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Balancing economical and environmental trade-off in modular construction yard planning: Models and properties

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ABSTRACT

This study investigates an integrated yard planning and module transportation problem in modular integrated construction (MiC). A Stackelberg game model is proposed to characterize the relations between the government and contractors. The government is the leader and decides the locations and areas of temporary storage yards to facilitate the cost-effective and eco-friendly transportation of MiC modules. The contractors are the followers and decide the transport mode (i.e., road transport or intermodal transport) for modules to minimize their total transportation costs. This study provides an in-depth analysis of model properties to derive a number of useful managerial insights. The economical and environmental trade-offs between costs and emissions are observed. Our study further proves that an optimal solution is likely to simultaneously reduce the overall costs and carbon emissions, in comparison to choosing the location with the largest area to construct a temporary storage yard. These insights offer a comprehensive framework for understanding the interactions between government and contractors. Overall, this paper aims to promote the implementation of MiC by achieving the economical and sustainable transportation of MiC modules.

1. Introduction

Modular integrated construction (MiC) is an innovative, sustainable, and revolutionary technology that represents the highest level of construction industrialization (Construction Industry Council, 2019). Now, a large number of completed and ongoing building projects worldwide are constructed using MiC. In these MiC projects, volumetric modules are finished both externally and internally in factories and then shipped to construction sites for rapid installation. MiC requires minimal on-site construction labor and activities, as the completion rate of MiC modules can be up to 90 % (Yang et al., 2022). Such a high integration offered by MiC brings numerous benefits in terms of time (e.g., rapid construction), cost (e.g., fast investment returns), and quality (e.g., high quality control).

To fully leverage the merits and promote the implementation of MiC, a smooth workflow across module manufacturing, transportation, and installation should be well coordinated, as the earliness and tardiness of module deliveries can result in severe time and cost overruns (Arshad and Zayed, 2022; Yi et al., 2021b, 2023). In real-life scenarios, however, a wide range of risks and uncertainties make it challenging to achieve a streamlined module logistics process. These uncertainties include module cross-border transport time, customs clearance procedures, and on-site assembly deviations (Construction Industry Council, 2020). To alleviate these uncertainties, the implementation of temporary module storage becomes necessary, because it provides a significant buffering effect to MiC supply chain (Wang et al., 2023a). Furthermore, MiC projects in densely populated cities often have site space constraints, resulting in a scarcity of available on-site space for module storage (Yi et al., 2018; Lee and Lee, 2021). Therefore, a more practical and effective solution would be a governmental planning of dedicated modular construction storage yards. The Hong Kong government, for example, plans to spare sufficient land in the Northern Metropolis to establish yards for module fitting-out and temporary storage (Chief Executive, 2022). The planning of temporary storage yards requires an in-depth consideration of various practical factors, such as the locations and areas of candidate yards, construction costs of yards, and transport costs and emissions. These factors are all essential and should be considered in yard planning, and neglecting any of them can cause cost and emission overruns. Additionally, the relationship between government and contractors needs to be carefully examined to ensure the effectiveness of

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governmental planning.

In real-life practices, MiC modules required by contractors are transported using two types of transport modes: road transport and intermodal transport. Road transport provides a flexible door-to-door delivery solution, where modules are transported directly from the manufacturing factory to the construction site by vehicles. However, due to limited vehicle capacity (typically allowing for the transportation of one or two modules per vehicle), road transport is associated with high transportation costs and carbon emissions. Intermodal transport is a combination of water transport and road transport. When intermodal transport is used, modules are transported to a port by vehicles, then shipped to another port by barges, and finally transported to the construction site by vehicles (Yi et al., 2021a). Intermodal transport can accommodate the shipment of 60 modules per barge (Hussein et al., 2023), thereby offering substantial cost savings and reducing carbon emissions, but it is not exempt from drawbacks. In addition to longer transportation time, the handling and lifting operations involved in intermodal transport increase the probability of module defects and damages. As the terminals of seaports usually provide a five-day free storage service for modules transported by barges (Construction Industry Council, 2019), temporary storage yards that are planned to be established should be designed specifically for modules transported by road.

This study is motivated by the challenges in MiC module logistics, the practical necessity for temporary storage yards, and the government's aspiration for yard planning. In this study, we endeavor to advance a wider adoption of MiC by accomplishing the objectives of cost-effective and environmentally sustainable transportation of MiC modules. Mathematical programming methodology is adopted to formulate the interactions between the government and contractors (Zhen et al., 2022; Zhu et al., 2022). Properties of the proposed model are analyzed to provide useful managerial insights.

The remainder of this paper is organized as follows. Section 2 reviews the related works. Section 3 proposes our modeling framework. Section 4 provides an in-depth analysis of properties. Section 5 concludes this study and provides suggestions for follow-up research.

2. Literature review

Extensive efforts have been devoted to the supply chain management of prefabs, leading to the recent publications of many papers on relevant topics, including prefab manufacturing (Chen et al., 2023), temporary storage (Zhang et al., 2020), transportation (Yi et al., 2020; Wang et al., 2023b), and on-site assembly (Yi and Sutrisna, 2021). This section reviews the most relevant studies of two research directions.

The first research stream is related to MiC supply chain management. Hussein and Zayed (2021) presented cross-scenario analyses of essential factors for MiC implementation using a *meta*-analysis approach. Yang et al. (2021) conducted an in-depth analysis of the uncertainties in the manufacturing, storage, and transportation of MiC modules. They collected extensive primary and secondary data and concluded that MiC supply chain is inherently vulnerable to these uncertainties. Arshad and Zayed (2022) highlighted that top-ranked factors dominating the performance of MiC supply chain are mostly associated with module assembly. Pan et al. (2023) performed an empirical study on the motivators and hindrances of the implementation of MiC in high-rise buildings. These studies acknowledged the significance of MiC supply chain and identified several existing challenges, but they did not propose practical strategies or design effective methods for improvement. Lee and Lee (2021) focused on addressing supply chain management challenges from a technical perspective. They developed an integrated framework of digital twin and building information modeling (BIM) to coordinate a smooth workflow in MiC supply chain. Yang et al. (2022) proposed a novel method to facilitate the collaboration between module manufacturers and contractors, but they neglected the role of the government and the interactive relationships between the government and contractors.

The other stream includes studies dedicated to module storage or transportation planning. There are few studies focused on MiC module storage. The scarcity of studies can be attributed to the lack of storage yards in most cities employing MiC. In Hong Kong, Construction Industry Council (2019) evaluated the candidate sites for establishing module storage yards using three criteria, i.e., size, location, and land ownership. Notably, the three proposed criteria have not been validated through real-life cases yet and there still lacks a scientific framework that offers guidance for planning modular storage yards. Additionally, many studies have been directed to the transportation planning of MiC modules. Wang et al. (2023a) proposed an integer programming model with the objective of transporting MiC modules in a cost-effective manner. Valinejadshoubi et al. (2019) introduced a BIM-based data management system that can effectively detect hidden structural defects and damages in module transportation. However, the above studies focus on road transportation only. According to the literature, only Yi et al. (2021a) and Hussein et al. (2023) considered the intermodal transport of MiC modules. Hussein et al. (2023) integrated different simulation methods to derive approximate optimal decisions for all stakeholders in MiC supply chain, aiming to enhance the sustainability of MiC intermodal transport. Yi et al. (2021a) emphasized that contractors prefer the transportation mode with the lowest costs to the one with the fewest carbon emissions. Our study is notably different from the literature, as we incorporate MiC module storage and transportation.

Based on the literature review, we find that the planning of temporary storage yards for MiC modules is still in its infancy. The interactions between the government and contractors, the trade-offs between costs and emissions, and the contractors' decisions on road transport and intermodal transport remain to be fully investigated. To the best of our knowledge, our study represents the first attempt to formulate a Stackelberg game model and analyze the properties to provide recommendations on modular construction yard planning, which not only contributes to an integrated modeling framework but also provides managerial implications for sustainable construction development.

3. Modeling framework

3.1. Problem description

All the notation of the parameters, decision variables, and vectors used in our problem setting is listed in Table 1. Consider a government that plans to establish local yards that are dedicated to the temporary storage of the MiC modules imported from offshore suppliers. There are K candidate locations for establishing temporary storage yards (indexed by k), each with a maximum coverage area of a_k (m^2). The construction cost of a storage yard at location k is p_k (\$/m^2). The government determines the area of the storage yard to be constructed at location k, denoted by α_k. There are J contractors that purchase MiC modules (indexed by j). Each contractor j owns a construction site and requires Q_j tons of MiC modules. The conversion ratio of area (m^2) to weight (ton) of MiC modules required by contractor j is r_j. For example, $r_j = 0.6$ for a realistic MiC project in Hong Kong (Construction Industry Council, 2023), which indicates that 1 ton of modules required by this contractor j occupy an area of 0.6 m^2.

Transportation of MiC modules from suppliers to contractors is composed of two stages: (1) cross-border transport that can be finished by either road transport or intermodal transport (from offshore module factories to cross-border checkpoints) and (2) local transport that can be finished by road transport only (from cross-border checkpoints to local construction sites). Each contractor j decides the transport mode in the first stage, denoted by λ_j, which equals 1 if intermodal transport is selected and 0 otherwise. Assuming that if a contractor chooses road transport (or intermodal transport) as the mode of cross-border transport, then all the required modules will be transported by this mode

Table 1
Notations used in problem setting.

Parameters	
K	the number of potential locations for establishing temporary storage yards
J	the number of contractors that require MiC modules
a_k	the maximum area of location k that can be used to establish a yard (m^2)
p_k	the cost of constructing a temporary storage yard at location k ($/$m^2$)
Q_j	the amount of MiC modules required by contractor j (ton)
r_j	the conversion ratio of area (m^2) to weight (ton) for MiC modules required by contractor j
$c_{j,k}$	the transportation cost from the supplier of contractor j to the temporary storage yard at location k via road transport and then to contractor j via road transport ($/ton)
C_j	the transportation cost from the supplier of contractor j to the terminal at port via intermodal transport and then to contractor j via road transport ($/ton)
$e_{j,k}$	the transport emission from the supplier of contractor j to the temporary storage yard at location k via road transport and then to contractor j via road transport ($kgCO_2$/ton)
E_j	the transport emission from the supplier of contractor j to the terminal at port via intermodal transport and then to contractor j via road transport ($kgCO_2$/ton)
Decision variables	
α_k	the area of the temporary storage yard constructed at location k (determined by government)
λ_j	binary, it equals 1 if contractor j chooses intermodal transport as the mode of cross-border transportation and 0 otherwise (determined by contractors)
$\beta_{j,k}$	the amount of MiC modules that are required by contractor j and stored in temporary storage yard k (ton) (determined by contractors)
Vectors	
$\boldsymbol{\alpha} = (\alpha_1, \alpha_2, \cdots, \alpha_K)$	
$\boldsymbol{\lambda} = (\lambda_1, \lambda_2, \cdots, \lambda_J)$	
$\boldsymbol{\beta} = (\beta_{1,1}, \cdots, \beta_{1,K}, \cdots, \beta_{J,1}, \cdots, \beta_{J,K})$	

during the first stage. If intermodal transport is chosen, all the imported modules are stored in terminals at seaports before being delivered to sites. If road transport is chosen, imported modules are stored in one or more temporary storage yards before being delivered to sites. Contractor j that chooses road transport will further determine the amount of MiC modules stored in temporary storage yard k, denoted by $\beta_{j,k}$. The transportation costs and the transport emissions from the supplier of contractor j to the terminal at port via intermodal transport and then to contractor j via road transport are C_j ($/ton) and E_j ($kgCO_2$/ton), respectively. The transportation costs and the transport emissions from the supplier of contractor j to the temporary storage yard at location k via road transport and then to contractor j via road transport are $c_{j,k}$ ($/ton) and $e_{j,k}$ ($kgCO_2$/ton), respectively. We assume that all contractors cooperate to minimize the transportation cost of all MiC modules. The government aims to minimize the total construction and transportation costs and the total carbon emissions.

3.2. Stackelberg game model

To simplify the notation, we define the following vectors: $\boldsymbol{\alpha} = (\alpha_1, \alpha_2, \cdots, \alpha_K)$, $\boldsymbol{\lambda} = (\lambda_1, \lambda_2, \cdots, \lambda_J)$, and $\boldsymbol{\beta} = (\beta_{1,1}, \cdots, \beta_{1,K}, \cdots, \beta_{J,1}, \cdots, \beta_{J,K})$. The investigated problem can be formulated as a Stackelberg game model, where the government first makes the decision on the construction of temporary storage yards and the contractors then make decisions on the selection of cross-border transport mode and temporary storage yards. Specifically, given government's decision $\boldsymbol{\alpha}$, the optimal values of $\boldsymbol{\lambda}$ and $\boldsymbol{\beta}$ can be calculated, denoted by $\boldsymbol{\lambda}(\boldsymbol{\alpha})$ and $\boldsymbol{\beta}(\boldsymbol{\alpha})$, respectively. Then, the decisions made by the contractors in turn affect the objectives of the government. The total construction and transportation costs and carbon emissions corresponding to yard construction scheme $\boldsymbol{\alpha}$ are denoted by $A(\boldsymbol{\alpha})$ and $B(\boldsymbol{\alpha})$, respectively. The Stackelberg game model of the problem is presented as follows:

$$[\text{G}] \quad \begin{cases} \min A(\boldsymbol{\alpha}) = \underbrace{\sum_{k=1}^{K} p_k \alpha_k}_{\text{construction cost}} + \underbrace{\sum_{j=1}^{J}\sum_{k=1}^{K} c_{j,k}\beta_{j,k}(\boldsymbol{\alpha})}_{\text{road transportation cost}} + \underbrace{\sum_{j=1}^{J} C_j Q_j \lambda_j(\boldsymbol{\alpha})}_{\text{intermodal transportation cost}} \\ \min B(\boldsymbol{\alpha}) = \underbrace{\sum_{j=1}^{J}\sum_{k=1}^{K} e_{j,k}\beta_{j,k}(\boldsymbol{\alpha})}_{\text{carbon emission of road transport}} + \underbrace{\sum_{j=1}^{J} E_j Q_j \lambda_j(\boldsymbol{\alpha})}_{\text{carbon emission of intermodal transport}} \end{cases} \tag{1}$$

$$\text{s.t.} \quad 0 \le \alpha_k \le a_k, \qquad \forall k = 1, \cdots, K, \tag{2}$$

where $\lambda_j(\boldsymbol{\alpha})$ is the element of vector $\boldsymbol{\lambda}(\boldsymbol{\alpha})$ corresponding to contractor j and $\beta_{j,k}(\boldsymbol{\alpha})$ is the element of vector $\boldsymbol{\beta}(\boldsymbol{\alpha})$ corresponding to location k and contractor j, which can be derived by solving the following model [C]:

$$[\text{C}] \qquad \min \sum_{j=1}^{J}\sum_{k=1}^{K} c_{j,k}\beta_{j,k} + \sum_{j=1}^{J} C_j Q_j \lambda_j \tag{3}$$

$$\text{s.t.} \quad \sum_{j=1}^{J} r_j \beta_{j,k} \le \alpha_k, \quad \forall k = 1, \cdots, K \tag{4}$$

$$\sum_{k=1}^{K} \beta_{j,k} = Q_j(1 - \lambda_j), \quad \forall j = 1, \cdots, J \tag{5}$$

$$\lambda_j \in \{0, 1\}, \quad \forall j = 1, \cdots, J \tag{6}$$

$$\beta_{j,k} \ge 0, \quad \forall k = 1, \cdots, K, \ \ j = 1, \cdots, J. \tag{7}$$

Objective function (1) indicates the two objectives considered by the government. Constraints (2) require that the constructed area of each temporary storage yard cannot exceed the maximum area of each potential location. Objective function (3) indicates that the contractors aim to minimize the transportation cost for MiC modules. Constraints (4) mandate that the total area occupied by all MiC modules stored in the established temporary storage yard at location k cannot exceed its constructed area. Constraints (5) link variable λ_j and $\beta_{j,k}$. Specifically, if road transport is chosen as the mode of cross-border transport by contractor j (i.e., $\lambda_j = 0$), the MiC modules required by the contractor will be stored in one of the K temporary storage yards; otherwise (i.e., $\lambda_j = 1$), no MiC module required by the contractor will be stored in any temporary storage yard. Constraints (6) and (7) define the domains of decision variables.

4. Property analysis

The proposed model has several appealing properties. This section provides a comprehensive analysis of these properties. Propositions 1–3 are derived from the contractors' perspective and Propositions 4–8 are derived from the government's perspective. For simplicity, we assume that $a_k \ne a_{k'}$ for any two locations $k, k' = 1, \cdots, K, k \ne k'$ and $c_{j,k} \ne c_{j,k'} \ne C_j$ for any contractor $j = 1, \cdots, J$.

Proposition 1. *If α is sufficiently large, for example, if $\alpha_k \ge \sum_{j=1}^{J} Q_j$ for all potential locations $k = 1, \cdots, K$, the optimal solution to [C] satisfies that, for any contractor $j = 1, \cdots, J$: (i) If there exists a $k_1 = 1, \cdots, K$ such that $c_{j,k_1} < c_{j,k'}$ for all $k' = 1, \cdots, K$, $k' \ne k_1$ and $c_{j,k_1} < C_j$, then $\lambda_j(\boldsymbol{\alpha}) = 0$, $\beta_{j,k_1}(\boldsymbol{\alpha}) = Q_j$, and $\beta_{j,k'}(\boldsymbol{\alpha}) = 0$. (ii) Otherwise $C_j < c_{j,k'}$ for all $k' = 1, \cdots, K$, then $\lambda_j(\boldsymbol{\alpha}) = 1$ and $\beta_{j,k'}(\boldsymbol{\alpha}) = 0$ for all $k' = 1, \cdots, K$.*

Proof: In the first case, if there exists a $k' = 1, \cdots, K, k' \ne k_1$ satisfying that $\beta_{j,k'}(\boldsymbol{\alpha}) > 0$, we define $\varepsilon = \beta_{j,k'}(\boldsymbol{\alpha})$. A new solution can be designed to [C] by setting $\beta_{j,k_1}(\boldsymbol{\alpha}) \leftarrow \beta_{j,k_1}(\boldsymbol{\alpha}) + \varepsilon$ and $\beta_{j,k'}(\boldsymbol{\alpha}) \leftarrow \beta_{j,k'}(\boldsymbol{\alpha}) - \varepsilon$. The value of the objective will decrease, and this contradicts the optimality of solution $\boldsymbol{\beta}(\boldsymbol{\alpha})$. If $\lambda_j(\boldsymbol{\alpha}) = 1$, a new solution can be designed to [C] by setting $\lambda_j(\boldsymbol{\alpha}) \leftarrow 0$ and $\beta_{j,k_1}(\boldsymbol{\alpha}) \leftarrow Q_j$. The value of the objective will decrease, and this contradicts the optimality of solution $\boldsymbol{\beta}(\boldsymbol{\alpha})$.

In the second case, if there exists a $k' = 1, \cdots, K$ satisfying that $\beta_{j,k'}(\boldsymbol{\alpha}) > 0$, we define $\varepsilon = \beta_{j,k'}(\boldsymbol{\alpha})$. A new solution can be designed to [C] by setting $\lambda_j(\boldsymbol{\alpha})\leftarrow 1$ and $\beta_{j,k'}(\boldsymbol{\alpha})\leftarrow\beta_{j,k'}(\boldsymbol{\alpha})-\varepsilon$. The value of the objective will decrease, and this contradicts the optimality of solution $\boldsymbol{\beta}(\boldsymbol{\alpha})$. If $\lambda_j(\boldsymbol{\alpha})=0$, a new solution can be designed to [C] by setting $\lambda_j(\boldsymbol{\alpha})\leftarrow 1$ and $\beta_{j,k'}(\boldsymbol{\alpha})\leftarrow 0$. The value of the objective will decrease, and this contradicts the optimality of solution $\boldsymbol{\beta}(\boldsymbol{\alpha})$. ■

Proposition 1 implies that if each yard at the potential locations is capable of storing all required MiC modules, then all contractors can store the imported modules in the yard with the lowest transportation cost (when road transport is more economical than intermodal transport). In real-life scenarios, however, α_k may not be sufficiently large, indicating that some of the contractors may not store the required modules in the yard with the lowest transportation cost.

Proposition 2. *For any contractor $j=1,\cdots,J$, if there exists a location $k=1,\cdots,K$ satisfying that $C_j<c_{j,k}$, then $\beta_{j,k}(\boldsymbol{\alpha})=0$.*

Proof: Suppose that $\beta_{j,k}(\boldsymbol{\alpha})>0$. We have $\sum_{k'=1}^{K}\beta_{j,k'}(\boldsymbol{\alpha})=Q_j$ according to Constraints (5). A new solution to [C] can be designed by setting $\beta_{j,k'}(\boldsymbol{\alpha})=0$ for any location $k'=1,\cdots,K$ and $\lambda_j=1$. The value of the objective will decrease, and this contradicts the optimality of solution $\boldsymbol{\beta}(\boldsymbol{\alpha})$. ■

Proposition 2 implies that for any contractor, if the cost of intermodal transport is lower than that of road transport and storage in the yard at location k, then the yard at location k is redundant for the contractor. That is, due to high transportation cost, the contractor will not store any module in the yard, even if it is constructed. The proposition highlights the importance of considering the transportation costs for contractors beyond the construction cost when the government plans yard selection, as a yard may appear to have minimal investment but requires high transportation costs for contractors using this yard. As a result, the yard would be redundant, rendering the government's scheme ineffective.

Proposition 3. *If there exist a location $k_1=1,\cdots,K$ satisfying that $\sum_{j=1}^{J}r_j\beta_{j,k_1}(\boldsymbol{\alpha})<\alpha_{k_1}$ and a contractor $j_1=1,\cdots,J$ satisfying that $0<\beta_{j_1,k_1}(\boldsymbol{\alpha})<Q_{j_1}$, then (1) $\lambda_{j_1}=0$ and (2) there exists a $k_2=1,\cdots,K$ satisfying that $c_{j_1,k_2}<c_{j_1,k_1}$, $c_{j_1,k_2}<C_{j_1}$, and $\sum_{j=1}^{J}r_j\beta_{j,k_2}(\boldsymbol{\alpha})=\alpha_{k_2}$.*

Proof: As $\beta_{j_1,k_1}(\boldsymbol{\alpha})>0$, we have $\lambda_{j_1}=0$ according to Constraints (5).

Suppose that there exists a $k_2=1,\cdots,K$ satisfying that $c_{j_1,k_2}<c_{j_1,k_1}$ and $c_{j_1,k_2}<C_{j_1}$, but $\sum_{j=1}^{J}r_j\beta_{j,k_2}(\boldsymbol{\alpha})\neq\alpha_{k_2}$. Define $\varepsilon=\min\left\{\beta_{j_1,k_1}(\boldsymbol{\alpha}),\alpha_{k_2}-\sum_{j=1}^{J}r_j\beta_{j,k_2}(\boldsymbol{\alpha})\right\}$. As $c_{j_1,k_2}<c_{j_1,k_1}$, a new solution can be designed by setting $\beta_{j_1,k_1}(\boldsymbol{\alpha})\leftarrow\beta_{j_1,k_1}(\boldsymbol{\alpha})-\varepsilon$ and $\beta_{j_1,k_2}(\boldsymbol{\alpha})\leftarrow\beta_{j_1,k_2}(\boldsymbol{\alpha})+\varepsilon$. The objective value will decrease, and this contradicts the optimality of solution $\boldsymbol{\beta}(\boldsymbol{\alpha})$.

Suppose that there does not exist a $k_2=1,\cdots,K$ satisfying that $c_{j_1,k_2}<c_{j_1,k_1}$. As $\beta_{j_1,k_1}(\boldsymbol{\alpha})<Q_{j_1}$, there must be a $k=1,\cdots,K,k\neq k_1$ satisfying that $\beta_{j_1,k}(\boldsymbol{\alpha})>0$. Define $\varepsilon=\min\left\{\alpha_{k_1}-\sum_{j=1}^{J}\beta_{j,k_1}(\boldsymbol{\alpha}),\beta_{j_1,k}(\boldsymbol{\alpha})\right\}$. As $c_{j_1,k}>c_{j_1,k_1}$, a new solution can be designed by setting $\beta_{j_1,k_1}(\boldsymbol{\alpha})\leftarrow\beta_{j_1,k_1}(\boldsymbol{\alpha})+\varepsilon$ and $\beta_{j_1,k}(\boldsymbol{\alpha})\leftarrow\beta_{j_1,k}(\boldsymbol{\alpha})-\varepsilon$. The objective value will decrease, and this contradicts the optimality of solution $\boldsymbol{\beta}(\boldsymbol{\alpha})$.

Suppose that all $k_2=1,\cdots,K$ satisfying that $c_{j_1,k_2}<c_{j_1,k_1}$ do not satisfy that $c_{j_1,k_2}<C_{j_1}$, i.e., $c_{j_1,k_2}\geq C_{j_1}$. Then, $C_{j_1}\leq c_{j_1,k_2}<c_{j_1,k_1}$. As $C_{j_1}<c_{j_1,k_1}$, we have $\beta_{j_1,k_1}(\boldsymbol{\alpha})=0$ according to Proposition 2, contradicting that $0<\beta_{j_1,k_1}(\boldsymbol{\alpha})<Q_{j_1}$. ■

Proposition 4. *In comparison to selecting the location with the maximum area, the optimal solution to the Stackelberg game model can reduce the total construction and transportation costs. That is, there may be a solution $\boldsymbol{\alpha}^*$ such that $A(\boldsymbol{\alpha}^*)<A(\boldsymbol{\alpha})$, where $\boldsymbol{\alpha}$ is composed of elements satisfying that $\alpha_{k'}>0$ and $\alpha_{k''}=0$ and $a_{k'}>a_{k''}$ for all $k',k''=1,\cdots,K,k'\neq k''$.*

Proof: We construct the following case. There are three candidate locations (location 1, location 2, and location 3) of temporary storage yards and one contractor (contractor 1). Let $a_1=3$, $a_2=a_3=2$, $p_1=p_2=p_3=1$, $c_{11}=10$, $c_{12}=5$, $c_{13}=1$, $C_1=8$, $r_1=1$, and $Q_1=3$.

Consider a solution $\boldsymbol{\alpha}$, where the government only selects location 1 to establish a temporary storage yard (because it has the maximum area). That is, $\alpha_1>0$ and $\alpha_2=\alpha_3=0$. As intermodal transport is more economical than road transport and storage of modules in the yard at location 1 ($C_1<c_{11}$), the contractor will not store any module in location 1 (according to Proposition 2). Also, as yards at locations 2 and 3 are not constructed ($\alpha_2=\alpha_3=0$), no modules can be stored in these two locations. Thus, we have $\beta_{11}=\beta_{12}=\beta_{13}=0$ and $\lambda_1=1$. The total costs $A(\boldsymbol{\alpha})$ can be calculated as $p_1\alpha_1+0+Q_1\times C_1=\alpha_1+24$. Thus, as long as the government constructs a yard at location 1 (i.e., $\alpha_1>0$), $A(\boldsymbol{\alpha})>24$. Further, if the government decides to construct the yard to its maximum area (i.e., $\alpha_1=a_1=3$), then $A(\boldsymbol{\alpha})=27$.

Consider a solution $\boldsymbol{\alpha}^*$, where $\alpha_1^*=0$, $\alpha_2^*=1$, and $\alpha_3^*=2$. Thus, $\beta_{11}^*=0$, $\beta_{12}^*=1$, $\beta_{13}^*=2$, and $\lambda_1^*=0$. The total costs $A(\boldsymbol{\alpha}^*)$ can be calculated as $(p_2\alpha_2^*+p_3\alpha_3^*)+(c_{12}\beta_{12}^*+c_{13}\beta_{13}^*)=(1\times 1+1\times 2)+(5\times 1+1\times 2)$. $A(\boldsymbol{\alpha}^*)=10$.

The above example shows that it is possible that $A(\boldsymbol{\alpha}^*)<A(\boldsymbol{\alpha})$. ■

Proposition 5. *In comparison to selecting the location with the maximum area, the optimal solution to the Stackelberg game model can reduce carbon emissions. That is, there may be a solution $\boldsymbol{\alpha}^*$ such that $B(\boldsymbol{\alpha}^*)<B(\boldsymbol{\alpha})$, where $\boldsymbol{\alpha}$ is composed of elements satisfying that $\alpha_{k'}>0$ and $\alpha_{k''}=0$ and $a_{k'}>a_{k''}$ for all $k',k''=1,\cdots,K,k'\neq k''$.*

Proof: Continue with the example in the proof of Proposition 4. Let $e_{11}=10$, $e_{12}=5$, $e_{13}=1$, and $E_1=8$. To solution $\boldsymbol{\alpha}$, the total amount of carbon emissions $B(\boldsymbol{\alpha})$ can be calculated as $Q_1\times E_1$. $B(\boldsymbol{\alpha})=24$. To solution $\boldsymbol{\alpha}^*$, the total amount of carbon emissions $B(\boldsymbol{\alpha}^*)$ can be calculated as $e_{12}\beta_{12}^*+e_{13}\beta_{13}^*$. $B(\boldsymbol{\alpha}^*)=7$.

The above example shows that it is possible that $B(\boldsymbol{\alpha}^*)<B(\boldsymbol{\alpha})$. ■

Proposition 6. *In comparison to selecting the location with the maximum area, the optimal solution to the Stackelberg game model can not only reduce the total construction and transportation costs but also reduce the carbon emissions. That is, there may be a solution $\boldsymbol{\alpha}^*$ such that $A(\boldsymbol{\alpha}^*)<A(\boldsymbol{\alpha})$ and $B(\boldsymbol{\alpha}^*)<B(\boldsymbol{\alpha})$, where $\boldsymbol{\alpha}$ is composed of elements satisfying that $\alpha_{k'}>0$ and $\alpha_{k''}=0$ and $a_{k'}>a_{k''}$ for all $k',k''=1,\cdots,K,k'\neq k''$.*

Proof: This proposition can be proved by combining the cases in the proofs of Proposition 4 and Proposition 5. ■

Propositions 4–6 imply the importance of scientific decision-making on yard selection and construction: an optimal solution has a significantly positive impact on reducing overall costs and controlling carbon emissions. Therefore, the government must make scientifically-driven decisions, rather than simply choosing a location with the largest available area.

Proposition 7. *The objectives of minimizing the total construction and transportation costs and minimizing the carbon emissions are not always consistent. That is, there may be two solutions $\boldsymbol{\alpha}'$ and $\boldsymbol{\alpha}''$ such that (i) $A(\boldsymbol{\alpha}')\leq A(\boldsymbol{\alpha})$, $B(\boldsymbol{\alpha}'')\leq B(\boldsymbol{\alpha})$ for all $\boldsymbol{\alpha}$ that satisfy Constraints (2), (ii) $A(\boldsymbol{\alpha}')\leq A(\boldsymbol{\alpha}'')$, (iii) $B(\boldsymbol{\alpha}'')\leq B(\boldsymbol{\alpha}')$.*

Proof: We construct the following case. There are two candidate locations (location 1 and location 2) of temporary storage yards and one contractor (contractor 1). Let $a_1=a_2=1$, $p_1=1$, $p_2=10$, $c_{11}=10$, $c_{12}=1$, $e_{11}=10$, $e_{12}=1$, $C_1=5$, $r_1=1$, and $Q_1=1$.

If the government minimizes the total construction and transportation cost, the scheme of constructing the temporary storage yards, denoted by $\boldsymbol{\alpha}'$, should be $\alpha_1'=\alpha_2'=0$. Thus, $A(\boldsymbol{\alpha}')=5$ and $B(\boldsymbol{\alpha}')=5$.

If the government minimizes the total carbon emissions, the scheme of constructing the temporary storage yards, denoted by $\boldsymbol{\alpha}''$, should be $\alpha_1''=0$ and $\alpha_2''=1$. Thus, $A(\boldsymbol{\alpha}'')=11$ and $B(\boldsymbol{\alpha}'')=1$.

The above example proves the proposition. ■

Proposition 7 implies that if the government is concerned about both costs and carbon emissions, then the investigated problem cannot be treated as a single-objective optimization problem. The government should consider all Pareto optimal solutions. To be more straightforward, we assume there are such five Pareto optimal solutions, denoted by $\boldsymbol{\alpha}^1$, $\boldsymbol{\alpha}^2$, $\boldsymbol{\alpha}^3$, $\boldsymbol{\alpha}^4$, and $\boldsymbol{\alpha}^5$. Solution $\boldsymbol{\alpha}^1$: $A(\boldsymbol{\alpha}^1) = 20.5$ million EUR and $B(\boldsymbol{\alpha}^1) = 800$ ton CO_2; solution $\boldsymbol{\alpha}^2$: $A(\boldsymbol{\alpha}^2) = 20.35$ million EUR and $B(\boldsymbol{\alpha}^2) = 1000$ ton CO_2; solution $\boldsymbol{\alpha}^3$: $A(\boldsymbol{\alpha}^3) = 20.2$ million EUR and $B(\boldsymbol{\alpha}^3) = 1400$ ton CO_2; solution $\boldsymbol{\alpha}^4$: $A(\boldsymbol{\alpha}^4) = 20.15$ million EUR and $B(\boldsymbol{\alpha}^4) = 1700$ ton CO_2; solution $\boldsymbol{\alpha}^5$: $A(\boldsymbol{\alpha}^5) = 20.1$ million EUR and $B(\boldsymbol{\alpha}^5) = 2400$ ton CO_2. Fig. 1 presents a method for the government to determine the most satisfactory solution among the five Pareto-optimal alternatives. First, the government can exclude several impractical solutions based on cost limitations and carbon emission targets. For example, if the threshold for the total construction and transportation costs is set to 20.4 million EUR and the carbon emissions need to be controlled below 2,000 ton, then solutions $\boldsymbol{\alpha}^1$ and $\boldsymbol{\alpha}^5$ (in the grey region of Fig. 1) are eliminated. Second, the government can integrate the two objectives by calculating the environmental cost using the "price of carbon" in the region, denoted by π. Then, the bi-objective model [G] can be transformed into a single-objective problem. Define $Z(\boldsymbol{\alpha})$ as the weighted objective value. $Z(\boldsymbol{\alpha}) = A(\boldsymbol{\alpha}) + \pi B(\boldsymbol{\alpha})$. For example, when $\pi = 98$ (European Commission, 2022), $Z(\boldsymbol{\alpha}^2) = 20.448$ million, $Z(\boldsymbol{\alpha}^3) = 20.3372$ million, and $Z(\boldsymbol{\alpha}^4) = 20.3166$ million. Therefore, $\boldsymbol{\alpha}^4$ is the optimal solution.

Proposition 8. *The Pareto optimal solution* $\boldsymbol{\alpha}$ *satisfies that* $\sum_{j=1}^{J} r_j \beta_{j,k}(\boldsymbol{\alpha}) = \alpha_k$ *for all* $k = 1, \cdots, K$.

Proof: Suppose that there exists a $k' = 1, \cdots, K$ such that $\sum_{j=1}^{J} r_j \beta_{j,k'}(\boldsymbol{\alpha}) > \alpha_{k'}$. It does not satisfy Constraints (4) and thereby contradicts the feasibility of solution $\boldsymbol{\alpha}$. Suppose that there exists a $k' = 1, \cdots, K$ such that $\sum_{j=1}^{J} r_j \beta_{j,k'}(\boldsymbol{\alpha}) < \alpha_{k'}$. Define $\varepsilon = \alpha_{k'} - \sum_{j=1}^{J} r_j \beta_{j,k'}(\boldsymbol{\alpha})$. A new solution to [G] can be designed by setting $\alpha_{k'} \leftarrow \alpha_{k'} - \varepsilon$. The value of the first objective will decrease and the value of the second objective remains unchanged, which contradicts the Pareto optimality of solution $\boldsymbol{\alpha}$. ■

Proposition 8 implies that the constructed temporary storage yard should refrain from having surplus areas beyond that occupied by the stored modules for economic considerations. This proposition further suggests that the government should not construct large yards all at once, but can instead periodically (e.g., annually) evaluate the need for expansion based on the yard utilization by the contractors.

5. Conclusions and future research directions

This paper formulates a Stackelberg game model for the government to carry out modular construction yard planning and for the contractors to design the transportation plans for MiC modules. From the perspective of the government, decisions on the locations and areas of the yards to be constructed are made to balance the economical and environmental trade-offs. From the perspective of the contractors, cost minimization is the primary objective. The contractors choose the cross-border transport mode and further determine the amount of modules stored in each constructed yard. In the current practice, industry experts prefer selecting the location with the maximum area to establish yards for module storage purposes (Construction Industry Council, 2019). A comprehensive analysis of model properties, however, proves that an optimal solution is likely to simultaneously reduce costs and carbon emissions than simply constructing a largest storage yard. It is imperative for the government to acknowledge the importance of informed and scientific decision-making in modular construction yard planning. Furthermore, there exists a trade-off between cost reduction and emission control goals, which is a typical characteristic inherent in many real-life problems. In addition, our analysis confirms the necessity for the government to consider the costs incurred by the contractors during modular construction yard planning, which is essential to ensure the effectiveness of the government's scheme. For follow-up research, there are three promising research directions. The first is to incorporate more

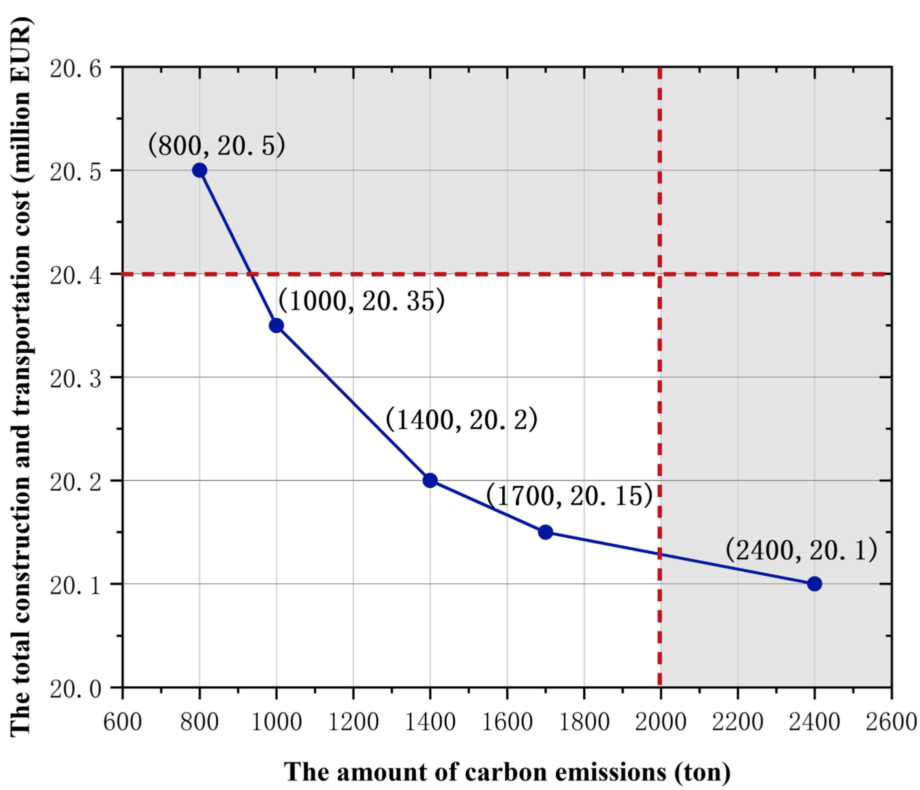

Fig. 1. An illustrative example of Pareto optimal solutions.

practical factors in the module transportation planning for contractors, e.g., various types of vehicles in road transport and ships in intermodal transport (Tan et al., 2021; Guillot et al., 2022; Ji et al., 2022). Another potential extension is to explore the impact of various uncertainties (e.g., the uncertain demand and transportation time for MiC modules) on the optimal solutions for both government and contractors (Nie et al., 2021). Third, more efforts could be dedicated to developing exact or heuristic algorithms to derive solutions to the investigated problem of practical scales (Yao et al., 2022).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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