Embodied carbon and cost variation of steel modules by using low-carbon steel considering carbon price's influence

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Abstract

Greenhouse gases (GHGs) contribute to the climate change intensely, in which carbon emissions play an important role. The building sector has been widely regarded as a primary contributor to carbon emissions. Steel modular construction has been considered as an innovative approach for building project delivery, particularly in temporary and emergent projects where steel modules alone can normally form the whole building structure. However, few studies have examined the embodied carbon (EC) of steel modules and to what extent the adoption of low-carbon steel products can achieve the EC reductions as well as its influence on the module cost variation, particularly considering the carbon price's influence. This paper aims to close this research gap by examining the EC and cost variation of a selected steel module from a temporary steel modular building project in Hong Kong. Process-based LCA method was adopted for EC assessment and linear programming analysis was conducted to examine the module's cost variation by considering the low-carbon steel adoption and carbon price. Results showed that the EC of steel production contributed the most (53%) to the cradle-to-end-of-construction EC of a steel module. Adopting electronic arc furnace made steel could significantly reduce the EC of the module by 36%. The economic benefits of considering carbon price were marginal, but could still be considered to stimulate the adoption of low-carbon strategies.

Keywords –

Embodied carbon; Modular buildings; Cost; Carbon price

1 Introduction

Greenhouse gases (GHGs) contribute to the climate change intensely, leading to severe and irreversible climate problems such as global warming [1]. Carbon emissions play an important role in the total GHG emissions [2]. The building sector has been widely regarded as a primary contributor to carbon emissions, accounting for 39% of worldwide energy-related carbon emissions [3,4]. The percentage is even higher in high-density cities, e.g. being over 60% in HK [5]. Reducing the carbon emissions from buildings has been considered important and urgent to achieve carbon reductions [6,7].

The carbon emissions of building can be divided into operational carbon (OC) and embodied carbon (EC) [8]. Comparing with the OC generated by energy consumption during the building operation stage, EC is generated from material extraction, transportation, construction, maintenance, and deconstruction in a building's life cycle, which can be emitted within a shorter period and lead to more intensive annual carbon impacts, particularly in import-dominated and high-density cities such as HK [9,10]. It is anticipated that the EC reduction from buildings will be increasingly important, as the EC will comprise nearly 50% of the overall carbon emissions of new building projects by 2050 considering the continuous reduction of OC [4,11]. Reducing the EC emissions during a building's life cycle has been considered as an important path to achieve the carbon neutrality of new buildings [12,13].

Modular construction (MC), as an innovative construction approach that uses three-dimensional modules prefabricated in offsite factories and assembled onsite to form the main building structure, has been increasingly implemented worldwide [14-16]. It has been proved that MC can realize multi-aspect advantages such as enhancing construction productivity, reducing construction waste, and improving construction quality [17].

MC systems can be categorized into three major types by material, i.e., steel, concrete, and timber systems [18]. Steel MC systems have been widely used worldwide, showing its advantages in simple inter-module connection designs, flexible module designs, and light module weight [10]. Particularly, steel modules have a better potential for disassembly and reuse, which are suitable for low- to mid-rise temporary modular building projects, such as transitional housing and emergency facilities [19].

A few studies have investigated the EC emissions of steel modules and steel modular buildings, and some of them provided preliminary comparisons of the EC results with other building types. For example, Aye et al. [20] compared the EC emissions of an 8-story residential building using three construction approaches: steel-framed modules, timber-framed modules, and traditional concrete, and suggested that both steel and timber MC could help reduce the EC from the buildings. Iuorio et al. [21] investigated a 2-story modular steel-framed house, and showed the modular method to reduce EC by half compared to traditional masonry approach. Recent studies also examined the EC of high-rise modular buildings. Zhang et al. [10] investigated the cradle-to-end-of-construction EC of a steel modular high-rise building, and identified 6% initial EC increasement, but nearly half EC reduction in the transportation and construction stages comparing with a hypothesized cast-in-situ building with the same layout. Kosajan et al. [19] explored the EC of steel modules for emergency facilities in Hong Kong considering different end-of-life strategies, and identified the significant whole lifecycle EC reduction potential of steel modules by reuse and recycling strategies.

A few studies also investigated the construction costs of steel modular buildings. Pan et al. [22] estimated the construction costs of a steel Modular building in HK, indicating that a maximum 10% construction costs could be achieved by using MC with a good project management. Lopez and Froese [23] identified a marginal cost reduction (around 7%) of the MC comparing with panelized prefabrication in a single family home. Jang et al. [24] identified 8% cost increasement of MC than conventional concrete method during the production phase in Korea.

It has been acknowledged that the adoption of low-carbon steel could significantly reduce the EC emissions of steel modules, and thus reducing the EC of steel modular buildings [10]. Particularly in low- to mid-rise steel modular buildings that are primarily structured by steel modules without in-situ concrete cores, EC reduction of modules is more important. However, on one hand, it is still unclear to what extent the EC of steel modules could be reduced by using low-carbon steel products, for example, using low-carbon steel produced by electronic arc furnace (EAF) instead of blast furnace-basic oxygen furnace (BF-BOF). On the other hand, up-front module factories are normally economic profit-oriented, and the cost of low-carbon steel products is important to be considered. Despite the emerging and development of the carbon market worldwide in recent years to encourage the industry decarbonization, it is still unknown how the trade-off between the carbon reduction and cost variation could be made for steel modules considering the influence of carbon price, particularly in China where the EAF-made steel products are normally more expensive than BF-made steel due to the small market share [25].

This paper aims to investigate the cradle-to-site EC emissions of steel modules, and examine the EC reduction potential by using low-carbon steel products and corresponding cost variance of modules considering the influence of carbon price.

2 EC assessment and cost evaluation

2.1 EC assessment method

Life cycle assessment (LCA) has been widely adopted to quantify and evaluate the environmental impacts of building projects. LCA is defined as "*the compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle*" [26]. Three types of LCA methods can be adopted for the life-cycle carbon assessment of buildings: the input-output (IO) method, process-based LCA method, and hybrid LCA method that integrates the IO and process-based LCA methods [27]. By breaking down the intricate material production and building construction procedures into interconnected yet distinct processes, the process-based LCA method facilitates a more comprehensive EC analysis at each stage for the entire building project than the other two methods, i.e. input-output and hybrid LCA. LCA has also been adopted for construction cost analysis (lifecycle cost assessment, LCCA) in recent years considering its feasibility and efficiency in identifying cost-intensive building elements and construction activities [28].

This paper examines the cradle-to-end-of-construction EC emissions of the steel modules using the process-based LCA method. The covered lifecycle includes raw materials excavation, raw materials transport to factory, module manufacturing, module transportation to construction site, and site installation. The corresponding scope for the lifecycle EC assessment includes the initial EC emissions associated with the module's materials (including both structural and architectural materials) and module components (e.g. steel frame), together with relevant activities during the prefabrication, transportation and installation stages. Specifically, major structural and architectural materials and their corresponding production and transportation processes were considered, which included steel frame, metal works, mortar, plastering, painting, tiles, timber, and glass. Furniture and building services (e.g., electricity and ventilation systems) were excluded in the assessment because these materials only accounted for a marginal fraction of the total amount of materials, and substantially varied in different modules. The EC was calculated as:

$$\text{EC}_{Si} = \sum Q_{Si,m} \times e_{Si,m} \quad (1)$$

Where Si is the examined life stage i, $Q_{Si,m}$ is the quantity of the material or process m that generates EC in stage i, $e_{Si,m}$ is the corresponding emission factor of the material or process m in life stage i. Ecoinvent database was adopted. The 'IPCC2013 GWP (100 years)' method was chosen as the life cycle inventory analysis (LCIA) method for the EC assessment. This LCIA method quantifies the equivalent CO_2 emissions, which is a standard and widely used metric indicator for evaluating the global warming potential (GWP) of various GHGs [1]. Appropriate database adjustment was made for the consistency of emissions factors with the local context of Hong Kong and the Greater Bay Area (GBA) of China based on the Ecoinvent database. For example, the electricity supply in the GBA and Hong Kong was adjusted according to the power generation sources of the two locations correspondingly, and the emission factor of low-carbon steel products was determined based on the data provided by World Steel Association (WSA). Data gaps were filled using benchmarking records of other similar modular building projects in Hong Kong and published results in the literature [10, 19].

2.2 Cost evaluation method

In terms of the lifecycle cost assessment (LCCA), the same lifecycle stages (i.e. cradle-to-end-of-construction stage) was examined. Different from the EC assessment, cost data was more sensitive under the project contractor's considerations, of which the detailed data of each budget item was difficult to collect. Based on the desk analysis of the documents of a temporary steel modular building project in Hong Kong (the selected case project, which is introduced in Section 2.3), the overall budget was obtained, and the sub-category budget for the superstructure construction of the project was adopted, which covered the direct cost of the material, equipment and labor for module's material and corresponding production, transportation and installation activities, excluding the building services and equipment relevant costs. This sub-category budget was then averaged by the construction floor area (CFA) of the project for the cost variation analysis of the steel module.

Since only low-carbon steel products were examined for the EC reduction and they were provided by the Chinese steel market, the prices of different steel products from the statistic records in China [29] were reviewed considering the selected case project's construction period. In terms of the steel products made by BF-BOF steel, an average price of CNY 6000 was adopted for the baseline scenario. The price for EAF steel products was a bit higher in previous years, reaching CNY 6000~6500/t considering the price variance of recycled steel scraps and the electricity used during the steel production in different time and locations of China. The cost of the other materials and relevant construction activities were assumed unchanged for the cost evaluation.

By exploring the records of Chinese official carbon market [30], the carbon price generally varied between 50 and 105 CNY/tCO_2e since the market opening, with the average being around 60 to 75 CNY/tCO_2e in recent two years. Therefore, a series of varied carbon price was examined to investigate its influence on the cost variation of the module with low-carbon steel adoptions.

As the selected case modular building project was in Hong Kong, the cost evaluation was based on HKD. The currency exchange ratio of HKD to CNY was 0.89.

2.3 Case information and scenarios establishment

A real-life temporary steel modular building project in Hong Kong was selected as the case. The project is one of the emergency facilities in Hong Kong to fight the COVID, which was constructed in only 56 days in 2020. The case project provided 234 modular units, of which each unit was made by a steel module with toilets and necessary sanitary equipment [19]. All modules were designed the same to maximize the productivity for the emergent use. One module was selected for the EC assessment and cost evaluation. Figure 1 shows the layout of the project and a module, and Table 1 summarizes the general information of the module. The cost data in Table 1 referred to the overall budget of the project, and only covered the direct cost of superstructure building construction.

Figure 1 The layout of the project (left) and a module (right)

Table 1. General information of the project and module

Item	Value
Module type	Steel module with steel-concrete bondek floor
Factory location	Zhuhai, China
Site location	Lei Yue Mun, HK China
Project area (CFA)	6030 m^2
Module CFA	18 m^2
Module size	6m x 3m x 3m
Superstructure cost	HKD 21.6 million
Cost per CFA	HKD 3582/m^2

As implicated by previous study of steel modules in Hong Kong [10], structural steel could contribute to a significant percentage of the total EC in a steel module, particularly in the steel components forming the module carcass and the steel envelope. Using low-carbon steel products would be efficient for initial EC reduction of steel modules. Using EAF-steel instead of BF-BOF-made steel has been considered as a common decarbonization strategy in the steel industry worldwide [31]. The steel components of the module were made by BF-BOF process, which has been a dominant method in China for more than 85% market share for many years [32]. Therefore, the EAF-steel was selected to establish the low-carbon scenario to investigate the EC reduction potential of the module. Based on the status of Chinese steel market, the EAF-made steel was assumed to be produced by a mix of 70% scrap and 30% direct reduced iron (DRI). Table 2 summarizes the general information and variable values for the two scenarios (i.e. baseline and low-carbon scenario), e.g. emission factors and market prices for the two different steel products.

Table 2 Scenarios and major variable values

Item	Baseline	Low-carbon scenario
Steel-made method	BF-BOF	EAF (70% scrap +30% DRI)
Emission factor of steel product	2.91 [19]	0.919 [31]
Market price of steel product (HKD/t)	6740	6740~7300
Carbon price (HKD/t)	/	56~118

3 Results and discussions

3.1 EC emissions of the module

The cradle-to-end-of-construction EC of the module was quantified as 18.8 tCO_2e, equivalent to 1042 $kgCO_2e/m^2$. Most of the EC was generated from materialization, accounting for more than 90% of the module's EC emissions. Steel products alone (3446 kg per module, 33.7% of the module's weight) contributed to 53% (557 $kgCO_2e/m^2$) of the module's EC emissions. The other materials, including the concrete for the bondek floor and other architectural materials, generated 41% of the module's EC. The EC from transportation of raw materials to factory and of the module from factory to the site was only 3% of the overall EC of the module, similar with that generated from the module production and construction (i.e. in-situ installation). In general, the quantified EC results conform with previous studies on the carbon assessment of steel modular buildings.

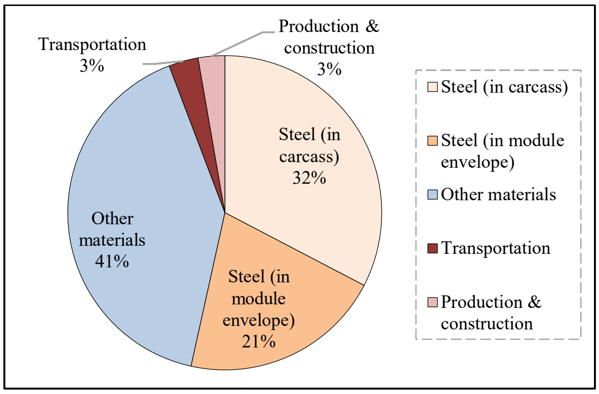

Figure 2 EC percentage of different sources in the module (baseline scenario)

In the low-carbon scenario in which the steel was replaced from BF-BOF process to EAF process, the EC generated from steel material was significantly reduced by 68.4%. Namely, the EC intensity was reduced from 557 $kgCO_2e/m^2$ (baseline) to 176 $kgCO_2e/m^2$ (low-carbon scenario) for the steel. Regarding the overall cradle-to-end-of-construction EC of the module, the EC intensity (1042 $kgCO_2e/m^2$ for the baseline) was reduced by 36.6% (660 $kgCO_2e/m^2$ for the low-carbon scenario). This result indicates that using the EAF-made steel products could lead to 6.86 tCO_2e EC reduction in the module.

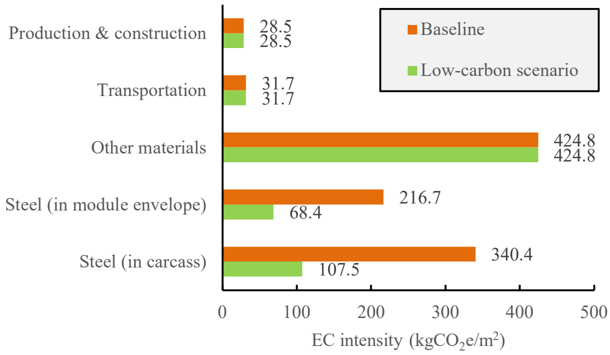

Figure 3 EC intensity of the module of the two scenarios

3.2 Cost variation of the module by using low-carbon steel products

3.2.1 Results without considering carbon price

In the baseline scenario, the cost of steel products alone was quantified as HKD 1291/m^2, accounting for 36% of the project's superstructure cost (HKD 3582/ m^2, as shown in Table 1 and explained in Section 2.2). Considering this percentage, the price variation of the steel products may noticeably influence the cost of the module. In Chinese steel market, the price of steel products made by EAF process is generally higher than those made by BF-BOF process due to the small percentage of the market share. Without considering the influence of carbon market, HKD 200/t price increasement of the low-carbon steel product (i.e. steel price increases by 3.3%) could lead to the cost increasement of the module by HKD 37.6/m2 (1% of the module cost), i.e. HKD 338 increasement per module. Therefore, the adoption of the EAF steel product with highest price (i.e. HKD 7300/t) could increase the module cost by HKD 106/m2 (3% increasement).

It should be noted that during the past several years, particularly considering the outburst and post-COVID stage worldwide, the production costs of steel varied significantly, with the largest price difference reaching 46% for BF-BOF steel and 36% for EAF steel among the major economic bodies [25]. There could be a chance that the price variation of the low-carbon steel products would be more significant in China. Without the increased market share of EAF-steel products to drive down the price or other economic stimulations from non-commercial stakeholders, it can predict that the up-stream steel factories and module factories would probably be reluctant to use these low-carbon steel products due to the marginal or even negative profits.

3.2.2 Results considering carbon price

The carbon markets established worldwide aim to achieve the decarbonization of the industry and society to facilitate the low-carbon and climate-resilient economies development. Considering the influence of carbon market on the transformation from decarbonization to economic profits could be beneficial to the adoption of low-carbon steel products in the steel modular building project delivery. However, since the carbon price, carbon reduction amount by using low-carbon products, and the steel product price are not constant, it will be difficult to provide a one-for-all conclusion for different steel modular building projects.

Since the established low-carbon scenario only focuses on the use of low-carbon steel and the scope is narrowed down to the EC quantification of a module, the cost analysis in this paper can be simplified. The cost variation of the module in the low-carbon scenario (ΔC_{module}) is only caused by the price variance of low-carbon steel products (ΔC_{steel}) and the economic profit by decarbonization (ΔC_{EC}), namely,

$$\Delta C_{module} = \Delta C_{steel} + \Delta C_{EC} \quad (2)$$

$$\Delta C_{EC} = \Delta e_{steel} \times M_{steel} \times C_{carbon} \quad (3)$$

$$\Delta C_{steel} = \Delta C_{steel} \times M_{steel} \quad (4)$$

Therefore, the cost variation of the module by a unit weight of steel product ($\Delta C_{module,unit}$) can be quantified as:

$$\Delta C_{module,unit} = \Delta e_{steel} \times C_{carbon} + \Delta C_{steel} \quad (5)$$

Where Δe_{steel} is the emission factor variation of the steel between baseline and low-carbon scenarios, M_{steel} is the steel amount in the module, and C_{carbon} is the carbon price.

As the four variables in Formula (5) are all in linear relations, the cost variation analysis of the module can be simply conducted using linear programming method.

Figure 4 can be used to examine the relations among these variables. First, the two axes indicate the EC reduction potential and the price variations, respectively. 1) The x-axis indicates the carbon emission factor reduction of the steel product (Δe_{steel}), which means to what extent per unit weight of low-carbon steel can reduce the EC comparing to the baseline scenario during its production stage, for example, EAF (100% DRI)-made steel (Δe_{steel} is about 1.5 tCO_2e/t), the low-carbon steel of the low-carbon scenario (Δe_{steel} is about 2 tCO_2e/t), and the EAF (100% scrap)-made steel (Δe_{steel} is about 2.2 tCO_2e/t). In general, the Δe_{steel} of other types of EAF-made steel products should fall in this range (i.e. $1.5<x<2.2$). Direct reusing steel products (e.g. disassembly and reuse of an existing steel frame component from a module) may have higher Δe_{steel} (shown in the white area of the figure), but this type of low-carbon strategy is beyond this paper's scope. 2) The y-axis indicates the unit price variation of the steel product comparing with that in the baseline scenario. The economic benefits from carbon price ΔC_{EC}, is also shown.

Second, since ΔC_{EC} is linearly changed with Δe_{steel}, these two parameters can be drawn by a line crossing the original point in the diagraph. Considering the highest and lowest carbon price in Chinese carbon market, all potential carbon price change can be confined in Zone B (yellow area) between the two red lines. With a given Δe_{steel} and potential carbon price (e.g., Point E), the economic benefits from the carbon price (ΔC_{EC}) can be obtained.

Third, after establishing the linear relations between Δe_{steel} and ΔC_{EC}, and proposing the different zones, the final price variation of the module by using per unit weight of low-carbon steel product can be simply identified. Taking Point E (blue dot line) as an example, if the potential price variation of the selected low-carbon steel product (i.e. Point G, crossing point of the green dot line and the blue dot line) is higher than Point E, it means the price of the module by using the low-carbon steel product can be more expensive. The price change $\Delta C_{module,unit}$ can be read from the change of these two points on the y-axis. In other words, if the price increasement of the low-carbon steel product can be covered by the benefits from carbon price, i.e. Point G is under Point E, the module can be made with both lower EC emissions and lower price. Considering the variation of previous carbon price, any low-carbon steel with point G falling into Zone C (red area) will increase the module price, and those falling into Zone A (green area) will drive down the price as well as the EC of the module.

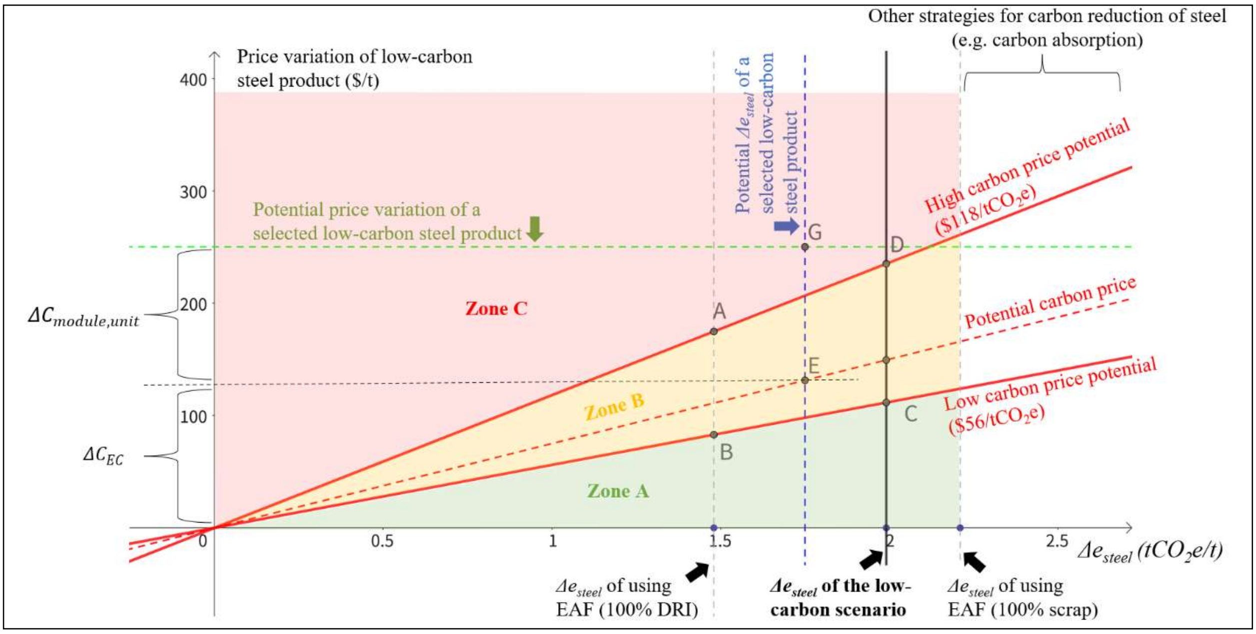

Figure 4 Relationship between the low-carbon steel product selection (i.e. emission factor reduction and price variation) and the carbon price

Fourth, in terms of the low-carbon scenario, considering the current carbon price (HKD84/tCO_2e), the price of the low-carbon steel should be less than HKD 6908/t to keep the cost of the module. Based on these results, the contribution of the economic benefits from carbon market is marginal (only HKD168/tCO_2e, equivalent to HKD64/m^2 and around 2% of the module).

4 Conclusions

This paper has examined the cradle-to-end-of-construction EC of a steel module in a temporary steel modular building project, and investigated the influence of using low-carbon steel product on the EC reduction of the module, as well as the influence on the cost of the module considering the carbon price. Major conclusions of this paper are drawn as follows: 1) the EC of steel production contributed the most to the cradle-to-end-of-construction EC of a steel module, accounting for 53% of the EC in the examined case module. This result complies with previous studies on the EC emissions of steel modular buildings[10,19,21], indicating that the production of steel products is the most significant EC source for this type of building. 2) Adopting low-carbon steel products, e.g. using EAF-made steel to replace BF-BOF-made steel, should significantly contribute to the EC reduction of the module. The EC from steel production can be reduced by nearly 70%, and the initial EC of the module can be reduced by 36% in the examined case. It is anticipated that in other steel modular building projects worldwide, reducing the EC by adopting low-carbon steel products should also perform well in terms of EC reductions, since steel is known as one of the most carbon-intensive building materials. The major difference may be the EC reduction potential results, which will be influenced by the different low-carbon strategies and the EC percentage of the steel products. And 3) the influence of carbon price by only using low-carbon steel is marginal to the cost of the examined module. However, it can still be considered as a bonus to stimulate the use of low-carbon strategies in the building industry. In other building cases worldwide, the EC and cost reduction benefits can be increased if more low-carbon strategies can be adopted, e.g. using other low-carbon materials, and increasing the reusing and recycling rates of existing module components. In the steel markets in other economies that have a cheaper price for EAF-made steel products than BF-BOF ones, or have a higher carbon price, the benefits from carbon market should be taken as a good bonus for the low-carbon building project delivery. The linear programming method used for determining the cost of the module should also perform as a good reference and a basic tool for more complex situations in the EC and cost analysis of other modular buildings.

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