in F$$

[3] Quality requirement:

1) Supplier, only raw materials from quality-compliant suppliers can be selected: $z_{k,m}^{\text{mat}} \leq \text{Qual}_{k,m}^{\text{mat}}, \forall k \in K, \forall m \in M$; link binary variables with raw material procurement: $x_{m,f}^{k} \leq M \cdot z_{k,m}^{\text{mat}}, \forall k \in K, \forall m \in M, \forall f \in F$.

2) Factory, only modules from quality-compliant factories can be selected: $z_{h,f}^{\text{mod}} \leq \text{Qual}_{h,f}^{\text{mod}}, \forall h \in H, \forall f \in F$; link binary variables with module production and procurement: $y_{f,s}^{h} \leq M \cdot z_{h,f}^{\text{mod}}, \forall h \in H, \forall f \in F, \forall s \in S$

[4] Capacity:

1) Supplier, the total quantity of raw material k supplied by supplier m can not exceed their capacity:

$$\begin{cases} \sum_{f\in F} x_{m,f}^{k} \leq \text{Cap}_{k,m}^{\text{mat}} \cdot z_{k,m}^{\text{mat}}, \forall k \in K, \forall m \in M \\ x_{m,f}^{k} \leq \text{Cap}_{k,m}^{\text{mat}} \cdot z_{k,m}^{\text{mat}}, \forall k \in K, \forall m \in M, \forall f \in F \end{cases}$$

2) Factory, the total quantity of MC module h produced by factory f can not exceed their capacity:

$$\begin{cases} \sum_{s\in S} y_{f,s}^{h} \leq \text{Cap}_{h,f}^{\text{mod}} \cdot z_{h,f}^{\text{mod}}, \forall h \in H, \forall f \in F \\ y_{f,s}^{h} \leq \text{Cap}_{h,f}^{\text{mod}} \cdot z_{h,f}^{\text{mod}}, \forall h \in H, \forall f \in F, \forall s \in S \end{cases}$$

[5] Cost: ensure that the total cost does not exceed the project's allocated budget:

$$\begin{aligned} &\sum_{k\in K} \sum_{m\in M} \sum_{f\in F} c_{k,m}^{\text{mat}} \cdot x_{m,f}^{k} + \sum_{h\in H} \sum_{f\in F} \sum_{s\in S} c_{h,f}^{\text{mod}} \cdot y_{f,s}^{h} \\ &+ c^{\text{tr}} \left(\sum_{k\in K} \sum_{m\in M} \sum_{f\in F} d_{xm,f} \cdot w_{k}^{\text{mat}} \cdot x_{m,f}^{k} + \sum_{h\in H} \sum_{f\in F} \sum_{s\in S} d_{yf,s} \cdot w_{h}^{\text{mod}} \cdot y_{f,s}^{h} \right) \\ &+ c^{\text{ins}} \cdot \sum_{h\in \text{⍰⍰}} \sum_{f\in F} \sum_{s\in S} y_{f,s}^{h} \leq \text{Budget} \end{aligned}$$

[6] Non-negativity and binary:

$$\begin{cases} x_{m,f}^{k} \geq 0, & \forall k \in K, \forall m \in M, \forall f \in F \\ y_{f,s}^{h} \geq 0, & \forall h \in H, \forall f \in F, \forall s \in S \\ z_{k,m}^{\text{mat}} \in \{0,1\}, & \forall k \in K, \forall m \in M \\ z_{h,f}^{\text{mod}} \in \{0,1\}, & \forall h \in H, \forall f \in F \end{cases}$$

2.2 Data Collection and Analysis

The data required for the optimization model are mainly divided into carbon emissions, costs, and quality. The data collection related to carbon emissions is strategically divided into two principal domains: the engineering quantities of the activities in each stage (material production, modularization, transportation, and on-site installation) and corresponding carbon emission factors. The engineering quantity is based on the project drawings and other engineering documents. The emission factors related to materials are mainly from the CIC carbon assessment tool, while the emission factors related to transportation and equipment are mainly from the Ecoinvent database embedded in SimaPro 9.4 and local standards. In addition, the emission factors of some equipment have been adjusted according to the parameters related to carbon used by the local construction industry to meet local conditions. Since cost data is sensitive, relevant data was obtained and validated through two rounds of semi-structured interviews with project stakeholders. The first round of interviews focused on the composition of project costs, the budgeting process, and the range of historical data, while the second round of interviews verified the availability of upper and lower limits estimated based on public information and market prices. Interviewees were selected from those with experience in project cost management and budget development, including project engineers, the general contractor and the subcontractor responsible for the project, material suppliers, and transporters, to ensure multi-role representation and cross-validation of information. Quality data is also derived from interviews and site surveys, and the materials considered by the factory and the general contractor are all up to standard. This means that all combinations in this paper are within the quality requirements.

2.3 Case Study

The selected case project for empirical analysis is a university student dormitory project in Hong Kong to verify the effectiveness of the optimization model proposed in this paper. The case project consists of four high-rise buildings, three of which are 13 floors and one is 14 floors, with a total construction area of 50,200 square meters. The basic information of the case project is summarized in Table 1. The project is a steel modular residential building, which includes a total of 893 modules of 7 types. Considering the case project chooses to use high-strength steel Q690C to reduce carbon emissions, this paper will include the traditional carbon emissions scenario. Besides, this paper will also consider different measures involving management, transportation, and materials. Management measures include electric energy saving, and the relevant data come from the past electricity use and conservation of the factories investigated in the site survey, supplemented by interviews with project engineers. Transportation measures consider the current mainstream transport vehicles for engineering and construction. Material-related emission reductions include using concrete with different proportions of mineral admixtures, such as ground granulated blast-furnace slag (GGBS) and fly ash, as well as the influence of different strength steel frames. Specific optimization measures are shown in Table 2.

Table 3: The basic information of the case project

Category	Detail
Location	Hong Kong
Project type	Residential building (university dormitory building)
Superstructure stories	Three 13-storey buildings and one 14-storey building
Number of modules	893
Number of types of modules	7
GFA (m^2)	50,200
Construction period	04/2023 – 10/2027
Structure	Steel MC

Table 4: The optimization measures considered in this paper

Stage	Category	Detail	Code	Note	Carbon Reduction Ratio	Carbon Reduction (t)
Management measures	Electric energy saving (Percentage)	0%	A1	Baseline	0.00%	0.00
		1%	A2		0.03%	14.97
		2%	A3		0.06%	29.95
		3%	A4		0.09%	44.92
		4%	A5		0.12%	59.89
		5%	A6		0.15%	74.86
		6%	A7		0.18%	89.84
		7%	A8		0.21%	104.81
		8%	A9		0.24%	119.78
		9%	A10		0.27%	134.75
		10%	A11		0.30%	149.73
Transportation		Diesel semi-trailer tractor	B1	Baseline	0.00%	0.00
		Diesel cargo truck	B2		2.10%	1039.02
		Diesel dump truck	B3		1.59%	784.50
		Pure electric cargo truck	B4		-0.69%	-341.36
		Pure electric dump truck	B5		-1.06%	-524.54
		Pure electric semi-trailer tractor	B6		-1.33%	-656.56
		Fuel cell cargo truck	B7		1.45%	716.81
		Fuel cell dump truck	B8		0.70%	347.79
		Fuel cell semi-trailer tractor	B9		-0.10%	-50.34
Material production	Concrete Composition	Normal concrete	C1	Baseline	0.00%	0.00
		<=25% fly ash	C2		3.40%	1681.13
		>=25% fly ash	C3		4.51%	2226.02
		35%-55% GGBS	C4		5.36%	2649.64
		55%-75% GGBS	C5		7.90%	3902.44
		Q690	D1	Baseline	0.00%	0.00

	Steel Composition	Traditional steel_Q355	D2	-5.74%	-2834.83

3. RESULTS AND DISCUSSION

Considering the combinations of different emission reduction measures described above, a total of 990 emission reduction solutions were obtained. The performance of different emission reduction measures on carbon emissions and costs is shown in Figure 1. In the scatter plot, each point represents a combination of measures, with the x-axis indicating total cost and the y-axis showing total carbon emissions. All combinations of measures are represented by blue scatter points, and the large red dot represents the optimal combination selected by the optimization model. Specifically, the optimal combination of measures includes the use of 55%-75% GGBS to replace traditional concrete materials and Q690 high-strength steel frames, with diesel trucks used for transportation, and a daily reduction in electricity waste through lean management and other means to achieve an 8% reduction in carbon emissions. The green dashed line represents the cost constraint of the project. The trend line shown in blue has a small slope and is close to flat, which indicates that the correlation between total cost and total carbon emissions is not significant. Therefore, it is not possible to reduce carbon emissions by increasing costs. Alternatively, there may be combinations of measures that significantly differ in carbon emissions within a certain cost range. Since there is no significant trend between cost and carbon emissions, the role of the optimization model is crucial. It can find the optimal combination of measures that meets the cost constraints and minimizes carbon emissions, rather than choosing more expensive options. Through a reasonable combination of strategies, it is possible to achieve a ‘win-win’ situation that reduces both costs and carbon emissions.

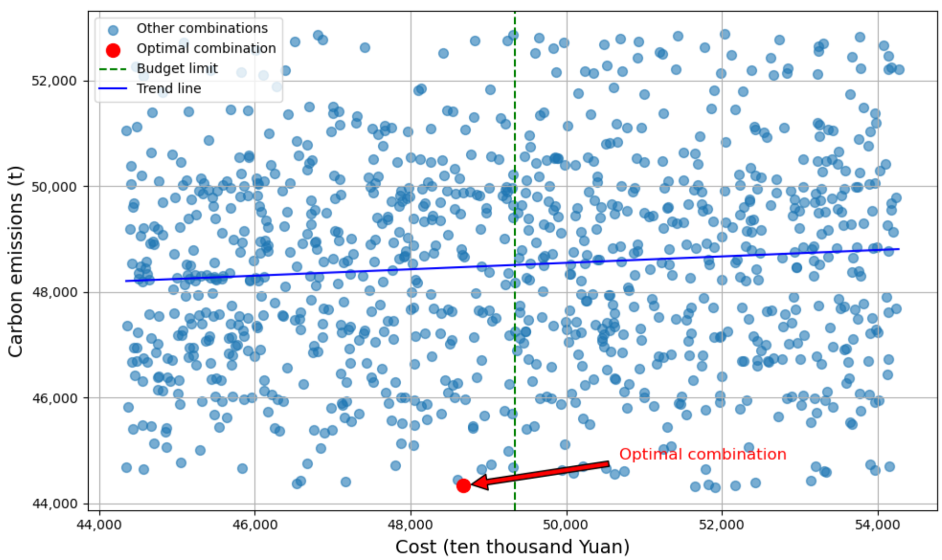

Figure 1: The performance of different emission reduction measures on carbon emissions and costs

The scatter plot shows that some points lie in the lower left-hand area, where both total cost and total carbon emissions are low. These points represent the most optimal combination of measures. First, the measures generally use energy-efficient vehicles with clean fuels in the transportation stage. Choosing clean energy vehicles (such as electric or fuel cell vehicles) can significantly reduce carbon emissions, but the purchase and operating costs are high (Ajanovic and Haas, 2019; Zhang et al., 2023). Therefore, optimizing the fuel efficiency of traditional diesel vehicles (such as reducing the empty load rate and optimizing driving routes) has become an effective way to reduce carbon emissions and costs (Ayyildiz et al., 2017; Turkensteen, 2017).

Second, these optimization measures typically involve the use of lower-carbon materials. Since cement production is the main carbon source in manufacturing concrete, reducing the amount of cement used can reduce carbon emissions (Barcelo et al., 2014). This can be achieved by increasing the amount of mineral admixtures (such as GGBS and fly ash) (Wu et al., 2018). Some studies have found that the use of high mineral admixture does not significantly increase material costs (Cyr et al., 2006), it can even reduce costs in some cases (Tangadagi et al., 2021), because the cost of mineral admixtures is lower than that of cement (Zhang et al., 2021). Consequently, concrete with a high mineral admixture content (e.g., 55% to 75% GGBS) effectively reduces carbon emissions during the production of materials while limiting material costs.

Third, using high-strength steel in the structural design of modular construction results in lower carbon emissions. Since the selected case is a steel modular dormitory project, it innovatively used Q690C steel for the structural frame. In the optimization measures, the Q355 steel used in traditional steel frames is taken into account. According to the principle of equal-strength design, the yield strength of Q690C high-strength steel is nearly twice that of Q355 steel (Shi et al., 2024). This means that the amount of steel used can be reduced by half while maintaining the same structural strength. Related research shows that as the strength of steel increases from Q355 to Q690, the increase in the embodied carbon in the product is between 0 and 6% (SCI-RT 1925: 2023). Theoretically, using Q690 as the steel frame would significantly reduce carbon emissions during production. The optimization results also support this assertion. Additionally, the weight of the components is reduced due to the reduced amount of high-strength steel used. Apart from reducing transport costs, this also reduces carbon emissions during the transportation stage. Moreover, lighter components are easier to handle during installation, potentially reducing the time and energy consumption of on-site machinery, thereby further reducing carbon emissions during the construction stage.

4. CONCLUSION

This study aims to optimize the embodied carbon emissions of modular construction from cradle to end-of-construction stage and achieve the carbon reduction target. For this purpose, this paper proposes a single-objective optimization problem to minimize carbon emissions and solves the problem by formulating a mixed-integer linear programming (MILP) model that covers four stages: material production, modularization, transportation, and on-site installation. The model considers the quality requirements of suppliers and factories, as well as the cost constraints of the project. Through systematic optimization of resource allocation and process design, it seeks to minimize carbon emissions while ensuring construction quality and within budget. Combined with the case study and the analysis of the results, the following findings are highlighted in this study. First, carbon emissions are significantly reduced by optimizing measures, including materials, transport, and management. Second, there is no significant linear relationship between cost and carbon emissions. It is therefore possible to achieve carbon emission reductions without increasing costs through an effective combination of measures. Third, reducing the amount of cement used by increasing the amount of mineral admixtures (such as GGBS and fly ash) can reduce carbon emissions and have no significant impact on costs. Fourth, high-strength steel can effectively reduce carbon emissions during the material production stage because less high-strength steel is used, and it only adds little carbon emissions compared to traditional steel.

The optimization model proposed in this paper, which comprehensively considers quality, cost, and carbon emissions, differs from previous models that only focus on a single dimension. It fully integrates quality requirements, cost constraints, and climate targets, making it more practical and feasible. In addition, this paper introduces the analysis of using high-strength steel in modular construction. This paper selects a practical case to explore the impact of using Q690C high-strength steel on carbon emissions, filling a gap in this field and providing a guide for the wider use of high-strength steel in modular construction. The research in this paper expands the existing theory on carbon emission optimization in the construction industry and provides new ideas and methods for carbon reduction in modular construction. Additionally, by integrating quality, cost, and carbon emissions into an optimization model, this paper provides a reference for dealing with similar multi-constraint, multi-objective optimization problems. At the practical level, the results can guide construction companies in achieving carbon reduction targets through optimization in actual projects, which has direct application value and is significant for promoting green and sustainable development in the construction industry.

Although the MILP model developed in this paper has achieved results and recommendations for reducing carbon emissions of high-rise steel-framed modular construction from cradle to end-of-construction stages, there are still some limitations to this study. First, the model does not fully consider dynamic factors such as resource idle time and equipment utilization during production and modularization, which may impact the actual carbon emissions. Second, this paper mainly focuses on the carbon emissions of equipment and materials during the material production, modularization, transportation, and on-site installation processes, and insufficient consideration is given to worker-related carbon emissions. Finally, as some of the parameters and data are limited by existing on-site research and industry standards, the data collection techniques can be further expanded in the future. Based on this, future research can explore from related directions. These include incorporating resource idle time, equipment utilization, and dynamic scheduling factors in the production line into the model to reflect carbon emissions more comprehensively in the actual production and modularization process. In addition, the emissions generated by workers can be further considered and optimized to reduce carbon emissions.

ACKNOWLEDGMENTS

The work presented in this paper was supported by the General Research Fund of the Hong Kong Research Grants Council (No.: 15220923), Shenzhen Municipal Science and Technology Innovation Commission Key Basic Research Fund (No.: JCYJ20220818102211024), Young Scientists Fund of the National Natural Science Foundation of China (No.: 72301232), Guangdong Basic and Applied Basic Research Foundation (No.: 2023A1515012558), and Hong Kong Polytechnic University Carbon Neutrality Fund (No. P0043733). Also acknowledged is support from Campus Development Office of Hong Kong Polytechnic University and AluHouse Company Limited for access to the case building for study.

REFERENCES

Ajanovic, A. & Haas, R. 2019. Economic and environmental prospects for battery electric-and fuel cell vehicles: a review. *Fuel cells,* 19**,** 515-529.

Aye, L., Ngo, T., Crawford, R. H., Gammampila, R. & Mendis, P. 2012. Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. *Energy and buildings,* 47**,** 159-168.

Ayyildiz, K., Cavallaro, F., Nocera, S. & Willenbrock, R. 2017. Reducing fuel consumption and carbon emissions through eco-drive training. *Transportation Research Part F: Traffic Psychology and Behaviour,* 46**,** 96-110.

Banihashemi, S., Tabadkani, A. & Hosseini, M. R. 2018. Integration of parametric design into modular coordination: A construction waste reduction workflow. *Automation in Construction,* 88**,** 1-12.

Barcelo, L., Kline, J., Walenta, G. & Gartner, E. 2014. Cement and carbon emissions. *Materials and structures,* 47**,** 1055-1065.

Chen, L., Zhao, Y., Xie, R., Su, B., Liu, Y. & Renfei, X. 2023. Embodied energy intensity of global high energy consumption industries: A case study of the construction industry. *Energy,* 277**,** 127628.

Chen, S., Zhang, Y., Teng, Y., Poon, C. S. & Pan, W. Estimating Embodied Carbon Reduction in Modular High-Rise Residential Buildings Through Low Carbon Concrete. International Symposium on Advancement of Construction Management and Real Estate, 2022. Springer, 1357-1369.

CIC, 2020. Promote sustainable construction towards a low carbon model. Construction Industry Council.

Cyr, M., Lawrence, P. & Ringot, E. 2006. Efficiency of mineral admixtures in mortars: Quantification of the physical and chemical effects of fine admixtures in relation with compressive strength. *Cement and concrete research,* 36**,** 264-277.

Generalova, E. M., Generalov, V. P. & Kuznetsova, A. A. 2016. Modular buildings in modern construction. *Procedia engineering,* 153**,** 167-172.

Greer, F. & Horvath, A. 2023. Modular construction's capacity to reduce embodied carbon emissions in California's housing sector. *Building and Environment,* 240**,** 110432.

Hariyani, D., Hariyani, P., Mishra, S. & Sharma, M. K. 2024. Leveraging digital technologies for advancing circular economy practices and enhancing life cycle analysis: A systematic literature review. *Waste Management*

Bulletin.
Hauashdh, A., Nagapan, S., Jailani, J. & Gamil, Y. 2024. An integrated framework for sustainable and efficient building maintenance operations aligning with climate change, SDGs, and emerging technology. *Results in Engineering,* 21**,** 101822.
Huisingh, D., Zhang, Z., Moore, J. C., Qiao, Q. & Li, Q. 2015. Recent advances in carbon emissions reduction: policies, technologies, monitoring, assessment and modeling. *Journal of cleaner production,* 103**,** 1-12.
IPCC 2023. Synthesis report of the IPCC Sixth Assessment Report (AR6), Longer report. IPCC.
Kamali, M. & Hewage, K. 2016. Life cycle performance of modular buildings: A critical review. *Renewable and sustainable energy reviews,* 62**,** 1171-1183.
Li, L., Li, Z., Li, X., Zhang, S. & Luo, X. 2020. A new framework of industrialized construction in China: Towards on-site industrialization. *Journal of Cleaner Production,* 244**,** 118469.
Liu, J., Zhang, Z., Zhang, Y., Liu, S., Chen, F. & Yin, T. 2022. Mixed-integer programming model and hybrid immune clone select algorithm for multi-objective double floor corridor allocation problem with vertical conveyor. *Robotics and Computer-Integrated Manufacturing,* 77**,** 102364.
Ma, M., Zhou, N., Feng, W. & Yan, J. 2024. Challenges and opportunities in the global net-zero building sector. *Cell Reports Sustainability*.
Pervez, H., Ali, Y. & Petrillo, A. 2021. A quantitative assessment of greenhouse gas (GHG) emissions from conventional and modular construction: A case of developing country. *Journal of Cleaner Production,* 294**,** 126210.
Pimenov, D. Y., Mia, M., Gupta, M. K., Machado, Á. R., Pintaude, G., Unune, D. R., Khanna, N., Khan, A. M., Tomaz, Í. & Wojciechowski, S. 2022. Resource saving by optimization and machining environments for sustainable manufacturing: A review and future prospects. *Renewable and Sustainable Energy Reviews,* 166**,** 112660.
SCI-RT 1925: 2023. High strength steel structures: Design and construction using high strength steel in China.
Shi, Y., Yu, X. & Ban, H. 2024. Research and Progress on Application of High Performance Steel. *STEEL CONSTRUCTION (Chinese & English),* 39**,** 97.
Tangadagi, R. B., Manjunatha, M., Seth, D. & Preethi, S. 2021. Role of mineral admixtures on strength and durability of high strength self compacting concrete: An experimental study. *Materialia,* 18**,** 101144.
Teng, Y., Li, K., Pan, W. & Ng, T. 2018. Reducing building life cycle carbon emissions through prefabrication: Evidence from and gaps in empirical studies. *Building and Environment,* 132**,** 125-136.
Turkensteen, M. 2017. The accuracy of carbon emission and fuel consumption computations in green vehicle routing. *European Journal of Operational Research,* 262**,** 647-659.
Wang, J., Yao, S., Sheng, J. & Yang, H. 2019. Minimizing total carbon emissions in an integrated machine scheduling and vehicle routing problem. *Journal of Cleaner Production,* 229**,** 1004-1017.
Wang, Z.-J., Chen, Z.-S., Su, Q., Chin, K.-S., Pedrycz, W. & Skibniewski, M. J. 2023. Enhancing the sustainability and robustness of critical material supply in electrical vehicle market: an AI-powered supplier selection approach. *Annals of Operations Research***,** 1-38.
Wen, X., Teng, Y. & Shen, G. Q. 2024. Extended end-of-life carbon assessment and savings: A case study of steel-framed modular buildings in Hong Kong. *Building and Environment,* 266**,** 112056.
WorldGBC 2019. Bringing Embodied Carbon Upfront: Coordinated action for the building and construction sector to tackle embodied carbon.
Wu, M., Zhang, Y., Ji, Y., Liu, G., Liu, C., She, W. & Sun, W. 2018. Reducing environmental impacts and carbon emissions: Study of effects of superfine cement particles on blended cement containing high volume mineral admixtures. *Journal of Cleaner Production,* 196**,** 358-369.
Wu, X., Shen, G. Q., Teng, Y. & Jiang, R. 2025. Comparative cradle to end-of-use embodied carbon analysis of high-rise concrete buildings using volumetric modular and panelized construction. *Journal of Building Engineering,* 100**,** 111736.
Yang, Y., Ng, S. T., Xu, F. J. & Skitmore, M. 2018. Towards sustainable and resilient high density cities through better integration of infrastructure networks. *Sustainable Cities and Society,* 42**,** 407-422.
Zhang, T., Ma, B., Jiang, D., Jiang, Q. & Jin, Z. 2021. Comparative research on the effect of various mineral admixtures on the early hydration process of cement. *Construction and Building Materials,* 301**,** 124372.
Zhang, W., Fang, X. & Sun, C. 2023. The alternative path for fossil oil: electric vehicles or hydrogen fuel cell vehicles? *Journal of Environmental Management,* 341**,** 118019.
Zhang, Y. & Pan, W. Reducing construction waste through modular construction. International Symposium on Advancement of Construction Management and Real Estate, 2021. Springer, 339-347.
Zheng, J., Shi, J., Lin, F., Hu, X., Pan, Q., Qi, T., Ren, Y., Guan, A., Zhang, Z. & Ling, W. 2023. Reducing manufacturing carbon emissions: Optimal low carbon production strategies respect to product structures and batches. *Science of the Total Environment,* 858**,** 159916.