Cleaner Logistics and Supply Chain 1 (2021) 100005

Contents lists available at ScienceDirect

Cleaner Logistics and Supply Chain

journal homepage: www.elsevier.com/locate/clscn

Bi-level programming subsidy design for promoting sustainable prefabricated product logistics

Wen Yi [a], Shining Wu [b], Lu Zhen [c,*], Gregory Chawynski [a]

[a] School of Built Environment, College of Sciences, Massey University, 0632 Auckland, New Zealand
[b] Department of Logistics and Maritime Studies, The Hong Kong Polytechnic University, Hong Kong Special Administrative Region
[c] School of Management, Shanghai University, Shang Da Road 99, Shanghai 200444, China

ARTICLE INFO

Keywords:
Bi-level programming
Subsidy model
Sustainable construction logistics,
prefabricated products

ABSTRACT

This paper considers the transportation of prefabricated products in the construction industry. Prefabricated products can be transported by road transport or intermodal transport, the latter of which incurs lower carbon emissions. A construction contractor always selects the transport mode with a lower cost rather than one with a lower carbon emission. A bi-level programming model was formulated to decide the optimal subsidy for intermodal transport to achieve the lowest carbon emissions while accounting for the cost minimization decisions faced by construction contractors who use prefabricated products. A numerical example was conducted to demonstrate the effectiveness of the proposed model. This research is important with regard understanding carbon emissions and how they relate to transportation options for industry.

1. Introduction

Prefabrication construction means manufacturing (prefabricating) sub-structures of buildings in a factory, transporting the prefabricated (prefab) products to a construction site, and then assembling the prefab products at the site. Prefabrication applies the modular production and mass customization concepts in the manufacturing industry to the construction industry (Lee and Hyun, 2019). Compared with traditional in-situ construction practices, prefabrication has several advantages. Since the sub-structures are manufactured in a factory instead of in the open air, the production schedule is not subject to adverse weather conditions and the workers enjoy a safer and healthier working environment. The prefab products are often standardized to be of a few variants, and as a result, the production cost can be reduced, the quality can be improved, and the carbon emissions can be decreased. For instance, Pervez et al. (2021) estimated that over 40% of carbon emissions can be reduced using prefabrication. Finally, prefabrication construction involves much fewer items than traditional in-situ construction methods (Bengtsson, 2019), and this significantly increases the productivity on site. It is not uncommon to build one floor in three days using prefabricated products.

Prefab products are transported by road transport or intermodal transport. Road transport means the prefab products are transported by truck from the manufacturing factory directly to the construction site. Prefab products are usually large and heavy weight (Liu, 2016; Niu et al., 2019). Some prefab products are even transported by vehicles that require escort services such as a pilot vehicle (Liu, 2016). For example, in Hong Kong, vehicles planning to carry a load wider than 2.5 m must be escorted by two vehicles and must obtain a permit from the government. This can be a challenge as many prefab products are wider than 3 m (Construction Industry Council of Hong Kong, 2020). The heavy-duty trucks transporting prefab products generate a considerable amount of carbon emissions (Zhu et al., 2021). Intermodal transport means the prefab products are first transported by truck from the manufacturing factory to a port, then transported by ship to another port, and finally transported by truck to the construction site. For instance, some prefab products assembled at sites in Singapore and Canada are manufactured in China (Liu, 2016; Yang et al., 2021), and some prefab products assembled at sites in Hong Kong are manufactured in Guangdong Province of China and delivered to Hong Kong using intermodal transport.

Road transport and intermodal transport have significantly different amounts of carbon emissions (Kholod et al., 2016). Ship transport by water is much cleaner than truck transport by road in terms of carbon emissions. For example, a heavy-duty truck carrying 40 tons of cargo can consume 50L of fuel per 100 km, while a ship carrying 100,000 tons of cargo can consume 100 tons of fuel per 800 km. Assuming the density of truck fuel is 0.85 ton/m^3, a truck consumes

* Corresponding author.
E-mail addresses: yiwen96@163.com (W. Yi), sn.wu@polyu.edu.hk (S. Wu), lzhen@shu.edu.cn (L. Zhen), g.chawynski@massey.ac.nz (G. Chawynski).

https://doi.org/10.1016/j.clscn.2021.100005
Received 22 July 2021; Revised 4 September 2021; Accepted 4 September 2021

0.01 kg/(ton·km) of fuel, whereas a ship consumes 0.000001 kg/(ton·km) of fuel. As a result, intermodal transport is a potential option to reduce the carbon emissions of prefab products. This logistics fact must be further brought to the attention to government agencies around the world.

This study aims to examine the optimal subsidy design to enable the government to promote intermodal transport of prefab products, which is interdisciplinary in nature (Qu and Wang, 2021). For each unit of prefab products delivered by intermodal transport mode, the government could provide a subsidy to the site building contractor. As a result, more prefab products could be delivered using an intermodal transport mode. The purpose of this research is to assist the government in understanding the importance (with regard to mathematically estimated figures) of how to achieve maximum carbon emission reductions by using a limited subsidy budget. This is a new problem that has not yet been addressed in the literature.

The remainder of this paper is organized as follows. Section 2 summarizes the related literature. Section 3 describes the problem. A bi-level programming model is presented in Section 4. Section 5 presents an illustrative example to demonstrate the effectiveness of the proposed model. Section 6 concludes this study.

2. Literature review

The literature on logistics management of prefab products is scarce. Li et al. (2017) have developed a radio frequency identification device (RFID)-enabled that has assisted in building information modeling (BIM) platforms that can share information among stakeholders involved in prefabrication construction; in particular, drivers of prefab product transportation vehicles can check via a mobile phone App the transportation tasks and update their status (e.g., arrival at pickup location, arrival at construction site, task completed).

Hsu et al. (2018) presented a two-stage stochastic optimization model that considers three tiers of prefabrication construction, namely, manufacturing, storage, and assembly, and uncertain demand for prefab products on sites. Hsu et al. (2019) addressed a similar problem using robust optimization approaches. The work of Hsu et al. (2018) is extended in Hsu et al. (2020) who examined a multi-period setting using multi-stage optimization techniques.

Fang and Ng (2019) optimized the logistics of prefabricated products for a construction company using genetic algorithm and activity-based costing approach. The goal is to assist construction managers and manufacturers to determine an informed delivery schedule of prefab products.

Lee and Hyun (2019) have presented an optimization model for scheduling the production and delivery of multi-type prefab products. They examined a setting in which the prefab products are manufactured on a production line and the switching between two types of prefab products takes significant time. A genetic algorithm was proposed to solve the model, based on a South Korean case study project.

Niu et al. (2019) modeled the transportation of prefab products as a vehicle routing problem and solved the problem using an artificial bee colony algorithm. Yi et al. (2020) examined the grouping of prefab products onto trucks and the schedule of the trucks in a way that minimizes the number of trucks used and the inventory holding cost of the prefab products.

Xu et al. (2019) developed a transportation management service sharing platform that allows multiple transport service providers to share their vehicle fleet information and multiple construction sites to share their demand for transporting prefab products. This platform was validated using a public housing project in Hong Kong that used prefab products.

Based on the above literature review, it can be seen that, to date, there has not yet any study that examines effectively using a government subsidy to promote the use of intermodal transport for prefab products. Methodologically, the existing studies focus on one stakeholder, i.e., the contractor (if there is a manufacturer of prefab product, the manufacturer is controlled by the contractor). In contrast, our study has two types of stakeholders—government and contractors—and different stakeholders have different objectives—the government aims to minimize the carbon emissions while a contractor aims to minimize her cost. As a result, the model in our paper is a bi-level programming one, instead of a single-level optimization model as identified in the literature.

3. Problem statement

We consider a total of V contractors, indexed by v, who will purchase prefab products from a total of U manufacturers, indexed by u. Each contractor has one construction site that uses prefab construction methods. A single type of prefab products is considered. The quantity of prefab products required by contractor $v = 1, \cdots, V$ is q_v. The selling price at manufacturer $u = 1, \cdots, U$ is p_u. Each contractor needs to choose a manufacturer to purchase prefab products and then transports them to her construction site. There are two transport modes from a manufacturer u to the construction site of contractor v: road transport and intermodal transport. The costs per unit prefab product of road transport and intermodal transport from manufacturer u to contractor v are C_{uv} and c_{uv}, respectively, and the carbon emission of road transport and intermodal transport are E_{uv} and e_{uv}, respectively. Since contractor v has to pay the purchase price and the transport cost, she will choose a manufacturer, denoted by $u_v^*(0)$ (note that the number 0 in the parentheses means there is no subsidy from government), that has the lowest total cost per unit prefab product, denoted by $\Pi_v^*(0)$:

$$u_v^*(0) \in \operatorname{argmin}_{u=1,\cdots,U}(p_u + \min\{C_{uv}, c_{uv}\}) \tag{1}$$

$$\Pi_v^*(0) = \min_{u=1,\cdots,U}(p_u + \min\{C_{uv}, c_{uv}\}) \tag{2}$$

It is possible that there is more than one manufacturer and/or transport mode with the lowest total cost. In this case, we assume that the contractor will choose the combination of manufacturer and transport mode among those with the lowest total cost that has the lowest carbon emissions. As a result, the amount of carbon emissions per unit prefab product from contractor v, denoted by $\Theta_v^*(0)$, can be calculated as shown below:

$$\Theta_v^*(0) = \min\{\Theta_v^{*r}(0), \Theta_v^{*i}(0)\} \tag{3}$$

where $\Theta_v^{*r}(0)$ is carbon emissions of using road transport mode if road transport mode has the lowest total cost and $\Theta_v^{*i}(0)$ is carbon emissions of using intermodal transport mode if intermodal transport mode has the lowest total cost; $\Theta_v^{*r}(0)$ and $\Theta_v^{*i}(0)$ can be calculated as shown below:

$$\Theta_v^{*r}(0) = \min\left\{+\infty, \min_{u' \in \{u=1,\cdots,U | p_u + C_{uv} \le \Pi_v^*(0)\}} E_{u'v}\right\} \tag{4}$$

$$\Theta_v^{*i}(0) = \min\left\{+\infty, \min_{u' \in \{u=1,\cdots,U | p_u + c_{uv} \le \Pi_v^*(0)\}} e_{u'v}\right\} \tag{5}$$

where $+\infty$ in Eq. (4) defines $\Theta_v^{*r}(0)$ to be infinity if no road transport mode has the lowest total cost and $+\infty$ in Eq. (5) defines $\Theta_v^{*i}(0)$ to be infinity if no intermodal transport mode has the lowest total cost.

The total amount of carbon emissions from all the contractors, denoted by $\Xi(0)$, can be calculated as:

$$\Xi(0) = \sum_{v=1}^{V} q_v \Theta_v^*(0) \quad (6)$$

The government aims to promote cleaner intermodal transport modes by providing a subsidy of x to contractor for each unit of prefab product that is transported by intermodal mode. This means, the cost c_{uv} of intermodal transport mode from manufacturer u to contractor v essentially decreases to $c_{uv} - x$ for the contractor. The government's total budget is B and the subsidy x is a decision variable for the government. The subsidy x has a lower bound a (e.g., 0) and an upper bound b (e.g., making sure the intermodal transport cost after subsidization is nonnegative).

With subsidy x, contractor v will choose a manufacturer, denoted by $u_v^*(x)$, that has the lowest total cost per unit prefab product, denoted by $\Pi_v^*(x)$:

$$u_v^*(x) \in \text{argmin}_{u=1,\cdots,U}(p_u + \min\{C_{uv}, c_{uv} - x\}) \quad (7)$$

$$\Pi_v^*(x) = \min_{u=1,\cdots,U}(p_u + \min\{C_{uv}, c_{uv} - x\}) \quad (8)$$

Again, when there is more than one combination of manufacturer and transport mode with the lowest total cost, we assume that the contractor will choose the combination among those with the lowest total cost that has the lowest carbon emissions. When there is more than one combination with the lowest total cost and with the same amount of carbon emissions, we assume that the contractor will choose a combination with road transport mode (if there exists such a combination) because a road transport mode does not require a government subsidy. As a result, the amount of carbon emissions per unit prefab product from contractor v, denoted by $\Theta_v^*(x)$, can be calculated as shown below:

$$\Theta_v^*(x) = \min\{\Theta_v^{*r}(x), \Theta_v^{*i}(x)\} \quad (9)$$

where $\Theta_v^{*r}(x)$ and $\Theta_v^{*i}(x)$ can be calculated as shown below:

$$\Theta_v^{*r}(x) = \min\left\{+\infty, \min_{u' \in \{u=1,\cdots,U|p_u + C_{uv} \le \Pi_v^*(x)\}} E_{u'v}\right\} \quad (10)$$

$$\Theta_v^{*i}(x) = \min\left\{+\infty, \min_{u' \in \{u=1,\cdots,U|p_u + c_{uv} - x \le \Pi_v^*(x)\}} e_{u'v}\right\} \quad (11)$$

The total amount of carbon emissions from all the contractors, denoted by $\Xi(x)$, can be calculated as:

$$\Xi(x) = \sum_{v=1}^{V} q_v \Theta_v^*(x) \quad (12)$$

The aim of the government is to identify the optimal value of x that induces the lowest total carbon emissions from all the contractors subject to a limited budget.

4. Bi-level programming model

To address the problem, a bi-level programming model has been formulated (Wang, 2013; Qu et al., 2017; Tian et al., 2021). In the bi-level programming model, the government can make the decision of subsidy x at the upper level and each of the contractors can choose the combination of manufacturer and transport mode at the lower level. The government's decision can affect, but not determine, the contractors' decisions (Wu and Wang, 2020).

With subsidy x, define y_{uv} as a binary decision variable that equals 1 if and only if contractor v chooses manufacturer u and road transport mode (0 otherwise), and define z_{uv} as a binary decision variable that equals 1 if and only if contractor v chooses manufacturer u and intermodal transport mode (0 otherwise). We can further define $\hat{z}_v$ as a binary decision variable that equals 1 if and only if contractor v chooses intermodal transport mode no matter which manufacturer is chosen (0 otherwise). Finally, we can use y_{uv}^*, z_{uv}^*, and $\hat{z}_v^*$ as the optimal value of y_{uv}, z_{uv}, and $\hat{z}_v$, respectively, $u = 1, \cdots, U, v = 1, \cdots, V$. The bi-level (BL) programming model is as follows:

[BL] $\min_x \sum_{v=1}^{V} q_v \sum_{u=1}^{U} (E_{uv} y_{uv}^* + e_{uv} z_{uv}^*)$ (13)subject to:

$$\sum_{v=1}^{V} q_v \hat{z}_v^* x \le B \quad (14)$$

$$a \le x \le b \quad (15)$$

where the optimal values y_{uv}^*, z_{uv}^*, and $\hat{z}_v^*$ can be obtained by solving the lower-level (LL) model for each contractor $v = 1, \cdots, V$:

[LL-v] $\min \sum_{u=1}^{U} \{p_u + [C_{uv} y_{uv} + (c_{uv} - x) z_{uv}]\}$ (16)subject to:

$$\sum_{u=1}^{U} (y_{uv} + z_{uv}) = 1 \quad (17)$$

$$\sum_{u=1}^{U} z_{uv} = \hat{z}_v \quad (18)$$

$$y_{uv} \in \{0, 1\}, u = 1, \cdots, U \quad (19)$$

$$z_{uv} \in \{0, 1\}, u = 1, \cdots, U \quad (20)$$

$$\hat{z}_v \in \{0, 1\} \quad (21)$$

Objective function (13) is the government's objective: minimizing the total carbon emissions from all contractors. Constraint (14) requires that the total subsidy allocated to the contractors does not exceed the government's budget. Constraint (15) defines the lower and upper bounds of the subsidy. Objective (16) is the objective of contractor v: minimizing the total cost, consisting of purchasing cost and transportation cost minus subsidy. Constraint (17) mandates that exactly one manufacturer and one transport mode will be chosen. Constraint (18) defines whether intermodal transport mode is used. Constraints (19)–(21) define y_{uv}, y_{uv}, and $\hat{z}_v$ as binary decision variables.

Model [BL] has a few properties.

Proposition 1:. Constraints (21) can be removed from model [LL-v].

Proof:. Constraints (21) are implied by Constraints (17)–(20). □

Proposition 2:. The integrality requirements in Constraints (19) and (20) can be removed from model [LL-v], that is, Constraints (19) and (20) can be replaced with:

$$y_{uv} \le 1, u = 1, \cdots, U \quad (22)$$

$$z_{uv} \le 1, u = 1, \cdots, U \quad (23)$$

$$y_{uv} \ge 0, u = 1, \cdots, U \quad (24)$$

$$z_{uv} \ge 0, u = 1, \cdots, U \quad (25)$$

Proof:. The coefficient matrix of Constraints (17), (22), (23) is totally unimodular (Wang, 2014) and the right-hand side coefficients are all integral. Therefore, the linear programming relaxation of model [LL-v] admits at least one integral optimal solution. □

The following Proposition 3 and Corollary 1 are easy to check and hence their proofs are omitted.

Proposition 3:. Consider two subsidies x_1 and x_2, $x_1 < x_2$, whose values of $\hat{z}_v$ are $\hat{z}_v^{*1}$ and $\hat{z}_v^{*2}$, respectively. We have $\hat{z}_v^{*1} \le \hat{z}_v^{*2}$, $v = 1, \cdots, V$, that is, a higher subsidy leads to a higher share of intermodal transport mode.

Corollary 1:. If the intermodal transport mode always has a lower carbon emission than the corresponding road transport mode, that is, $E_{uv} \geq e_{uv}$, $u = 1, \cdots, U, v = 1, \cdots, V$, then a higher subsidy always leads to a lower total amount of carbon emissions.

To solve the bi-level programming model [BL], we define M as a large positive number and then we have:

Theorem 1:. The bi-level programming model [BL] can be transformed to the following single-level (SL) optimization model:

[SL] $\min \sum_{v=1}^{V} q_v \sum_{u=1}^{U} (E_{uv} y_{uv} + e_{uv} z_{uv})$ (26) subject to:

$$\sum_{v=1}^{V} q_v \sum_{u=1}^{U} z_{uv} x \leq B \tag{27}$$

$$a \leq x \leq b \tag{28}$$

$$p_u + C_{uv} - M(1 - y_{uv}) \leq p_{u'} + C_{u'v}, u = 1, \cdots, U, u' = 1, \cdots, U, v = 1, \cdots, V \tag{29}$$

$$p_u + C_{uv} - M(1 - y_{uv}) \leq p_{u'} + c_{u'v} - x, u = 1, \cdots, U, u' = 1, \cdots, U, v = 1, \cdots, V \tag{30}$$

$$p_u + (c_{uv} - x) - M(1 - z_{uv}) \leq p_{u'} + C_{u'v}, u = 1, \cdots, U, u' = 1, \cdots, U, v = 1, \cdots, V \tag{31}$$

$$p_u + (c_{uv} - x) - M(1 - z_{uv}) \leq p_{u'} + c_{u'v} - x, u = 1, \cdots, U, u' = 1, \cdots, U, v = 1, \cdots, V \tag{32}$$

$$\sum_{u=1}^{U} (y_{uv} + z_{uv}) = 1, v = 1, \cdots, V \tag{33}$$

$$y_{uv} \in \{0, 1\}, u = 1, \cdots, U, v = 1, \cdots, V \tag{34}$$

$$z_{uv} \in \{0, 1\}, u = 1, \cdots, U, v = 1, \cdots, V \tag{35}$$

The key trick of converting the bi-level programming model [BL] into the single-level programming model [SL] lies in Constraints (29)–(32). If a particular $y_{uv} = 1$, i.e., the combination of manufacturer u and road transport mode is chosen, Constraints (29)–(30) require that the resulting cost $p_u + C_{uv}$ is less than the cost of any other manufacturer using road transport mode and intermodal transport mode, respectively. In contrast, if $y_{uv} = 0$, then Constraints (29)–(30) are not binding because a “big-M” is deducted from the left-hand sides. Similarly, if a particular $z_{uv} = 1$, i.e., the combination of manufacturer u and intermodal transport mode is chosen, Constraints (31)–(32) require that the resulting cost $p_u + c_{uv} - x$ is less than the cost of any other manufacturer using road transport mode and intermodal transport mode, respectively. In contrast, if $z_{uv} = 0$, then Constraints (31)–(32) are not binding because a “big-M” is deducted from the left-hand side. The value of M can be set to:

$$M = \max_{u=1,\cdots,U, v=1,\cdots,V} \{p_u + C_{uv}, p_u + c_{uv}\}. \tag{36}$$

Of course, it is also possible to define a smaller “big-M” for each of the Constraints (29)–(32).

To solve the model [SL], we note that in reality the value of subsidy x is usually an integer amount of dollars. To simplify the notation, we assume that both a and b are integers; otherwise we set $a \leftarrow \lceil a \rceil$ and $b \leftarrow \lceil b \rceil$.Then we can enumerate all possible values of x, i.e., $a, a+1, \cdots, b$. Given the value of x, the choice of manufacturer and transport mode by each contractor can be addressed independently. This can be achieved using Algorithm 1:

***Algorithm* 1.** *Given x, choice of manufacturer and transport mode by contractor v.*

Step 0: Set the lowest total cost per unit prefab product $\Pi_v^*(x) \leftarrow +\infty$. Set the amount of carbon emissions per unit prefab product $\Theta_v^*(x) \leftarrow +\infty$. Set the current manufacturer ID $u \leftarrow 0$.
Step 1: Set $u \leftarrow u + 1$. If $u > U$, output the values of $\Pi_v^*(x)$, $\Theta_v^*(x)$, $y_{u'v}$, $z_{u'v}$, $u' = 1, \cdots, U$, and stop.
Step 2: If $p_u + C_{uv} < \Pi_v^*(x)$, or if $p_u + C_{uv} = \Pi_v^*(x)$ and $E_{uv} \leq \Theta_v^*(x)$, set $\Pi_v^*(x) \leftarrow p_u + C_{uv}$, $\Theta_v^*(x) \leftarrow E_{uv}$, $y_{uv} = 1$, $y_{u'v} \leftarrow 0, u' = 1, \cdots, u-1, u+1, \cdots, U$, and $z_{u'v} \leftarrow 0, u' = 1, \cdots, U$.
Step 3: If $p_u + (c_{uv} - x) < \Pi_v^*(x)$, or if $p_u + (c_{uv} - x) = \Pi_v^*(x)$ and $e_{uv} < \Theta_v^*(x)$, set $\Pi_v^*(x) \leftarrow p_u + (c_{uv} - x)$, $\Theta_v^*(x) \leftarrow e_{uv}$, $y_{u'v} \leftarrow 0, u' = 1, \cdots, U$, $z_{uv} = 1$ and $z_{u'v} \leftarrow 0, u' = 1, \cdots, u-1, u+1, \cdots, U$.
Step 4: Go to Step 1.

A few issues of Algorithm 1 are noteworthy. In Step 2, we check whether the contractor will choose manufacturer u and land transport mode. If $p_u + C_{uv} < \Pi_v^*(x)$, a lower cost is found and hence the contractor will choose manufacturer u and land transport mode. The second condition “$p_u + C_{uv} = \Pi_v^*(x)$ and $E_{uv} \leq \Theta_v^*(x)$” can be divided into two cases: $p_u + C_{uv} = \Pi_v^*(x)$ and $E_{uv} < \Theta_v^*(x)$ (case i) and $p_u + C_{uv} = \Pi_v^*(x)$ and $E_{uv} = \Theta_v^*(x)$ (case ii). The first case means the combination of manufacturer u and land transport mode has the same lowest cost as the best combination found but a lower emission, and we assume that the contractor will choose the combination with the lower emission. The second case means the combination of manufacturer u and land transport mode has the same lowest cost as the best combination found and the same amount of carbon emissions, and we assume that the contractor will choose the combination of manufacturer u and land transport mode because this combination does not require government subsidy. In contrast, in Step 3, the inequality in the condition “$p_u + (c_{uv} - x) = \Pi_v^*(x)$ and $e_{uv} < \Theta_v^*(x)$” is strict, because if an intermodal transport mode has the same cost and emissions as those of the best combination found, we assume the contractor does not choose the intermodal transport mode (if the best combination found is the land transport mode) because choosing the intermodal transport mode requires government subsidy.

5. Illustrative example

In this section, we present an illustrative example to demonstrate the effectiveness of the proposed bi-level programming model. The layout of the manufacturers and construction sites are shown in Fig. 1. The geographical area of interest is a 140 km×400 km, which is 56,000 km^2, equal to the size of the Guangdong-Hong Kong-Macao Greater Bay Area of China. A total of $U = 30$ manufacturers are randomly located in the northern half of area (i.e., rectangle GHJI) and a total of $V = 100$ contractors are randomly located in the southern half of area (i.e., rectangle IJLK). There are six ports in the area: A and B are river ports, located along a river, and C, D, E, and F are sea ports, located along coastlines.

We assume there are four ways of transporting prefab products from a manufacturer to a contractor: (i) using road transport only; (ii) using road transport from the manufacturer to port A, using ship

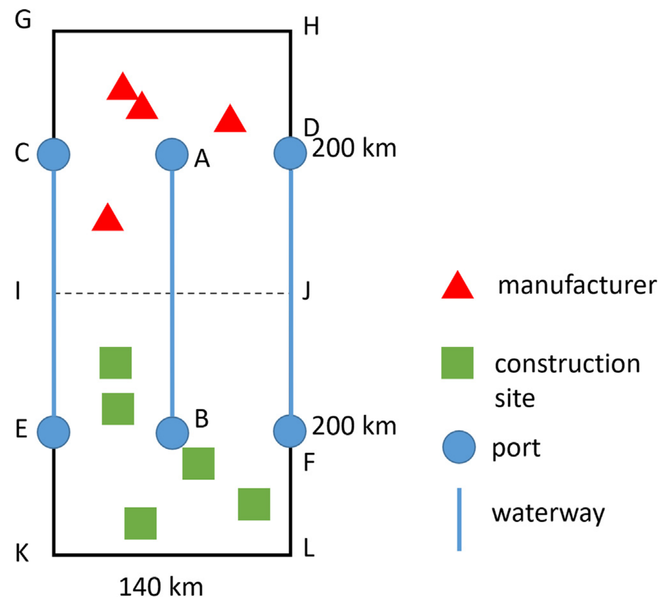

Fig. 1. Layout of the manufacturers and construction sites.

from A to B, and using road transport from B to the contractor; (iii) using road transport from the manufacturer to port C, using ship from C to E, and using road transport from E to the contractor; (iv) using road transport from the manufacturer to port D, using ship from D to F, and using road transport from F to the contractor. We further assume that there is direct and straight road connection between any two points in the area. The cost of road transport is assumed to be \$3/km per unit prefab products, and the cost of water transport is \$1.5/km. The handling of prefab products at ports is \$50 per unit each time. Therefore, the cost of transporting prefab products from a manufacturer to a contractor using road transport from the manufacturer to port A, using ship from A to B, and using road transport from B to the contractor is equal to \$3/km times the road transport distance from the manufacturer to port A, plus \$50, plus \$1.5/km times the water transport distance from A to B, plus \$50, and plus \$3/km times the road transport distance from port B to the contractor. The contractor will compare each of the three intermodal transport modes (via ports AB, via ports CE, and via ports DF) with the land transport mode and use the one with the lowest cost.

The carbon emission of road transport is set to 5 kg/km per unit prefab products, and of water transport is set to 0.5 kg/km. The other parameters are as follows: The quantity of prefab products required by contractor q_v is randomly selected from 10, 20, 30. The selling price at manufacturer p_u is assumed to be the same for all manufacturers and can thus be excluded from the analysis. The government's total budget B is \$300,000, the lower bound of subsidy $a = 0$, the upper bound $b = 500$, and the increment is \$5 (i.e., the subsidy can only be \$0, \$5, \$10,…,\$500).

5.1. Sensitivity with the subsidy

We first conducted a sensitivity analysis with the subsidy per unit prefab product without considering the total available budget. We set the subsidy per unit prefab product at 0, \$100, \$200, \$300, \$400, and \$500, and report in Fig. 2 the share of intermodal transport mode (i.e., the proportion of prefab products that are transported by intermodal mode) and the total carbon emission from all contractors. It can be seen that as the subsidy increases, the intermodal transport mode share increases and the total carbon emission decreases. However, when the subsidy is high, all prefab products use intermodal transport and a further increase in subsidy will not affect the results.

5.2. Sensitivity with total budget

We then conduct sensitivity analysis with the total budget available. We set the total budget at 0, \$100,000, \$200,000,…, and \$800,000, and report in Fig. 3 the share of intermodal transport mode and the total carbon emission from all contractors. It can be seen that as the total budget increases, the intermodal transport mode share increases and the total carbon emission decreases. However, when the total budget is over \$600,000, a further increase in the total budget will have little effect. The change of the optimal unit subsidy with the total budget is plotted in Fig. 4. It can be seen that the optimal unit subsidy increases with the total budget.

5.3. Sensitivity with the size of barges in water transport

The unit water transport emission depends on the size of the ship used. If larger ships are used, a lower unit emission will be the result. However, larger ships mean the prefab products have to wait longer at the port of loading, resulting in a holding cost. A sensitivity analysis was conducted with the unit water transport emission with the assumption that the unit water transport cost does not change. The unit water transport emission was set at 0.1 kg/km, 0.2 kg/km, 0.3 kg/km, 0.4 kg/km, and 0.5 kg/km, and shown in Fig. 5 against the total carbon emission from all contractors. It can be seen that as

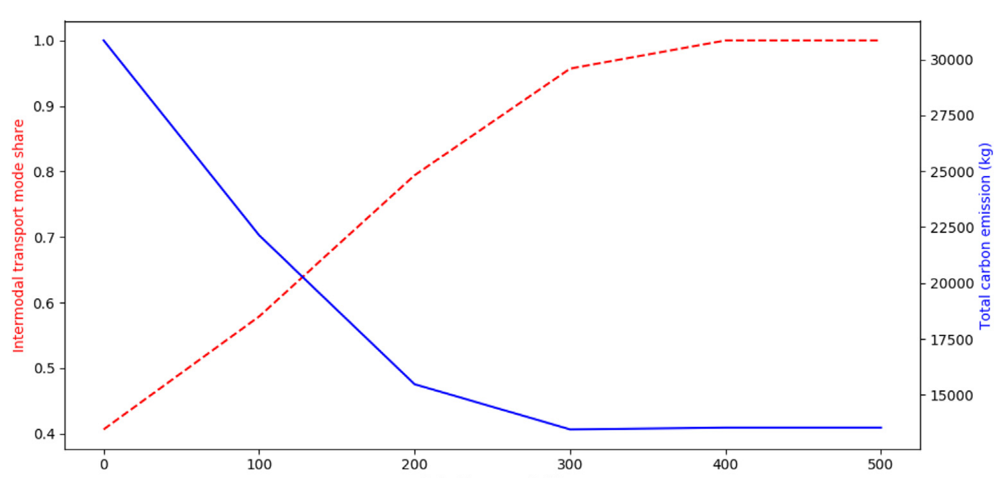

Fig. 2. Sensitivity of intermodal transport mode share and total carbon emission with subsidy.

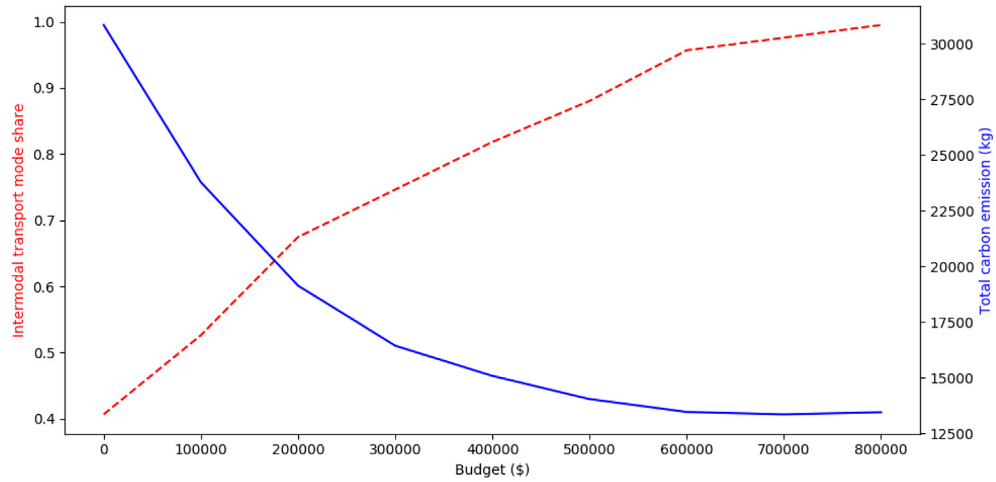

Fig. 3. Sensitivity of intermodal transport mode share and total carbon emission with total budget.

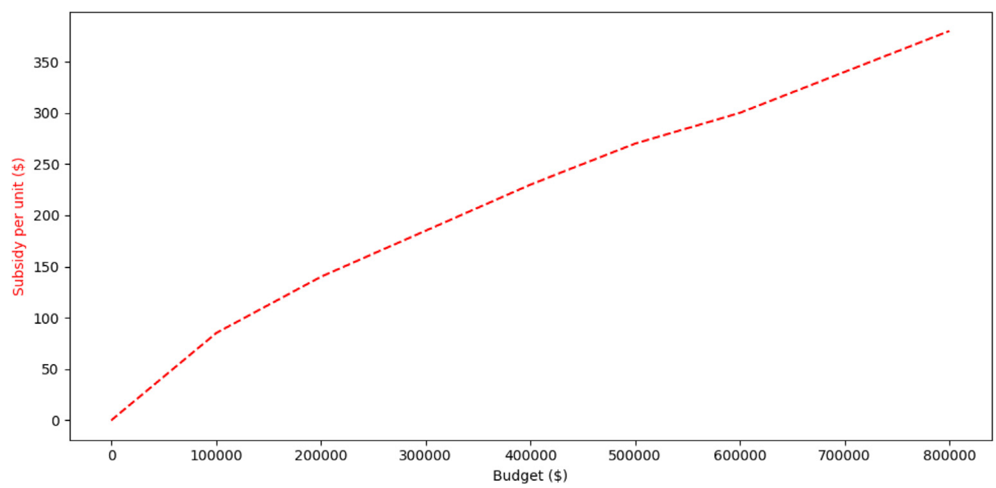

Fig. 4. Sensitivity of the optimal subsidy with total budget.

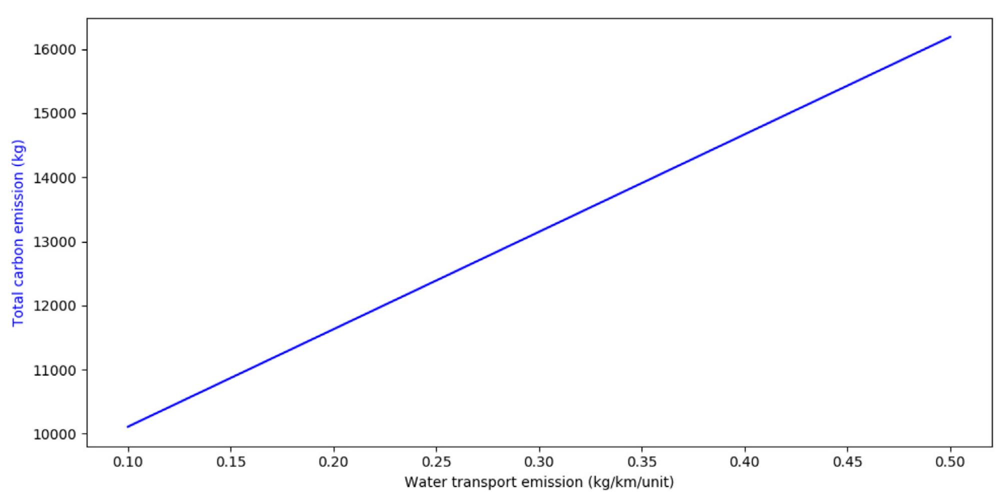

Fig. 5. Sensitivity of the total carbon emission with the unit water transport emission.

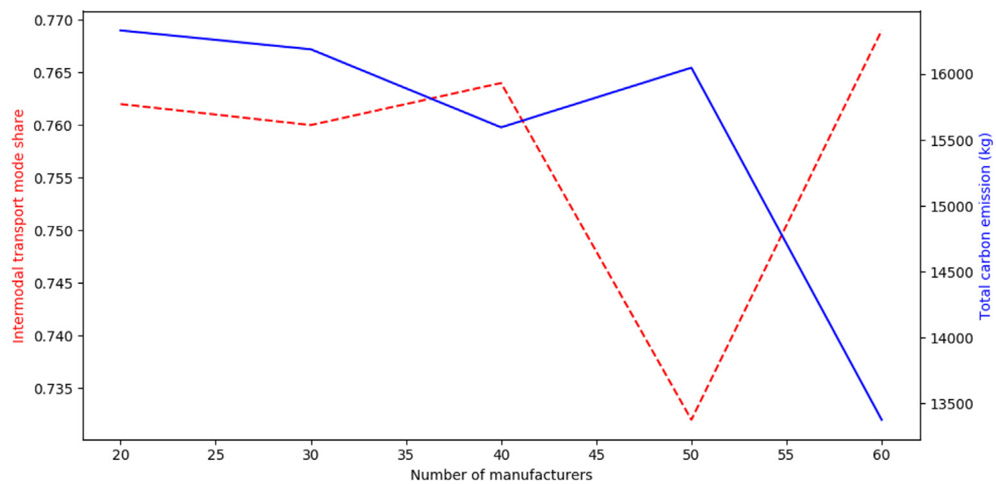

Fig. 6. Sensitivity of intermodal transport mode share and total carbon emission with the number of manufacturers.

the unit water transport emission increases, the total carbon emissions increase in an upward linear trajectory.

5.4. Sensitivity with the number of manufacturers

Finally, the study conducted a sensitivity analysis with the number of manufacturers. The numbers of manufacturers were noted as 20, 30, 40, 50, and 60, and shown in Fig. 6 against the share of intermodal transport mode and the total carbon emission from all contractors. It can be seen that due to randomness, there is no universal trend of the intermodal transport mode share or the total carbon emission with the number of manufacturers.

6. Conclusions

The research presented in this paper proposes a bi-level programming model for the government to decide the optimal subsidy for intermodal transport to achieve the lowest carbon emissions. The model takes into account the cost-minimization objective of contractors, which is not aligned with the government's primary objective. The bi-level programming model is converted into a single-level model and an efficient solution method is proposed to solve it. A number of sensitivity analysis simulations were carried out as a numerical study and these were conducted to demonstrate the effectiveness of the proposed model. The results demonstrated that an increase in the subsidy or in the total budget will lead to an increase in the share of intermodal transport mode and also in the total carbon emissions, however, the marginal benefit of the increase in the subsidy or the total budget will decrease. The results also showed that as the unit water transport emission increases, the total carbon emissions will increase linearly. Specific trends were not identified with regard to the intermodal transport mode share nor the total carbon emissions for the total number of manufacturers. We have assumed that diesel trucks are used for transport prefab products on road, but more and more electric and connected vehicles are used (Qu et al., 2020; Shi et al., 2021) and their adoption will change the emission picture of prefab transportation. Another future research could consider the effect of government subsidies on the total cost of prefab construction and how construction sites based on their location could benefit from adopting prefab construction methods.

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.

Acknowledgments

All authors contributed equally to the paper and are co-first author. This research is supported by the National Natural Science Foundation of China (Grant numbers 72025103, 71831008, 72071173).

References

Bengtsson, S.H., 2019. Coordinated construction logistics: an innovation perspective. Constr. Manage. Econ. 37 (5), 294–307.

Construction Industry Council of Hong Kong (2020). Reference Material on Logistics and Transport for Modular Integrated Construction Projects. http://mic.cic.hk/files/Information/2/File/Logistics_and_Transport_for_MiC_Projects.pdf. Accessed 28 May 2021.

Fang, Y., Ng, S.T., 2019. Genetic algorithm for determining the construction logistics of precast components. Eng., Constr. Archit. Manage. 26 (10), 2289–2306.

Hsu, P.-Y., Angeloudis, P., Aurisicchio, M., 2018. Optimal logistics planning for modular construction using two-stage stochastic programming. Autom. Constr. 94, 47–61.

Hsu, P.-Y., Aurisicchio, M., Angeloudis, P., 2019. Risk-averse supply chain for modular construction projects. Autom. Constr. 106, 102898. https://doi.org/10.1016/j.autcon.2019.102898.

Hsu, P.-Y., Aurisicchio, M., Angeloudis, P., 2020. Optimal logistics planning for modular construction using multi-stage stochastic programming. Transp. Res. Procedia 46, 245–252.

Kholod, N., Evans, M., Gusev, E., Yu, S., Malyshev, V., Tretyakova, S., Barinov, A., 2016. A methodology for calculating transport emissions in cities with limited traffic data: Case study of diesel particulates and black carbon emissions in Murmansk. Sci. Total Environ. 547, 305–313.

Lee, J., Hyun, H., 2019. Multiple modular building construction project scheduling using genetic algorithms. J. Constr. Eng. Manage. 145 (1), 04018116.

Li, C.Z., Zhong, R.Y., Xue, F., Xu, G., Chen, K., Huang, G.G., Shen, G.Q., 2017. Integrating RFID and BIM technologies for mitigating risks and improving schedule performance of prefabricated house construction. J. Cleaner Prod. 165, 1048–1062.

Liu, J., 2016. The Significance of Logistics Performance to Industrial Modular Construction Project under the "Big Site" Scenario Master's Thesis. University of Alberta, Canada.

Niu, S., Yang, Y., Pan, W., 2019. Logistics planning and visualization of modular integrated construction projects based on BIM-GIS integration and vehicle routing algorithm. Modular and Offsite Construction (MOC) Summit Proceedings, 579-586.

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. J. Cleaner Prod. 294, 126210. https://doi.org/10.1016/j.jclepro.2021.126210.

Qu, X., Li, X., Wang, M., Dixit, V., 2017. Advances in modelling connected and automated vehicles. J. Adv. Transp. 2017, 1–3.

Qu, X., Wang, S., 2021. Communications in transportation research: vision and scope. Commun. Transp. Res. 1, 100001.

Qu, X., Yu, Y., Zhou, M., Lin, C.-T., Wang, X., 2020. Jointly dampening traffic oscillations and improving energy consumption with electric, connected and automated vehicles: a reinforcement learning based approach. Appl. Energy 257, 114030.

Shi, X., Wang, Z., Li, X., Pei, M., 2021. The effect of ride experience on changing opinions toward autonomous vehicle safety. Commun. Transp. Res. 1, 100003.

Tian, Q., Wang, D.Z.W., Lin, Y.H., 2021. Service operation design in a transit network with congested common lines. Transp. Res. Part B: Methodol. 144, 81–102.

Wang, S., 2013. Efficiency and equity of speed limits in transportation networks. Transp. Res. Part C: Emerging Technol. 32, 61–75.
Wang, S., 2014. A novel hybrid-link-based container routing model. Transp. Res. Part E: Logist. Transp. Rev. 61, 165–175.
Wu, L., Wang, S., 2020. The shore power deployment problem for maritime transportation. Transp. Res. Part E: Logist. Transp. Rev. 135, 101883.
Xu, G., Li, M., Luo, L., Chen, C.-H., Huang, G.Q., 2019. Cloud-based fleet management for prefabrication transportation. Enterprise Information Systems 13 (1), 87–106.
Yang, Y., Pan, M., Pan, W., Zhang, Z., 2021. Sources of uncertainties in offsite logistics of modular construction for high-rise building projects. J. Manage. Eng. 37 (3), 04021011.
Yi, W., Wang, S., Zhang, A., 2020. Optimal transportation planning for prefabricated products in construction. Comput.-Aided Civ. Infrastruct. Eng. 35 (4), 342–353.
Zhu, M., Dai, J., Liu, R., Xu, J., Alwisy, A., 2021. Two-period based carbon-economy equilibrium strategy for modular construction supply planning. J. Cleaner Prod. 290, 125674.