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Multimodal transportation network with cargo containerization technology: Advantages and challenges

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ABSTRACT

Traditional multimodal transportation dispatching of roads, railways, and maritime has been studied for years. This study investigates a bulk cargo distribution problem in a multimodal transportation network considering both the transportation modes of inland waterways and containerization technology. First, we qualitatively discuss the advantages and challenges of transportation using cargo containerization technology from the aspects of transportation cost, time-saving, pollutant emission reduction, and customer preference. Second, a mixed-integer linear programming model is developed, wherein the influence of bridge heights on transportation is considered. The model is validated based on near-practice numerical experiments, and we can obtain the optimal transportation scenario by solving the model, including transportation mode selection, vehicle routing, depot selection, and cargo quantity for containerization. Third, we conduct numerical experiments based on the multimodal transportation network of the Yangtze River in China to discuss the performance of multimodal transportation with containerization technology considerations. The results show that containerization transportation can decrease the total transportation costs for logistics companies under certain parameter configurations. The model and experiments are then extended by considering pollutant emission reductions and time savings, respectively. We uncover the performance of containerization technology by analyzing the Pareto fronts of this technology and traditional bulk cargo transportation. This study elucidates the decision making of logistics companies and government policymaking.

1. Introduction

Inland waterways, such as the Rhine River in Europe, Yangtze River and Pearl River in China, and Mississippi River in America, have been the backbone of regional logistics (Notteboom et al., 2020) and play a significant role in multimodal logistics networks (Lam and Gu, 2016; Pant et al., 2015; Zhao et al., 2019; Chen et al., 2020; Deng et al., 2022). As important components of multimodal logistics networks, they are usually connected to global supply chains and maritime logistics networks by a hub, such as Shanghai for the Yangtze River and Rotterdam for the Rhine River (Lee et al., 2022). Compared to other modes of transportation (e.g., roads and railways (Zhang et al., 2022)), inland waterway transportation (IWT) could be competitive because of its higher cost efficiency and lower pollution emission consumption (Asian Development Bank, 2016). For example, the energy consumption per km•ton of the IWT is approximately 17% of that of road transportation and 50% of that of rail transportation (An et al., 2015). In Europe, more than 37,000 km of waterways connect hundreds of cities and industrial regions, and 13 member states of the European Union (EU) have interconnected waterway networks (https://ec.europa.eu/). The United States has approximately 25,000 miles of navigable inland waterways across 38 states (Pant et al., 2015). However, the IWT also has some limitations such as the spatial and seasonal variation of water depth. When the water level drops sharply, shipping on inland waterways will become difficult. But it is unlikely to happen except in extreme weather. It could be more likely to happen during the drought. Another disadvantage could result from the bridges on rivers which limit the height of vessels (Zhang et al., 2020). Moreover, more transhippment between different transport modes are required because river ports are usually not nearby the customers. Therefore, as can be seen in the real world, the

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sizes of vessels on inland waterways are relatively not big which reduces the productivity.Therefore, increasing the share of the IWT is significant. Moreover, the ongoing globalization of freight flows implies increasing requirements for IWTs. Substantial attention has been paid to IWTs from both practical and academic perspectives (Christodoulou et al., 2020; Doorga et al., 2021; Jiang et al., 2018; Li et al., 2019; Lu et al., 2017; Notteboom et al., 2020; Williamsson et al., 2020; Yang and Wang, 2016; Zhang et al., 2020; Zhao et al., 2019). For example, China possessed 127,700 km of waterways in 2020 and plans to establish a modern inland waterway system in 2035. The EU is also promoting IWT through various funding and financing programs, such as the Connecting Europe Facility, Horizon 2020, and the European Fund for Strategic Investments (https://ec.europa.eu/).

At present, most cargo transported by inland waterways is bulk cargo (e.g., agricultural products, coal, ores, sands, stones, and building materials). For example, the main product category transported through the inland waterways of the EU in 2018 is metal ores and other mining and quarrying products (https://ec.europa.eu/eurostat/). The main cargos through the river ports of China in 2015 are mineral building materials (31%) and coal (including coal products) (20%) (Asian Development Bank, 2016). Bulk cargo is typically transported via bulk carriers because of the scale economics of bulk carriers on ocean routes (Clott et al., 2015). However, the containerization of bulk cargo for transportation by container ships has attracted increasing attention. For example, a growing amount of grain transportation from North America and wheat transportation from Australia have witnessed containerized transportation (Yang et al., 2016). Most European coffee imports (Rodrigue and Notteboom, 2015) and some crop imports from Taiwan and China (Lirn and Wong, 2013b) have also been containerized for delivery. The containerization of bulk cargo is motivated by the following two reasons. First, it can significantly reduce cargo loss or damage. Second, its standard structure offers smooth transshipment operations between different parties in a supply chain or flexible transshipment between different transportation equipment (e.g., container ships, trucks, and rails) that reduce transit times and costs incurred in loading and unloading cargos. Hence, containerized shipping on inland waterways has become increasingly common in inland logistics networks (Braekers et al., 2013; Maraš et al., 2013; Notteboom et al., 2020; Zhang et al., 2020). Many governments also attempt to promote the implementation of this technology because of its environmental benefits (Kamal and Kutay, 2021). However, it should also be noted that the containerization of bulk cargo is not ubiquitous in the real world for certain reasons, such as a large amount of capital investments in infrastructures and equipment (e.g., giant cranes, stacking yards), complex container stacking on both the ground and containerships, and high cost of container acquisition.

A rich body of literature has investigated multimodal transportation problems. However, most studies focus on multimodal transportation without inland waterways, such as multimodal transportation of road-rail (Heinold and Meisel, 2020; Kumar and Anbanandam, 2020; Maia and do Couto, 2013; Wang et al., 2017), road-maritime (Qin et al., 2014), road-air (Huang et al., 2020), rail-maritime (Xie et al., 2017), and road-rail-maritime (Lin, 2019; Mokhtar et al., 2019; Resat and Turkay, 2015; Wang and Meng, 2017). Some studies focus on *relay transportation* with a single transportation mode during the transportation (Hu et al., 2019; Vergara and Root, 2013). On the contrary, of course, multimodal transportation has more than one transportation mode during the transportation. We study a multimodal transportation problem considering the transportation modes of inland waterways, roads, and railways. The transportation modes between different locations can be chosen for economic purposes. Most studies on multimodal transportation with inland waterways focus on optimizing the entire multimodal network from an operational viewpoint without considering containerization technology (Chen et al., 2021; Chen et al., 2022; Lam and Gu, 2016; Li et al., 2015; Liu et al., 2017; Xu et al., 2021; Zhang et al., 2013; Zhao et al., 2019; Zhou et al., 2018). Moreover, the specific navigable conditions of inland waterways, such as the tropical structure of corridors, drafts, and bridge height, are rarely considered. Here, we consider the navigable conditions of inland waterways for multimodal transportation. Containerization of cargo at proper locations is integrated into the transportation process.

In contrast to existing studies, this study investigates a bulk cargo distribution problem in a multimodal transportation network considering containerization technology. The network includes waterways, roads, and railway transport modes. Fig. 1 shows a conceptual framework surrounding the Yangtze River in China. A logistics company needs to deliver cargos from the sea hub (e.g., Shanghai port) to inland customers using trucks, trains, and vessels. Containerization services are available at river ports equipped with specific facilities. Containerized cargos are transported in containers until they are unpacked and transformed into bulk cargos at the factories of customers. The contributions of this study are twofold.

(i) It comprehensively uncovers the main advantages and challenges of containerization technology in terms of monetary cost, environmental benefits, time-saving, and customer preference.
(ii) It proposes a mixed-integer linear programming model to obtain an optimal plan of transportation that considers containerization.

The remainder of this paper is organized as follows. Section 2 reviews the literature related to bulk containerization and intermodal transport. Section 3 analyzes this problem and develops a mathematical model. In Section 4, experiments are conducted to provide numerical evidence for managerial insights. Section 5 discusses the limitations of containerization and presents the conclusions and some policy suggestions.

2. Literature review

This section reviews and discusses the literature related to bulk cargo containerization and intermodal networks. Table 1 summarizes the relationship between this study and some related studies.

2.1. Bulk cargo containerization

The bulk cargo containerization is a practice of bulk cargo transportation that has been widely studied. Lirn et al. (2018) studied the important factors that affects the quality of containerized grains through Analytic Hierarchy Process (AHP), and put forward suggestions on methods to reduce the damage rate of containerized grain cargo. Kawasaki and Matsuda (2015) took wood pulp as an example to establish a transport mode selection model and explored the key factors that influenced shipping companies' choice of bulk carriers or container ships for transportation. Matsuda et al. (2020) analyzed the cost of bulk containerized transportation to show the cost competitiveness of bulk containerized transportation. From their research results, reducing freight rates can effectively promote the bulk containerized transportation. Lirn and Wong (2013a) applied the Likert scale questionnaire and fuzzy AHP to analyze the importance of 12 service standards for grain bulk carrier and container shipping. That study also measured the overall satisfaction of grain shippers and importers. Some studies discussed the market potential of bulk cargo transported through containers by studying the nature of the commodities loaded in containers (e.g., Rodrigue and Notteboom, 2015). Yang et al. (2016) established an economic decision-making model to explore the advantages and disadvantages of coal containerization and traditional bulk transportation by taking China's coal transportation as an example. Clott et al. (2015) took the case of U.S. soybean export as an example to study the operational issues, actions, rules and policy implications affecting crop container transportation. Qin et al. (2014) developed an integer programming model by combining parcel delivery and container transportation based on an actual textile export case, and used a meme algorithm to find the

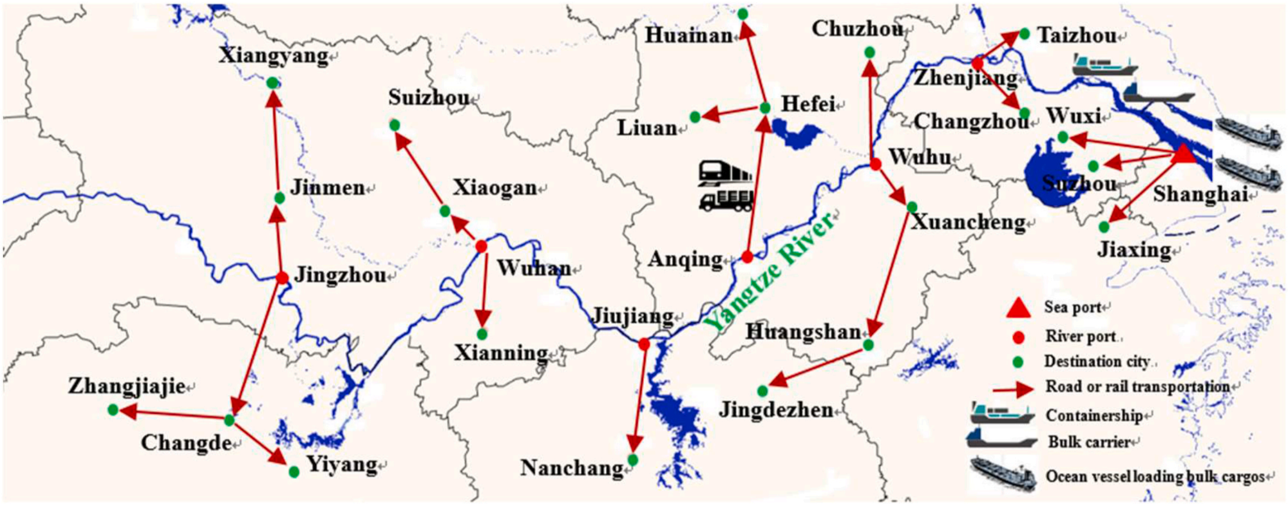

Fig. 1. The multimodal transportation network for cargo distribution.

Table 1
Comparison between this study and relevant previous studies.

	Multimodal transportation	Inland waterways	Navigation conditions	Bulk cargo transportation	Container transportation
(Huang et al., 2020)	✓				✓
(Wang et al., 2017)	✓				✓
(Fazayeli et al., 2018)	✓			✓	
(Lv et al., 2019)	✓			✓	
(Lam and Gu, 2016)	✓	✓			✓
(Zhao et al., 2019)	✓	✓			✓
(Liu et al., 2017)	✓	✓			✓
(Li et al., 2015)	✓	✓			✓
(Zhou et al., 2018)	✓	✓		✓	
(Zhang et al., 2020)		✓	✓		✓
(Li et al., 2019)		✓	✓	✓	
This study	✓	✓	✓	✓	✓

allocation method to minimize the total cost.

2.2. Bulk multimodal transportation

There exists a rich body of literature in the multimodal transportation problem for bulk cargos. For example, Zhou et al. (2018) analyzed the fright distribution of green logistics in multimodal transport by developing analytical models simultaneously with the consideration of economic and environmental performance. Maiyar and Thakkar (2019) studied intermodal (road, railway) food grain transportation with hub disruption, by considering the minimization of transportation, hub location, rerouting, environmental and social costs. Mogale et al. (2017) investigated a two-stage bulk wheat transportation and storage problem with a multi-period multi-modal in Public Distribution System. In the first step of that system, the transportation of wheat from an origin node to silos employed trucks and the next stage was the transportation of wheat from silos to destination nodes of consuming states with railway or road mode. Alumur et al. (2012) attempted to find the location of hub of multimodal (air, road) network design in small parcel delivery. Fazayeli et al. (2018) presented a location-routing problem (for depots) with time window constraints and fuzzy demands from the customers along with multimodal (railway, sea, or road) transportation to design a full distribution system from producer to customers by the genetic algorithm Lv et al. (2019) studied the combined transport problem of multimodal transport (road, railway, and water), with different capacities of each container through simultaneous loading and unloading. That study aimed to choose appropriate consolidation and transfer points to minimize the total cost of a container.

2.3. Container multimodal transportation

Another stream of related research focused on the transport of containers in multimodal transport networks. Caris et al. (2014) identified the challenges to integrate inland waterway transport in the intermodal supply chain. Yin et al. (2021) proposed a 0–1 planning model to minimize the total cost, transit time and carbon emissions by determining the location of major hub ports in the hinterland in a multimodal transport (road, railway, and inland waterways) network. Corey et al. (2022) developed a two mixed-integer linear programming models to select the best regional hub port in the Caribbean Sea region. Lam and Gu (2016) studied the intermodal container transport (import and export) network optimization problem with constrained carbon emission to address the trade-offs between inland transportation modes of railway, barge, and truck. In the same study, a bi-objective model is proposed to minimize the cost and transit time. Zhao et al. (2019) developed a programming model for the location and routing problem of intermodal transport (sea, road, railway, and inland waterways) for exporting containers along the Yangtze River to neighboring countries. Liu et al. (2017) analyzed the intermodal transportation in international logistics of agricultural exports. Li et al. (2015) investigated the intermodal (road, railway, and inland waterways) freight transport planning problem among deep-sea ports and inland terminals in hinterland haulage for a horizontally and fully integrated intermodal freight transport operator. That problem was solved with a receding horizon intermodal container flow control approach that addressed the dynamic transport demands and traffic conditions. Zhang et al. (2013) studied the optimization of multimodal networks, taking into account the costs of CO_2 emissions and economies of terminal scale. Hu (2011) studied container multimodal transportation in emergency relief based on an immune affinity model. Yang et al. (2011) discussed a multi-objective multimodal transportation network transportation route optimization problem that minimizes the transportation cost and time. Wiegmans and Konings (2015) developed a model to compare the transportation costs of inland multimodal transportation and single-modal road transportation to explore the cost competitiveness of multimodal transportation.

3. Advantage discussion and mathematical model

The advantages of containerization are as follows: The first is the lower transshipment cost. The unit cost and time of loading or unloading one container would be lower than moving the cargos of the same size in bulk. Hence, when cargos are loaded and unloaded in a container between different vehicles at depots, the unit transshipment cost and time can be reduced. Other advantages could result from the higher leakproof level of containers. When cargos (e.g., coal) are delivered in bulk by the conveyor or grab, some may spill into nature due to wind or the shake of the conveyor. This spilling not only results in cargo loss, but also pollutes the air, earth, and water. However, spilling can be significantly reduced when cargo is delivered in containers. The higher leakproof level also allows containers to be transshipped on windy and rainy days, which could be infeasible under traditional bulk transport. This means that the operation of containers is more robust to weather conditions that reduce the waiting time owing to rain and wind. When stored in containers at depots, cargo loss and damage may also be reduced. The storage cost can be further reduced because of the high space utilization of the containers. Moreover, many navigation locks on rivers assign container ships a higher priority to pass than bulk carriers. Hence, delivering cargos in containers by container ships may have a shorter waiting time in the queue of passing locks. Table 2 summarizes the main advantages of containerization in multimodal transportation networks.

Based on the foregoing discussion, we develop a mixed-integer linear programming model (MILPC-L) to analyze the optimal solution and containerization performance from the perspective of the logistics company. In Section 4, we first focus on the monetary cost of the logistics company and extend the model by considering the environmental and time-saving utility. In the current basic model, we consider a logistics company that delivers a type of bulk cargo from a seaport to several cities in which customers are located. Three types of vehicles are considered: ships, railways, and trucks. Both bulk carriers and containerships can shed loads at ports to satisfy the navigation constraints (e.g., water depth and bridge height) to continue sailing along the river, and these shed loads are transported by other vehicles. The logistics company needs to determine the transportation mode, ship deployment, cargo and container flow assignment, and selection of proper locations for containerization and load shedding to minimize the total transportation cost. We did not consider last-mile deliveries in customer cities for two reasons. First, an increasing number of customers have built their own railway stations near factories to receive cargos by train.

Table 2
A summary of the main advantages of containerization.

Advantage	Description	Beneficiary
Lower unit transshipment cost	● Lower operational cost of one container than the cargos in bulk of the same size	Logistics company
Lower cargo loss and storage cost	● Higher leakproof level of containers ● Higher space utilization ratio	Logistics company and customer
Environmental benefit	● Less leakage	The public
Time-saving	● Shorter unit operational time ● More robust to weather conditions ● Shorter waiting time to pass the navigation locks	Logistics company and customer

Second, the locations of customers may be different, and it is not easy to consider the exact locations of customers in each city. Note that this simplification is not expected to influence the study's key findings and conclusions. The assumptions employed in our model are as follows:

- The containers are 20-feet equivalent units.
- The cargo demand of inland customer cities must be satisfied.
- All information is known in advance.
- All ports are equipped with containerization and loading shedding facilities.
- Containers are unpacked at customer cities.
- The contribution of draught and warehouse height per unit container cargo is fixed.

We consider the unit of bulk cargo as *container*, instead of *ton*, to smooth the discussion. The equivalent number of containers for every ton of cargo can be obtained from the coefficient, which is defined as g^F. The notations used in the model are as follows.

K Set of vehicle types, K = {s, r, o} wherein s, r, and o respectively represent a ship, train, and truck.

Q The total number of cargos at the departure port.

P Set of river ports, and $P = 0$ represents the departure port.

V Set of vessels that can be used on rivers.

D Set of inland customer cities with cargo demands

q_i Cargo demand at customer city i, $i \in D$ (unit: container)

λ^{CE} Fixed costs of using the containerization facility (unit: CNY)

λ^{C} Unit costs of containerizing bulk cargos into one container (unit: CNY/container)

λ^{LE} Fixed costs of using the load shedding facility (unit: CNY)

λ^{BL} Unit costs of unloading bulk cargos of the same size as a container from vessels (unit: CNY/container)

λ^{TL} Unit costs of unloading one full container from vessels (unit: CNY/container)

λ^{U} Fixed cost of using one container (unit: CNY/container)

λ^{D} Unit cargo damage and storage costs (unit: CNY/container)

λ^{B}_{kl} Transshipment cost of bulk cargo converted from vehicle of type k to vehicle of type l, $k \in K$, $l \in K \backslash \{k\}$ (unit: CNY/container)

λ^{T}_{kl} Transshipment cost of container converted from vehicle of type k to vehicle of type l, $k \in K$, $l \in K \backslash \{k\}$ (unit: CNY/container)

d_{ijk} Transportation distance between positions i and j using the transportation mode k, $i \in D \cup P$, $j \in D \cup P \backslash \{i\}$, $k \in K$ (unit: km)

H_{ij} Height limit for a vessel sailing from port i to port j, $i \in P$, $j \in P$ (unit: m)

W_{ij} Draft limit for a vessel sailing from port i to port j, $i \in P$, $j \in P$ (unit: m)

λ_v Fixed cost of using vessel v, $v \in V$ (unit: CNY)

t_v The type of vessel v, $v \in V$, $t_v \in \{0, 1\}$ i.e., $t_v = 0$ represents bulk carrier, and $t_v = 1$ represents container ship

G_v The capacity of vessel v, $v \in V$ (unit: container)

ρ_v Contribution rate of unit container cargo to vessel v load, $v \in V$. That is, the contribution rate is set as $\rho_v = g^F + t_v g^W$ where g^W is the weight of an empty container

M_v Relative height of the cockpit to the cargo hold for a vessel v, $v \in V$, That is, for bulk carriers, there is no restriction on the height of the cargo hold, so $M_v = 0$, when $t_v = 0$ (unit: m)

H_v Relative height of the cockpit to the water surface when the vessel v is empty, $v \in V$ (unit: m)

Q_v Draft of the vessel v with no load, $v \in V$ (unit: m)

h_v Height contribution of a unit container cargo to the vessel v, $v \in V$. That is, for bulk carriers, there is no restriction on the height of the cargo hold, so $h_v = 0$, when $t_v = 0$ (unit: m)

w_v Draft contribution of a unit container cargo to the vessel v, $v \in V$ (unit: m)

f_v Transportation cost per kilometer of unit container cargo for vessel v, $v \in V$ (unit: CNY/km • container)

f_k^B Transportation cost of bulk cargo transported by vehicle of type k, $k \in K \backslash \{s\}$ (unit: CNY/km • container)

f_k^T Transportation cost of container transported by vehicles of type k, $k \in K \backslash \{s\}$ (unit: CNY/km • container)

F_k Fixed cost per vehicle of type k, $k \in K \backslash \{s\}$ (unit: CNY)

A_k The capacity per vehicle of type k, $k \in K \backslash \{s\}$ (unit: container)

The following decision variables are introduced:

$$x_{ijk} = \begin{cases} 1, & \textit{if vehicle of type k is used from position i to position j} \\ 0, & \textit{otherwise} \end{cases}, i \in D \cup P, j \in D, j \neq i, k \in K \backslash \{s\} \; or \; i \in P, j = i+1, k = s$$

$$m_{ikl} = \begin{cases} 1, & \text{if vehicle of type } k \text{ changes to vehicle of type } l \text{ at position } i \\ 0, & \text{otherwise} \end{cases}, i \in D \cup P \backslash \{0\}, k \in K, l \in K \backslash \{k\}$$

$$s_{ijv} = \begin{cases} 1, & \text{if vessel } v \text{ departs from port } i \text{ and arrives at port } j \\ 0, & \text{otherwise} \end{cases}, i \in P, j \in P, j > i, v \in V$$

$$c_{ijv} = \begin{cases} 1, & \text{if vessel } v \text{ departs from port } i \text{ and arrives at port } j \text{ for bulk containerization} \\ 0, & \text{otherwise} \end{cases}, i \in P, j \in P, j > i, v \in V$$

$$l_{ijv} = \begin{cases} 1, & \text{if vessel } v \text{ departs from port } i \text{ and arrives at port } j \text{ for load shedding} \\ 0, & \text{otherwise} \end{cases}, i \in P, j \in P, j > i, v \in V$$

n_{ikl}^B Number of bulk cargos involved in the transshipment from vehicle type k to type l at position i, $i \in D \cup P \backslash \{0\}$, $k \in K$, $l \in K \backslash \{k\}$ (unit: container)

n_{ikl}^T Number of containers involved in the transshipment from vehicle type k to type l at position i, $i \in D \cup P \backslash \{0\}$, $k \in K$, $l \in K \backslash \{k\}$ (unit: container)

B_{ijk} Number of bulk cargos transported by vehicles of type k from position i to position j, $i \in D \cup P$, $j \in D, j \neq i$, $k \in K \backslash \{s\}$ (unit: container)

T_{ijk} Number of containers transported by vehicles of type k from position i to position j, $i \in D \cup P$, $j \in D, j \neq i$, $k \in K \backslash \{s\}$ (unit: container)

b_{ijk} Number of tools used to transport bulk cargo by vehicles of type k from position i to position j, $i \in D \cup P$, $j \in D, j \neq i$, $k \in K \backslash \{s\}$

t_{ijk} Number of tools used to transport container by vehicles of type k from position i to position j, $i \in D \cup P$, $j \in D, j \neq i$, $k \in K \backslash \{s\}$

n_{ijv} Number of cargos on vessel v when it departs from port i and arrives at port j, $i \in P$, $j \in P, j > i$, $v \in V$ (unit: container)

n_{ijv}^C Number of containers into which bulk cargos are containerized when vessel v departs from port i and arrives at port j, $i \in P$, $j \in P, j > i$, $v \in V$ (unit: container)

n_{ijv}^L Number of load shedding when vessel v departs from port i and arrives at port j, $i \in P$, $j \in P, j > i$, $v \in V$ (unit: container)

The model is formulated as follows.

$$\min \; C^{TRT} + C^{TRF} + C^{CON} + C^{LIT} + C^{DAM} \tag{1}$$

$$s.t. \quad C^{TRT} = \sum_{k \in K \backslash \{s\}} z_k + z_s \tag{2}$$

$$z_k = \sum_{i \in D \cup P} \sum_{j \in D, j \neq i} d_{ijk} \left(f_k^B B_{ijk} + f_k^T T_{ijk} \right) + \sum_{i \in D \cup P} \sum_{j \in D, j \neq i} F_k \left(b_{ijk} + t_{ijk} \right), \forall k \in K \backslash \{s\} \tag{3}$$

$$z_s = \sum_{i \in P \backslash \{n\}} \sum_{v \in V} \left(N_{i,(i+1),v} f_v d_{i,(i+1),s} + \lambda_v s_{i,(i+1),v} \right) \tag{4}$$

$$N_{i,(i+1),v} = \sum_{j \in P, j \leq i} n_{j,(i+1),v} \; , \forall i \in P \backslash \{n\}, \forall v \in V \tag{5}$$

$$C^{TRF} = \sum_{i \in P \backslash \{0\}} \sum_{l \in K \backslash \{s\}} \left(\lambda_{sl}^B n_{isl}^B + \lambda_{sl}^T n_{isl}^T \right) + \sum_{i \in D} \sum_{k \in K \backslash \{s\}} \sum_{l \in K \backslash \{s,k\}} \left(\lambda_{kl}^B n_{ikl}^B + \lambda_{kl}^T n_{ikl}^T \right) \tag{6}$$

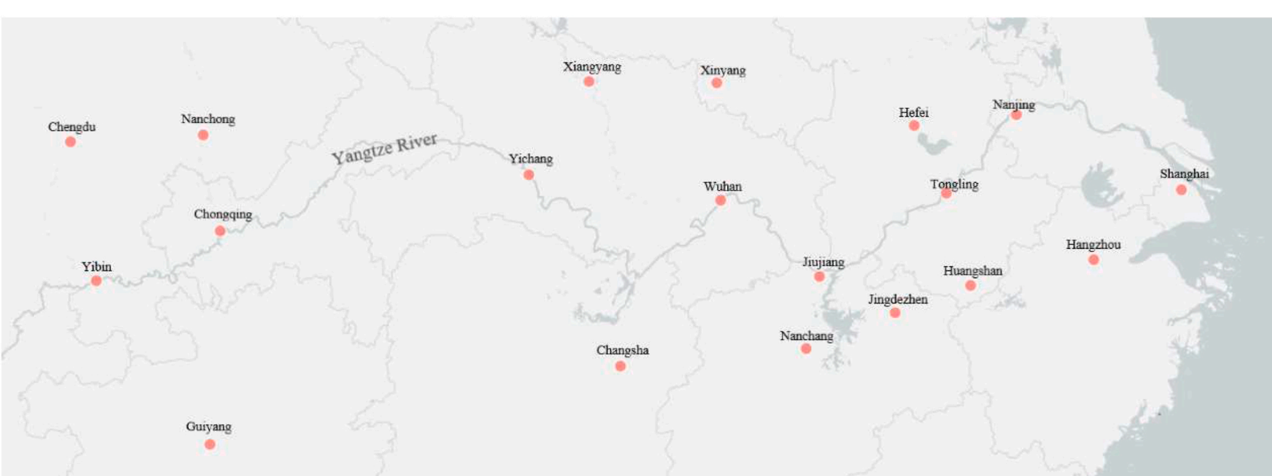

Fig. 2. Locations of the ports and customer cities in the experiments.

$$C^{CON} = \sum_{v\in V} t_v s_{01v}\left(\lambda^{CE} + n_{01v}\left(2\lambda^C + \lambda^U\right)\right) + \sum_{k\in K\backslash\{s\}}\sum_{j\in D} x_{0jk}\left(\lambda^{CE} + T_{0jk}\left(2\lambda^C + \lambda^U\right)\right) + \sum_{i\in P}\sum_{j\in P, j>i}\sum_{v\in V}(1-t_v)c_{ijv}\left(\lambda^{CE} + n^C_{ijv}\left(2\lambda^C + \lambda^U\right)\right) \quad 7$$

$$C^{LIT} = \sum_{v\in V}(1-t_v)s_{01v}\left(\lambda^{LE} + n_{01v}\lambda^{BL}\right) + \sum_{i\in P}\sum_{j\in P, j>i}\sum_{v\in V} l_{ijv}\left(\lambda^{LE} + n^L_{ijv}\left((1-t_v)\lambda^{BL} + t_v\lambda^{TL}\right)\right) \quad 8$$

$$C^{DAM} = \sum_{v\in V}\lambda^D n_{01v} + \sum_{k\in K\backslash\{s\}}\sum_{j\in D}\lambda^D\left(T_{0jk} + B_{0jk}\right) + \sum_{i\in P}\sum_{j\in P, j>i}\sum_{v\in V}(1-t_v)\lambda^D\left(n^C_{ijv} + n^L_{ijv}\right) \quad 9$$

$$\sum_{i\in P, i<j}\sum_{v\in V}\varepsilon s_{ijv} \le x_{(j-1),js} \le \sum_{i\in P, i<j}\sum_{v\in V} s_{ijv}, \forall j\in P\backslash\{0\} \quad 10$$

$$\sum_{k\in K\backslash\{s\}}\sum_{i\in D\cup P, i\neq j} x_{ijk} \le 1, \forall j\in D \quad 11$$

$$x_{ijk} \le b_{ijk} + t_{ijk} \le M x_{ijk}, \forall i\in D\cup P, \forall j\in D, j\neq i, \forall k\in K\backslash\{s\} \quad 12$$

$$x_{jik} + \sum_{h\in D}\varepsilon x_{ihl} - 1 \le m_{ikl} \le x_{jik} + \sum_{h\in D}\varepsilon x_{ihl}, \forall i\in P\backslash\{0\}, j=i-1, k=s, \forall l\in K\backslash\{k\}\ or \forall j\in D\cup P, \forall i\in D, i\neq j\neq h, \forall k\in K\backslash\{s\}, \forall l\in K\backslash\{s,k\} \quad 31$$

$$b_{ijk}A_k - A_k \le B_{ijk} \le b_{ijk}A_k, \forall i\in D\cup P, \forall j\in D, j\neq i, \forall k\in K\backslash\{s\} \quad 13$$

$$t_{ijk}A_k - A_k \le T_{ijk} \le t_{ijk}A_k, \forall i\in D\cup P, \forall j\in D, j\neq i, \forall k\in K\backslash\{s\} \quad 14$$

$$s_{ijv} \le n_{ijv}\rho \le s_{ijv}G_v, \forall i\in P, \forall j\in P, j>i, \forall v\in V \quad 15$$

$$c_{ijv} + (1-t_v)l_{ijv} \le (1-t_v)s_{ijv}, \forall i\in P, \forall j\in P, j>i, \forall v\in V \quad 16$$

$$c_{ijv} \le n^C_{ijv} \le n_{ijv}c_{ijv}, \forall i\in P, \forall j\in P, j>i, \forall v\in V \quad 17$$

$$l_{ijv} \le n^L_{ijv} \le n_{ijv}l_{ijv}, \forall i\in P, \forall j\in P, j>i, \forall v\in V \quad 18$$

$$s_{ihv} \le s_{ijv}, \forall i\in P\backslash\{n\}, \forall j\in P\backslash\{n\}, \forall h\in P, h>j>i, \forall v\in V \quad 19$$

$$n_{ijv} = n_{i,(j+1),v} + n^C_{ijv} + n^L_{ijv}, \forall i\in P\backslash\{n\}, \forall j\in P\backslash\{n\}, j>i, \forall v\in V \quad 20$$

$$n_{inv} = n^C_{inv} + n^L_{inv}, \forall i\in P\backslash\{n\}, \forall v\in V \quad 21$$

$$Q \ge \sum_{v\in V} n_{01v} + \sum_{k\in K\backslash\{s\}}\sum_{j\in D}\left(T_{0jk} + B_{0jk}\right) \quad 22$$

$$\sum_{i\in P, i<j}\sum_{v\in V}(1-t_v)n^C_{ijv} + \sum_{i\in P, i<j}\sum_{v\in V} t_v n^L_{ijv} = \sum_{k\in K\backslash\{s\}}\sum_{h\in D} T_{jhk} + \sum_{v\in V} t_v n_{j,(j+1),v}, \forall j \in P\backslash\{0,n\} \quad 23$$

$$\sum_{i\in P\backslash\{n\}}\sum_{v\in V}(1-t_v)n^C_{inv} + \sum_{i\in P\backslash\{n\}}\sum_{v\in V} t_v n^L_{inv} = \sum_{k\in K\backslash\{s\}}\sum_{h\in D} T_{nhk} \quad 24$$

$$\sum_{i\in P, i<j}\sum_{v\in V}(1-t_v)n^L_{ijv} = \sum_{k\in K\backslash\{s\}}\sum_{h\in D} B_{jhk} + \sum_{v\in V}(1-t_v)n_{j,(j+1),v}, \forall j\in P\backslash\{0,n\} \quad 25$$

$$\sum_{i\in P\backslash\{n\}}\sum_{v\in V}(1-t_v)n^L_{inv} = \sum_{k\in K\backslash\{s\}}\sum_{h\in D} B_{nhk} \quad 26$$

$$\sum_{k\in K\backslash\{s\}}\sum_{i\in D\cup P, i\neq j}\left(T_{ijk} + B_{ijk}\right) = \sum_{k\in K\backslash\{s\}}\sum_{h\in D\backslash\{j\}}\left(T_{jhk} + B_{jhk}\right) + q_j, \forall j\in D \quad 27$$

$$t_v h_v n_{ijv} \le M_v s_{ijv}, \forall i\in P, \forall j\in P, j>i, \forall v\in V \quad 28$$

$$H_v s_{ijv} - w_v n_{ijv} \le H_{ij} s_{ijv}, \forall i\in P, \forall j\in P, j>i, \forall v\in V \quad 29$$

$$Q_v s_{ijv} + w_v n_{ijv} \le W_{ij} s_{ijv}, \forall i\in P, \forall j\in P, j>i, \forall v\in V \quad 30$$

$$m_{ikl} \le n^B_{ikl} + n^T_{ikl} \le M m_{ikl}\ , \forall i\in P\backslash\{0\}, k=s, l\in K\backslash\{k\}\ or \forall i\in D, \forall k\in K\backslash\{s\}, \forall l \in K\backslash\{s,k\} \quad 32$$

$$n^B_{ikl} = \sum_{j\in D} B_{ijl}\ , \forall i\in P\backslash\{0\}, k=s, \forall l\in K\backslash\{s\}\ or \forall i\in D, j\neq i, \forall k\in K\backslash\{s\}, \forall l \in K\backslash\{s,k\} \quad 33$$

$$n^T_{ikl} = \sum_{j\in D} T_{ijl}\ , \forall i\in P\backslash\{0\}, k=s, \forall l\in K\backslash\{s\}\ or \forall i\in D, j\neq i, \forall k\in K\backslash\{s\}, \forall l \in K\backslash\{s,k\} \quad 34$$

$$x_{ijv}\in\{0,1\}, \forall i\in P\backslash\{n\}, j=i+1, k=s\ or \forall i\in D\cup P, \forall j\in D, j\neq i, \forall k \in K\backslash\{s\} \quad 35$$

Table 3
Transportation distance between cities and ports by road transportation.

Distance (km)	Shanghai	Nanjing	Tongling	Jiujiang	Wuhan	Yichang	Chongqing	Yibin
Hefei	466	180	162	313	383	692	1268	1513
Hangzhou	177	279	308	505	721	1029	1606	1851
Nanchang	706	580	409	124	354	641	1218	1464
Changsha	1063	888	720	434	333	401	893	1109
Chengdu	1960	1674	1596	1364	1140	862	306	259
Guiyang	1801	1579	1432	1148	1042	837	375	474
Xiangyang	1061	775	734	542	313	250	796	1037
Jingdezhen	547	431	260	152	370	677	1223	1464
Xinyang	781	485	488	445	210	435	989	1224
Huangshan	407	271	143	330	550	861	1416	1651
Nanchong	1742	1446	1375	1156	939	653	176	316

Table 4
Transportation distance between cities and ports by rail transportation.

Distance (km)	Shanghai	Nanjing	Tongling	Jiujiang	Wuhan	Yichang	Chongqing	Yibin
Hefei	468	157	139	327	355	651	1204	1784
Hangzhou	159	256	322	584	757	1053	1606	1992
Nanchang	741	585	382	135	333	533	1209	1410
Changsha	1083	874	724	484	362	451	1040	1068
Chengdu	1976	1665	1647	1597	1180	899	302	276
Guiyang	2022	1886	1658	1411	1068	882	357	374
Xiangyang	1497	797	716	574	317	233	1003	1297
Jingdezhen	629	538	312	151	374	666	1610	1703
Xinyang	960	610	483	422	234	495	1048	1629
Huangshan	447	742	167	296	519	811	1364	1813
Nanchong	1837	1526	1508	1506	1010	693	165	487

Table 5
Distance, water depth, and vessel heights limit between adjacent ports along the Yangtze River.

Adjacent ports	Distance (km)	Water depth (m)	Vessel height limit (m)
Shanghai - Nanjing	128	12.5	68
Nanjing - Tongling	200	9	23
Tongling - Jiujiang	309	7	23
Jiujiang - Wuhan	251	5	23
Wuhan - Yichang	475	4.5	17
Yichang - Chongqing	648	4	17
Chongqing - Yibin	384	3.2	17

$$m_{ikl} \in \{0,1\}, n_{ikl}^{B} \in N, n_{ikl}^{T} \in N, \forall i \in P \backslash \{0\}, \forall k \in K, \forall l \in K \backslash \{k\} \tag{36}$$

$$s_{ijv} \in \{0,1\}, l_{ijv} \in \{0,1\}, c_{ijv} \in \{0,1\}, n_{ijv} \in N, n_{ijv}^{L} \in N, n_{ijv}^{C} \in N, \forall i \in P, \forall j \in P, j > i, \forall v \in V \tag{37}$$

$$B_{ijk} \in N, T_{ijk} \in N, b_{ijk} \in N, t_{ijk} \in N, \forall i \in D \cup P, \forall j \in D, j \neq i, \forall k \in K \backslash \{s\} \tag{38}$$

Formulation (1) minimizes the total cost, including the transportation cost, transshipment cost, bulk cargo containerization cost, load shedding cost, cargo damage, and storage cost. Constraints (2)–(5) calculate the transportation cost, including the freight transportation cost proportional to the amount of goods and the fixed cost of the means of transportation. Constraint (6) calculates the transshipment cost, which is proportional to the amount of goods involved in transshipment. Constraint (7) calculates the cost of bulk containerization, including the fixed costs of special equipment, operating costs proportional to the amount of cargo, and container usage costs. Constraint (8) calculates the cost of load shedding, including the fixed cost of the load-shedding equipment and the operating cost proportional to the amount of cargo. Constraint (9) calculates the cargo damage and storage cost, which are proportional to the amount of bulk cargo transported.

Constraint (10) guarantees that cargo can only be transported by the inland waterways between the two ports. Constraint (11) indicates that cargo can only be transported to inland cities by road or rail. Constraints (12)–(14) count the number of road and rail vehicles. Constraint (15) represents the limit of the ship's cargo capacity. Constraint (16) indicates that at most, one operation of bulk containerization or load shedding is performed when the ship sails to the port, and the container ship cannot carry out the bulk containerization operation. Constraint (17) ensures that the number of bulk cargo containerized cannot exceed the cargo capacity of the ship. Constraint (18) indicates that the number of cargos that a ship can unload cannot exceed the cargo capacity of the ship. Constraint (19) indicates that the employed vessels must sequentially pass the ports from downstream to upstream. Constraints (20) and (21) ensure the flow balance of the ship's cargo after bulk containerization or load-shedding operations at a port. Constraint (22) indicates that the quantity of cargos delivered from a seaport cannot exceed the total quantity of cargos. Constraints (23) and (24) guarantee the flow balance of the containerized cargo at the port. Constraints (25) and (26) guarantee the flow balance of bulk cargo at the port. Constraint (27) represents the flow balance of cargos in an inland destination city. Constraint (28) ensures that the containers loaded by the container ship do not obstruct the view of the cockpit when sailing. Constraint (29) ensures that the height of the vessel does not exceed the height limit of the bridges. Constraint (30) ensures that the ship's draught does not exceed the inland waterway depth. Constraints (31) and (32) determine whether the transshipment is conducted at a port. Constraints (33) and (34) calculate the number of cargos involved in transshipment. Constraints (35)–(38) define decision variables.

Table 7
Road and railway transportation and capacity parameters.

	f_k^B (CNY/km•container)	f_k^T (CNY/km•container)	F_k (CNY)	A_k
Road transportation	6	6	50	1
Rail transportation	4.1	4.1	140	2

Table 6
Relevant parameters of vessels.

Vessel index	Vessel type	G_v (container)	M_v (m)	H_v (m)	Q_v (m)	h_v (m)	w_v (m)	f_v (CNY/km • container)
1–5	Bulk carrier	100	0	5.5	2.9	0	0.005	0.68
6–10	Bulk carrier	150	0	6.5	3.3	0	0.00334	0.55
11–15	Bulk carrier	250	0	7.5	4	0	0.002	0.42
16–20	Bulk carrier	400	0	8.5	6	0	0.00125	0.32
21–25	Bulk carrier	500	0	9	6.3	0	0.001	0.29
26–30	Container Ship	41	6.5	7	2	0.1	0.0082	1.10
31–35	Container Ship	83	7	7.5	2.4	0.07	0.005	0.84
36–40	Container Ship	125	7.5	8	2.8	0.05	0.0026	0.76
41–45	Container Ship	208	8.5	9	4.5	0.034	0.002	0.53
46–50	Container Ship	291	9.5	10	6.3	0.0271	0.00114	0.38

Table 8
Unit transshipment cost (CNY).

	Inland waterway - Road	Inland waterway - Railway	Road - Railway
Bulk cargo	570	970	640
Container	57	97	64

4. Numerical experiments and extended models

This section presents the experiments conducted based on a near-practical case of the Yangtze River economic zone in China to evaluate the effectiveness of the mathematical model and the performance of cargo containerization.

4.1. Experimental setting

The experiments were conducted on a computer with an Intel Core i5-9300H CPU 2.40 GHz and 8.00 GB RAM under the Windows 10 operating system. The linear programming models were solved using IBM ILOG CPLEX 12.6.1, with a CPU time limit of 1 h for CPLEX. The Yangtze River is the inland river with the largest freight volume in the world. The important cities along this river include Shanghai, Nanjing, Tongling, Jiujiang, Wuhan, Yichang, Chongqing, and Yibin. As a result, they are selected as the multimodal transport ports. Besides, the customer cities with close economic links are Hefei, Hangzhou, Nanchang, Changsha, Chengdu, Guiyang, Xiangyang, Jingdezhen, Xinyang, Huangshan, and Nanchong. Therefore, we design the experiment according to the Yangtze River area with the multimodal ports and customer cities aforementioned. Shanghai Port is a seaport and is regarded as the hub port. Fig. 2 illustrates the locations of the ports and customer cities.

Table 3 and Table 4 show the transportation distances between the city and the port. Table 5 shows the distance, water depth, and ship height restrictions between two adjacent ports on the Yangtze River. There are 50 vessels available at each port. Let $g^F = 20$ (ton/container) and $g^W = 4$ (ton). The vehicle parameters are listed in Table 6 and Table 7, respectively. The transshipment cost coefficients for the different modes of transportation are listed in Table 8. The cargo demand in each customer city is listed in Table 9. In addition, we set $\lambda^{CE} = 50000$, $\lambda^C = 70$, $\lambda^{LE} = 400$, $\lambda^{BL} = 200$, $\lambda^{TL} = 70$, $\lambda^D = 40$, and $\lambda^U = 120$.

4.2. Experimental results and analysis

The objective value of the optimal solution obtained by CPLEX is 8.30384 million CNY, with a computational time of 297 s. The transportation cost is 5,627,810 CNY, transshipment cost is 333,900 CNY, bulk containerization cost is 1,445,180 CNY, load reduction cost is 657,360 CNY, and cargo damage and storage cost is 239,520 CNY. Fig. 3 shows the transport routes of the optimal solution, and Table 10 summarizes the detailed routes and cargo amounts in the solution. As Hangzhou is geographically close to Shanghai port, cargos are directly delivered by trains. Most cargos are delivered from Shanghai port to river ports by vessels and then transshipped from the river ports to customer cities by train. Moreover, Tongling, Jiujiang, and Yichang ports serve as transshipment ports in the solution, from where cargos are transshipped to other ports. One reason for this is that large bulk carriers or container ships cannot meet the navigation conditions in the middle and upper reaches of the Yangtze River. It is then necessary to transport the cargos to the middle and upper upstream ports of the river through small- and medium-sized vessels.

We can also see that the Shanghai, Jiujiang, and Yichang ports serve as depots for cargo containerization. For instance, Vessel 22 delivers 500 container units of bulk cargo from Shanghai port to Jiujiang port, where these cargos are containerized and continuously delivered to other midstream and upstream ports by container ships. In the solution, 500 container units of cargo are delivered from Shanghai port to Yichang port by bulk cargo vessels. This means that bulk cargo could still be economically viable in some cases. The main advantage of bulk cargo transportation is the lower unit transportation cost because of the higher space utilization of vessels compared with container vessels. The logistics company could then benefit from delivering bulk cargo to long-distance target ports for lower transportation costs, such as Tongling and Yichang ports. However, for relatively short distances, containers

Table 9
Demand for cargoes at customer cities (containers).

City	Cargo demand	City	Cargo demand	City	Cargo demand	City	Cargo demand
Hefei	853	Changsha	290	Xiangyang	432	Huangshan	109
Hangzhou	557	Chengdu	213	Jingdezhen	200	Nanchong	202
Nanchang	168	Guiyang	178	Xinyang	798		

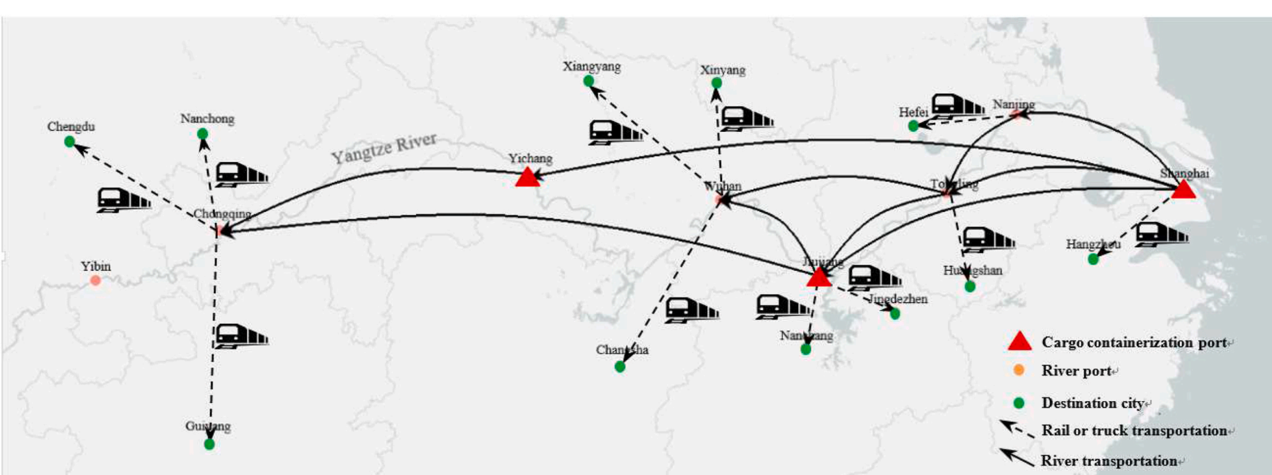

Fig. 3. Transport routes of the optimal solution from the MILC-L model.

Table 10
Detailed results of the optimal solution from the MILC-L model.

Transportation route	Transportation mode	Mode	Number of cargos transported (containers)
Shanghai → Jiujiang	Vessels 22, 24, 25	Bulk cargo	500, 500, 488
Shanghai → Yichang	Vessels 13, 14	Bulk cargo	250, 250
Shanghai → Nanjing	Vessels 46, 49	Container	291, 291
Shanghai → Tongling	Vessels 47, 50	Container	291, 291
Shanghai → Nanjing → Tongling → Jiujiang	Vessels 48	Container	Nanjing 271, Tongling 7, Jiujiang 13
Tongling → Wuhan	Vessels 41, 42, 45	Container	208, 64, 208
Jiujiang → Wuhan	Vessels 41-45	Container	208, 208, 208, 208, 208
Jiujiang → Chongqing	Vessels 38	Container	93
Yichang → Chongqing	Vessels 36, 37, 39, 40	Container	125, 125, 125, 125
Shanghai → Hangzhou	Railway	Bulk cargo	557
Nanjing → Hefei	Railway	Container	853
Tongling → Huangshan	Railway	Container	109
Jiujiang → Nanchang	Railway	Container	168
Jiujiang → Jingdezhen	Railway	Container	200
Wuhan → Changsha	Railway	Container	290
Wuhan → Xiangyang	Railway	Container	432
Wuhan → Xinyang	Railway	Container	798
Chongqing → Chengdu	Railway	Container	213
Chongqing → Guiyang	Railway	Container	178
Chongqing → Nanchong	Railway	Container	202

would be a more economical transportation mode when transshipment is involved. Hence, small- and medium-sized container vessels are mostly used as upstream ports or for short-distance transportation between two ports. Under these transportations, the capacity and cost advantages of bulk carriers are marginal for smaller vessels or short distances. When transporting from ports to inland customer cities, most of them choose railway transportation for lower transportation costs over long distances than trucks.

4.3. Comparison with the multimodal transportation network without containerization consideration

We simplified the MILPC-L model by setting the values of all decision variables related to containerization to 0. Let the simplified model be the MILPB-L. We aim to further evaluate the advantages of containerized bulk cargo in an intermodal network. Adjusted according to the mathematical model in Section 3, we remove the factors of bulk containerization and container transportation. The same values of the remaining parameters in Section 4.1 are used to run the MILPB-L model with CPLEX. In the obtained optimal solution, the total is 10,310,900 CNY, in which the transportation cost is 6,983,590 CNY, transshipment cost is 1,859,370 CNY, load shedding cost is 1,174,200 CNY, and cargo damage and storage cost is 293,760 CNY. Fig. 4 shows the transport route for the solution results. The results show that inland customer cities near the lower reaches of the Yangtze River transport goods directly by rail from Shanghai Port, such as Hangzhou, Huangshan, and Hefei. The ports of Jiujiang and Wuhan serve as transshipment ports. Bulk cargos are delivered from the Shanghai port to these ports, from which the cargos are transshipped to ports in the middle and upper reaches of the Yangtze River. For transportation from ports to customer cities, we find that rail transportation is usually employed when the city is far away from the port, whereas trucks are more popular when the distance is relatively short, such as Jiujiang to Nanchang and Chongqing to Nanchong. Table 11 lists the detailed routes obtained from the MILB-L model.

Fig. 5 shows a comparison of the detailed costs of the solutions obtained from the two models. Compared with the MILB-L model, the total cost has been reduced from 10.31 million CNY to 8.30 million CNY by the MILC-L model. First, because of the high unit transshipment cost of

Table 11
Detailed results of the MILB-L model.

Transportation route	Transportation mode	Number of bulk cargo (containers)
Shanghai → Jiujiang	Vessels 22, 24, 25	231,500,500
Shanghai → Wuhan	Vessels 16-19	250,250,250,250
Shanghai → Yichang	Vessels 20	250
Jiujiang → Wuhan	Vessels 17	20
Jiujiang → Chongqing	Vessels 11, 12, 14, 15	150, 150, 150, 143
Jiujiang → Wuhan → Yichang	Vessels 16	Wuhan 68, Yichang 182
Shanghai → Hangzhou	Railway	557
Shanghai → Hefei	Railway	853
Shanghai → Huangshan	Railway	109
Jiujiang → Nanchang	Road	168
Jiujiang → Jingdezhen	Road	200
Wuhan → Changsha	Railway	290
Wuhan → Xinyang	Road	798
Yichang → Xiangyang	Railway	432
Chongqing → Chengdu	Railway	213
Chongqing → Guiyang	Railway	178
Chongqing → Nanchong	Road	202

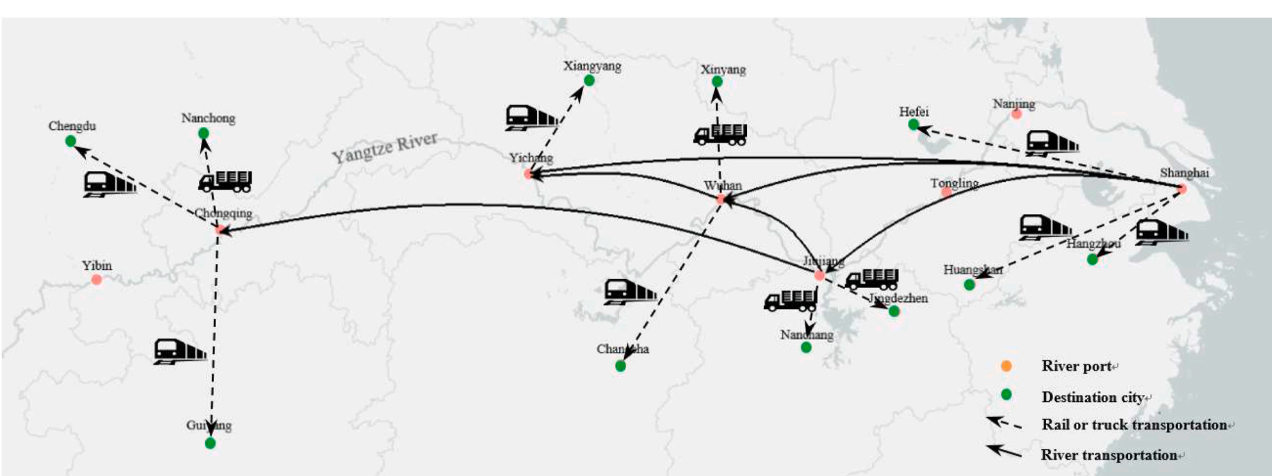

Fig. 4. Transport routs of the optimal solution from the MILB-L model.

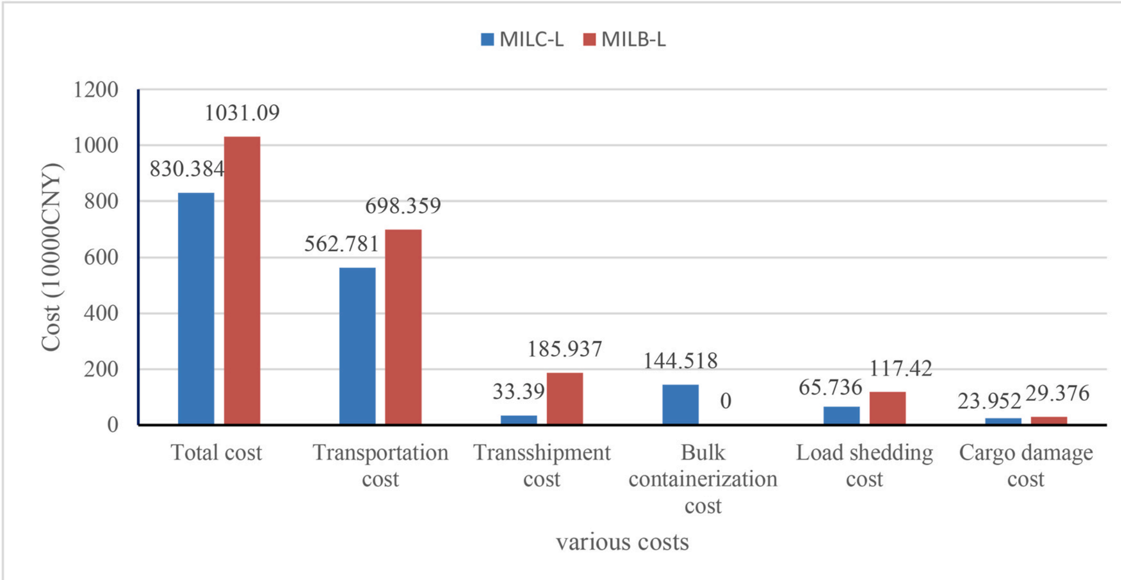

Fig. 5. The cost comparison between the solutions obtained from the MILC-L and MILB-L models.

bulk cargos, ports may select to directly deliver cargos to customer cities without transshipping at other ports. For instance, under the MILB-L model, bulk cargos are directly delivered from Shanghai port to Hefei and Huangshan by trains, which increases the transportation cost compared to the routes under the MILC-L model. Another reason could be the increased utilization of trucks in the MILB-L model. As the gap between the unit transshipment of cargos in bulk via waterway-railway and waterway-road is quite large, the logistics company employs more trucks under the MILB-L model to reduce the transshipment cost, which increases the transportation cost. Moreover, the transshipment costs decreased from 1.85 million CNY to 330,000 CNY. Even though the number of transshipments under the MILC-L model's solution is higher than that of the MILB-L model, the unit cost of transshipping a container could be lower than transshipping the same size of cargos in bulk, which would result in a lower total transshipment cost. Another significant reduction can be found in the cost of load shedding, from 1.17 million CNY to 660,000 CNY because the unit unloading cost of a full container (i.e., $\lambda^{TL} = 70$) is lower than the cost of the same size of cargos in bulk (i.e., $\lambda^{BL} = 200$).

4.4. Model extensions with other utility considerations

Both aforementioned models aim to minimize the total cost of the logistics company without considering the environmental and time-saving utility that might be interesting to governments and customers. Hence, we extended the models with these considerations to further analyze the cargo containerization performance.

4.4.1. Model extension from the government perspective

Based on the foregoing models, we modified the objective function to minimize carbon emissions, and let the models obtained from the MILC-L and MILB-L models be the MILC-G and MILB-G models, respectively. Carbon emissions are mainly generated during cargo transportation, transshipment, load shedding, and bulk containerization. These models may explain the decision making of state-owned logistics companies that focus on environmental utility. Table 12 lists the new notation for these extensions. Formulation (1) and Constraints (2)–(9) are rewritten as follows to obtain the BILC-G and MILB-G models.

$$\min\ E^{TRT} + E^{TRF} + E^{CON} + E^{LIT} \quad (39)$$

$$E^{TRT} = \sum_{i\in P\backslash\{n\}}\sum_{v\in V} N_{i,(i+1),v} d_{i,(i+1),s} E_v + \sum_{i\in D\cup P}\sum_{j\in D, j\neq i}\sum_{k\in K\backslash\{s\}} d_{ijk} f_k^E \left(B_{ijk} + T_{ijk}\right) \quad (40)$$

$$E^{TRF} = \sum_{l\in K\backslash\{s\}}\sum_{j\in D}\left(E_{sl}^B B_{0jk} + E_{sl}^T T_{0jk}\right) + \sum_{i\in P\backslash\{0\}}\sum_{l\in K\backslash\{s\}}\left(E_{sl}^B n_{isl}^B + E_{sl}^T n_{isl}^T\right) + \sum_{i\in D}\sum_{k\in K\backslash\{s\}}\sum_{l\in K\backslash\{s,k\}}\left(E_{kl}^B n_{ikl}^B + E_{kl}^T n_{ikl}^T\right) \quad (41)$$

$$E^{CON} = \sum_{v\in V} 2 t_v s_{01v} n_{01v} E^C + \sum_{k\in K\backslash\{s\}}\sum_{j\in D} 2 x_{0jk} T_{0jk} E^C + \sum_{i\in P}\sum_{j\in P, j>i}\sum_{v\in V} 2(1-t_v) c_{ijv} n_{ijv}^C E^C \quad (42)$$

Table 12
Notations in the MILC-G and MILB-G models.

E_v	The unit carbon emissions of the vessel v, $v \in V$ (unit: kg/km•container)
f_k^E	The unit carbon emissions of the transportation mode k, $k \in K\backslash\{s\}$ (unit: kg/km•container)
E_{kl}^B	The unit carbon emission of bulk cargo transferred from the transportation mode k to the transportation mode l, $k \in K$, $l \in K\backslash\{k\}$ (unit: kg/km•container)
E_{kl}^T	The unit carbon emission of the container transferred from the transportation mode k to the transportation mode l, $k \in K$, $l \in K\backslash\{k\}$ (unit: kg/km•container)
E^C	The unit carbon emission of bulk cargo containerization (unit: kg/km•container)
E^{BL}	The unit carbon emissions of bulk carrier load reduction (unit: kg/km•container)
E^{TL}	The unit carbon emissions of container ship load reduction (unit: kg/km•container)

Table 13
Carbon emission factors for various transportation modes.

Transportation mode	Unit carbon emission (kg/km•container)
Vessels 1–5	0.296
Vessels 6–10	0.196
Vessels 11–15	0.118
Vessels 16–20	0.074
Vessels 21–25	0.06
Vessels 26–30	0.98
Vessels 31–35	0.5
Vessels 36–40	0.331
Vessels 41–45	0.2
Vessels 46–50	0.142
Road	1.42
Railway	0.84

Table 14
Transshipment carbon emission factor (kg/container).

	Inland waterway - Road	Inland waterway - Railway	Road - Railway
Bulk	2.34	2.26	2.56
Container	1.8	1.8	1.8

Table 15
Detailed results of the MILC-G model.

Transportation route	Transportation mode	Mode	Number of cargos transported (containers)
Shanghai → Nanjing	Vessels 16–18	Bulk cargo	400, 400, 143
Shanghai → Tongling	Vessels 21,23	Bulk cargo	500, 500
Shanghai → Jiujiang	Vessels 22,24	Bulk cargo	500, 500
Shanghai → Tongling → Jiujiang	Vessels 25	Bulk cargo	Tongling 132, Jiujiang 368
Nanjing → Tongling	Vessels 22,25	Bulk cargo	80, 363
Nanjing → Tongling → Jiujiang	Vessels 24	Bulk cargo	Tongling 250, Jiujiang 250
Tongling → Wuhan	Vessels 11	Bulk cargo	250
Tongling → Yichang	Vessels 13	Bulk cargo	250
Tongling → Wuhan → Yichang	Vessels 12	Bulk cargo	Wuhan 158, Yichang 92
	Vessels 15	Bulk cargo	Wuhan 112, Yichang 1
Jiujiang → Wuhan	Vessels 11,13–15	Bulk cargo	250, 250, 250, 250
Jiujiang → Yichang	Vessels 12	Bulk cargo	250
Yichang → Chongqing	Vessels 6–8,10	Bulk cargo	150, 150, 150, 143
Shanghai → Hangzhou	Rail	Container	557
Tongling → Hefei	Rail	Container	853
Tongling → Huangshan	Rail	Container	109
Jiujiang → Nanchang	Rail	Container	168
Jiujiang → Jingdezhen	Rail	Container	200
Wuhan → Changsha	Rail	Container	290
Wuhan → Xiangyang	Rail	Container	432
Wuhan → Xinyang	Rail	Container	798
Chongqing → Chengdu	Rail	Container	213
Chongqing → Guiyang	Rail	Container	178
Chongqing → Nanchong	Rail	Container	202

$$E^{LIT} = \sum_{v\in V}(1-t_v)s_{01v}n_{01v}E^{BL} + \sum_{k\in K\setminus\{s\}}\sum_{j\in D}x_{0jk}B_{0jk}E^{BL} \quad 43$$

$$+\sum_{i\in P}\sum_{j\in P,j>i}\sum_{v\in V}l_{ijv}n^{L}_{ijv}\left((1-t_v)E^{BL}+t_vE^{TL}\right)$$

Formulation (39) indicates the minimization of the total carbon emissions, where E^{TRT} represents the carbon emissions generated during the transportation of cargos, the value of which is calculated using Equation (40). E^{TRF} represents the amount of carbon emissions, and its value is calculated using Equation (41). E^{CON} represents the carbon emissions from bulk containerization, and its value is calculated using Equation (42). E^{LIT} represents the carbon emissions from load shedding, and its value is calculated using Equation (43). Table 13 and Table 14 show the carbon emission coefficients of the different vehicles and transshipments, respectively. We set $E^{C} = 0.8$, $E^{BL} = 1.2$, $E^{TL} = 0.5$.

Table 16
Detailed results of the MILB-G.

Transportation route	Transportation mode	Number of bulk cargo (containers)
Shanghai → Nanjing	Vessels 16–18	400, 400, 143
Shanghai → Tongling → Jiujiang	Vessels 21	Tongling 250, Jiujiang 250
	Vessels 22	Tongling 250, Jiujiang 250
	Vessels 23	Tongling 250, Jiujiang 250
	Vessels 24	Tongling 250, Jiujiang 250
	Vessels 25	Tongling 250, Jiujiang 250
Nanjing → Tongling	Vessels 23	75
Nanjing → Tongling → Jiujiang	Vessels 21	Tongling 250, Jiujiang 250
	Vessels 22	Tongling 250, Jiujiang 250
Tongling → Wuhan	Vessels 11,12	250, 145
Tongling → Wuhan → Yichang	Vessels 14	Wuhan 125, Yichang 125
	Vessels 15	Wuhan 125, Yichang 93
Jiujiang → Wuhan	Vessels 12,15	250, 250
Jiujiang → Wuhan → Yichang	Vessels 11	Wuhan 125, Yichang 125
	Vessels 13	Wuhan 125, Yichang 125
	Vessels 14	Wuhan 125, Yichang 125
Yichang → Chongqing	Vessels 7–10	150, 143, 150, 150
Shanghai → Hangzhou	Railway	557
Tongling → Hefei	Railway	853
Tongling → Huangshan	Railway	109
Jiujiang → Nanchang	Railway	168
Jiujiang → Jingdezhen	Railway	200
Wuhan → Changsha	Railway	290
Wuhan → Xiangyang	Railway	432
Wuhan → Xinyang	Railway	798
Chongqing → Chengdu	Railway	213
Chongqing → Guiyang	Railway	178
Chongqing → Nanchong	Railway	202

By solving the MILC-G and MILB-G models, we obtain the corresponding carbon emissions and transportation routes. Table 15 and Table 16 show the detailed routes of the optimal solutions of these two models. According to the new parameters in Tables 13 and 14, we can also obtain the carbon emissions of the transportation solutions from the MILC-L and MILB-L models. Fig. 6 shows the detailed costs and carbon emissions of the optimal solutions from these four models. Undoubtedly, the MILC-G (MILB-G) model outperforms the MILC-L (MILB-L) model in terms of carbon emissions reduction because the former aims to minimize carbon emissions, while the latter focuses on the total cost. If we use the MILB-C model's solution as a benchmark, then we can see that the carbon emission decreased from 1584.43 tons to 1323.02 tons, while the total cost also has a significant reduction. When comparing the MILC-G and MILB-G models, we find that containerization technology can also simultaneously result in lower carbon emission and a lower total cost than traditional bulk cargo transportation when the target is to minimize carbon emissions. Therefore, we can conjecture that this technology could be useful for governments to incentivize logistics companies to make efforts to improve their environmental utility.

We define β as the weighted value of total cost and carbon emissions. Then, we obtain a new objective function as $\min \beta(C^{TRT} + C^{TRF} + C^{CON} + C^{LIT} + C^{DAM}) + (1-\beta)(E^{TRT} + E^{TRF} + E^{CON} + E^{LIT})$

By using this objective function with Constraints (2)–(38) and Constraints (40)–(43), we can obtain a new model wherein the value of β is limited to within the range of [0, 1]. This new model can also be simplified if we set the values of all decision variables related to containerization to 0. For each of these two models, we obtain different solutions for different values of β. A higher β is associated with an optimal solution that pays more attention to cost reduction, whereas a smaller β with such a solution pays more attention to carbon reduction. For each obtained solution, we calculate the original corresponding total cost and carbon emissions without considering β and obtain the Pareto frontier of the containerization technology, as shown in Fig. 7. For the same level of one target (e.g., carbon emission reduction), the implementation of containerization technology can always lead to better performance of the other target (e.g., total cost saving). Consequently,

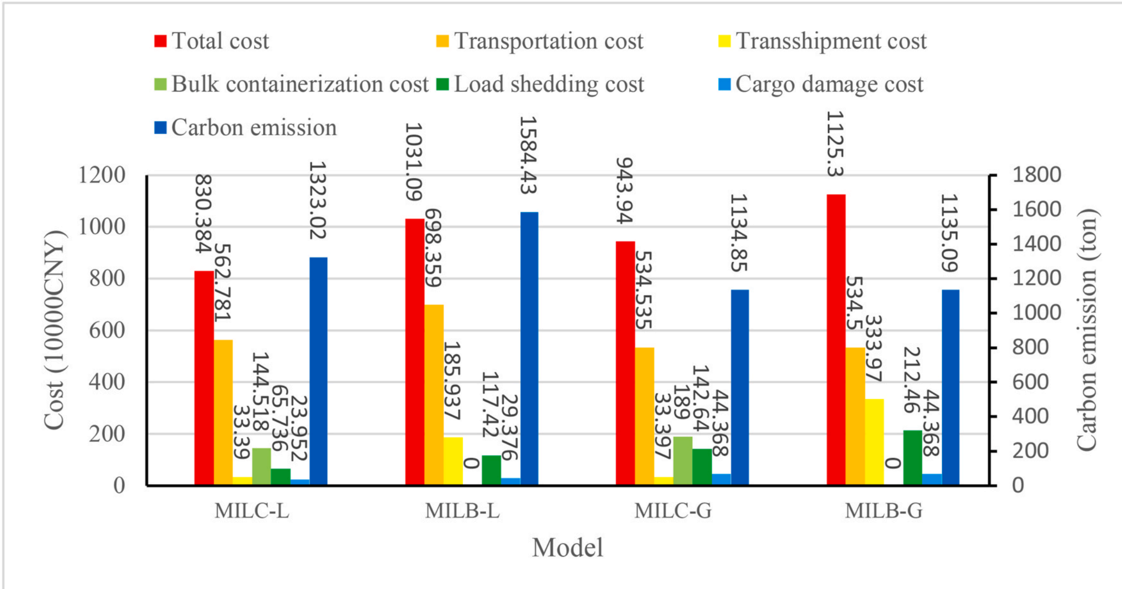

Fig. 6. The cost and carbon emissions comparison between the solutions obtained from the four models.

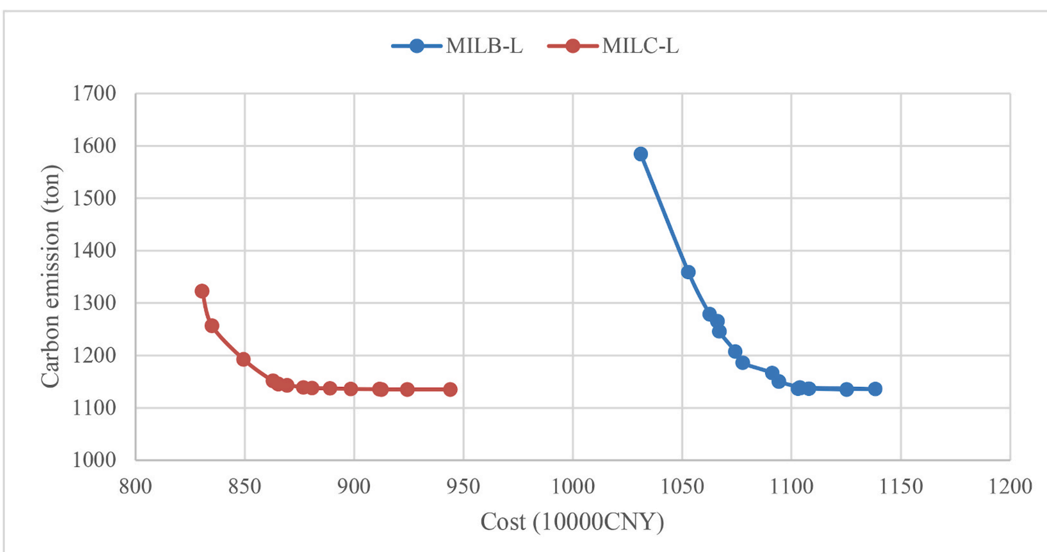

Fig. 7. Pareto-frontier of the containerization technology in terms of total cost and carbon emission.

Table 17
Symbol definitions introduced by time models.

S_v	The speed of the vessel v, $v \in V$ (unit: km/h)
S_k	The speed of the transportation mode k, $k \in K \backslash \{s\}$ (unit: km/h)
t^B_{kl}	The unit transit time of bulk cargo transferred from the transportation mode k to the transportation mode l, $k \in K$, $l \in K \backslash \{k\}$ (unit: h/container)
t^T_{kl}	The unit transit time of the container transferred from the transportation mode k to the transportation mode l, $k \in K$, $l \in K \backslash \{k\}$ (unit: h/container)
t^C	The unit time of bulk cargo containerization (unit: h/container)
t^{BL}	The unit time for load shedding of bulk carriers (unit: h/container)
t^{TL}	The unit time for load shedding of a container ship (unit: h/container)

we conjecture that this technology may improve the utilities of both logistics companies and governments compared with traditional bulk cargo transportation.

4.4.2. Model extension from the customer perspective

By using the method described in the previous subsection, we can analyze how containerization technology influences the customers or cargo owners who are more concerned about the total logistics time and cargo damage. Let the models obtained from the MILC-L and MILB-L models be the MILC-C and MILB-C models, respectively. These models may explain the decision making of logistics companies owned by cargo owners. Table 17 lists the relevant notations. Note that this extension did not include the time savings discussed in Section 3, which are uncertain

Table 18
Speed for each transportation mode.

Transportation mode	Speed(km/h)
Vessels 1–25	20
Vessels 26–50	30
Road	80
Rail	60

Table 19
Time factor for cargo transshipment (h/container).

	Inland waterway - Road	Inland waterway - Railway	Road - Railway
Bulk	0.2	0.2	0.2
Container	0.05	0.05	0.05

in the real world. Formulation (1) and Constraints (2)–(9) can be rewritten as follows.

$$\min t^{TRT} + t^{TRF} + t^{CON} + t^{LIT} \tag{44}$$

$$t^{TRT} = \sum_{i\in P\backslash\{n\}}\sum_{v\in V} s_{i,(i+1),v} d_{i,(i+1),s}\frac{1}{S_v} + \sum_{i\in D\cup P}\sum_{j\in D, j\neq i}\sum_{k\in K\backslash\{s\}} x_{ijk} d_{ijk}\frac{1}{S_k} \tag{45}$$

$$t^{TRF} = \sum_{l\in K\backslash\{s\}}\sum_{j\in D}\left(t_{kl}^B B_{0jk} + t_{sl}^T T_{0jk}\right) + \sum_{i\in P\backslash\{0\}}\sum_{l\in K\backslash\{s\}}\left(t_{sl}^B n_{isl}^B + t_{sl}^T n_{isl}^T\right) + \sum_{i\in D}\sum_{k\in K\backslash\{s\}}\sum_{l\in K\backslash\{s,k\}}\left(t_{kl}^B n_{ikl}^B + t_{kl}^T n_{ikl}^T\right) \tag{46}$$

$$t^{CON} = \sum_{v\in V} 2t_v s_{01v} n_{01v} t^C + \sum_{k\in K\backslash\{s\}}\sum_{j\in D} 2x_{0jk} T_{0jk} t^C + \sum_{i\in P}\sum_{j\in P, j>i}\sum_{v\in V} 2(1-t_v) c_{ijv} n_{ijv}^C t^C \tag{47}$$

$$t^{LIT} = \sum_{v\in V}(1-t_v) s_{01v} n_{01v} t^{BL} + \sum_{k\in K\backslash\{s\}}\sum_{j\in D} x_{0jk} B_{0jk} t^{BL} + \sum_{i\in P}\sum_{j\in P, j>i}\sum_{v\in V} l_{ijv} n_{ijv}^L\left((1-t_v)t^{BL} + t_v t^{TL}\right) \tag{48}$$

Formulation (44) indicates the minimization of the total logistics time, where t^{TRT} represents the time for the transportation of cargos, the value of which is calculated using Equation (45). t^{TRF} represents the transshipment time, and its value is calculated using Equation (46). t^{CON} represents the time of bulk containerization, and its value is calculated using Equation (47). t^{LIT} represents the load shedding time, and its value is calculated using Equation (48). Table 18 and Table 19 show the time coefficient of different vehicles, and transshipment, respectively. We set, $t^C = 0.05$, $t^{BL} = 0.2$, $t^{TL} = 0.02$.

Table 20 and Table 21 show the detailed routes obtained from the MILC-C and MILB-C models, respectively, based on which the corresponding total time and costs can be calculated. According to the new parameters in Tables 18 and 19, we can also obtain the total cost of transportation solutions from the MILC-L and MILB-L models. Fig. 8 shows the detailed costs and transportation times of the optimal solutions from these four models. Undoubtedly, the MILC-C (MILB-C) model outperforms the MILC-L (MILB-L) model in terms of total time reduction because the former model aims to minimize the total time, whereas the latter focuses on the total cost. However, it is surprising that MILC-L outperforms MILB-C in terms of both time-saving and cost reduction. This means that even if the MILC-L model aims to minimize the total cost, the optimal plan also results in a shorter time than that obtained from the MILB-C, which aims to minimize the time without containerization technology.

Table 20
Detailed results of the MILC-C.

Transportation route	Transportation mode	Mode	Number of cargos transported (containers)
Shanghai → Hangzhou	Road	Container	557
Shanghai → Hefei	Road	Container	853
Shanghai → Huangshan	Road	Container	109
Shanghai → Nanchang	Road	Container	168
Shanghai → Jingdezhen	Road	Container	200
Shanghai → Changsha	Road	Container	290
Shanghai → Xiangyang	Road	Container	432
Shanghai → Xinyang	Road	Container	798
Shanghai → Chengdu	Road	Container	213
Shanghai → Guiyang	Road	Container	178
Shanghai → Nanchong	Road	Container	202

Table 21
Detailed results of the MILB-C.

Transportation route	Transportation mode	Number of bulk cargo (containers)
Shanghai → Hefei	Road	853
Shanghai → Hangzhou	Road	557
Shanghai → Huangshan	Road	109
Shanghai → Nanchang	Road	168
Shanghai → Jingdezhen	Road	200
Shanghai → Changsha	Road	290
Shanghai → Xiangyang	Road	432
Shanghai → Xinyang	Road	798
Shanghai → Chengdu	Road	213
Shanghai → Guiyang	Road	178
Shanghai → Nanchong	Road	202

We define γ as the weighted value of total cost and carbon emissions. Then, we obtain a new objective function as $\min \gamma(C^{TRT} + C^{TRF} + C^{CON} + C^{LIT} + C^{DAM}) + (1-\gamma)(t^{TRT} + t^{TRF} + t^{CON} + t^{LIT})$

By using this objective function with Constraints (2)–(38) and Constraints (45)–(48), we obtain a new model wherein the value of γ is limited within the range of [0, 1]. Similar experiments and analyses of β can be conducted here, and a smaller γ is associated with an optimal solution that pays more attention to the total logistics time. We also obtain the Pareto frontier of the containerization technology in terms of the total logistics time and total cost, as shown in Fig. 9. For the same level of one target (e.g., total logistics time reduction), the implementation of containerization technology can always lead to better performance of the other target (e.g., total cost saving). Consequently, we conjecture that this technology may improve the utilities of both logistics companies and customers compared to traditional bulk cargo transportation.

5. Discussion, policy suggestions, and conclusions

5.1. Limitations of the containerization

Even if containerization has several advantages in terms of cost, environment, and time saving, we can still notice that this transportation mode is not ubiquitous in the real world. The limitations can be found in the following aspects.

First, the cost related to containerization should be reduced. One of the costs is associated with the fixed cost of containerization facilities. Ports and customers may need to install facilities to containerize cargos and unpack containers. This cost can be apportioned to each container and could be small if the number of containerizations by that facility is large. In current practice, however, the market scale of containerization is not large, which results in a high apportioned cost for each container. The other type of cost is empty container usage cost. The logistics company needs to supply empty containers to load bulk cargo associated with container purchases, rentals, or repositioning fees.

Second, it is not easy for governments to exactly evaluate environmental contributions and promote the implementation of containerization technologies. Containerization could increase environmental utility

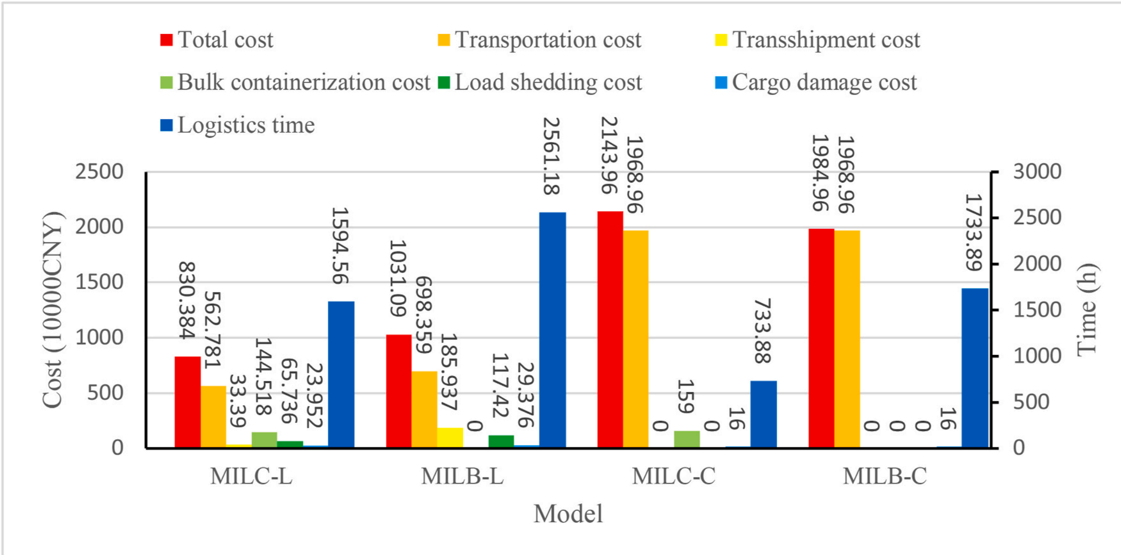

Fig. 8. The cost and logistics time comparison between the solutions obtained from the four models.

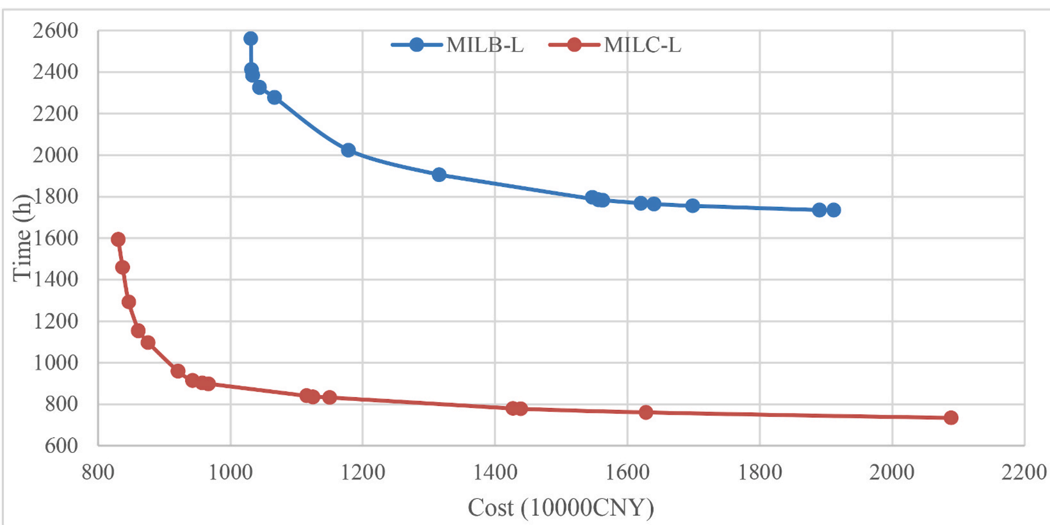

Fig. 9. Pareto-frontier of the containerization technology in terms of total cost and logistics time.

by reducing carbon emissions during cargo loading and unloading processes because of the high efficiency of container operation. Compared with this energy consumption saving and the corresponding carbon emission reduction, the performance of pollution prevention is more difficult to evaluate. For instance, containerization can significantly reduce cargo (e.g., iron ore and coal) spilling onto earth and water. Prevention of grain crop spilling can also reduce the risk of biological invasion and gene contamination. The utility of the foregoing contributions could be important but difficult to evaluate quantitatively. In addition, logistics companies usually aim to receive higher profits that may have a trade-off with environmental utility. Even though containerization technology might lead to a better Pareto frontier for these two targets, logistics companies may select a transportation plan to minimize their own costs, which may fail to improve environmental utility.

Third, it is still not clear how customers who benefit from containerization join the game. As discussed, containerization could shorten logistics time and reduce cargo damage during transportation. The former can reduce the lead time of inventory replenishment and the in-transit inventory level of customers, which may reduce inventory management costs. In practice, however, the containerization efforts of logistics companies might fail to be appreciated by customers. One main reason is that the logistics management departments of customers focus on the service fee charged by logistics companies, whereas inventory control is the responsibility of other departments. Moreover, it may also be challenging for customers to quantitatively evaluate the improvement in the overall performance from containerization. For example, in addition to containerization, time-saving may also result from weather and traffic conditions. Consequently, logistics companies may not be incentivized by the market to implement containerization technologies.

5.2. Policy suggestions

Based on the foregoing discussion, we provide the following policy suggestions for better implementation of containerization technology in multimodal transportation networks for bulk cargo. These suggestions also imply several future research directions that could be fruitful.

First, governments may find it helpful to invest in cargo containerization facilities at depots to reduce logistics companies' costs. This policy may also share the risk of depots and logistics companies facing uncertainty in the market scale of containerization. Moreover, empty containers are repositioned to meet the container demands of exporters in hinterland areas. This empty container flow may have the same delivery direction as bulk cargo. If cargo containerization can use those repositioned empty containers and share the same trips, then the usage cost of containers and transportation cost for containerization can be significantly reduced. However, it is challenging for individual logistics companies to meet containerization demands and empty container repositioning, which requires a comprehensive collection of market information. Therefore, it would be better for governments to encourage information sharing among logistics companies or develop third-party platforms that match the two sides.

Second, governments must propose tailored policies to incentivize logistics companies to conduct containerization for higher environmental utility. Big data analytics technology can be applied to quantitatively analyze pollution reduction per unit containerization. Based on the obtained relationship, governments can design a subsidy scheme for containerization that is measured by the number of fulfilled containers. The efforts of logistics companies are then appreciated and rewarded. Considering the diffusion of spilling cargos via air and water, the central government needs to pay attention to the sharing of subsidy supplies among local governments. As areas without ports and transshipment operations also benefit from pollution emission reduction, it would be better for the government to join the subsidy scheme.

Third, new supply chain contracts could be helpful for customers in promoting the implementation of containerization. Customers may include logistics time in their business contracts with logistics companies. The contract may also offer monetary incentives to logistics companies for a unit decrease in cargo loss during logistics. Logistics companies may find it more beneficial to shorten the total logistics time and reduce cargo loss by using containerization. Moreover, the new supply chain mode could be fruitful under tailored supply chain contracts. For instance, logistics companies can enjoy a lower price from empty container suppliers by signing a long-term contract with them. In this case, however, the risk to logistics companies would also be high because of the uncertainty in customer demand. If customers would like to share the risk of the logistics companies with supply chain contracts (e.g., target-rebate contract, revenue-sharing contract, and buy-back contract), then the supply chain can be coordinated and a win-win relationship between customers and logistics companies can be achieved.

6. Conclusions

This study investigated how the introduction of bulk cargo containerization technology influences the performance of the multimodal transport network and the utility of different stakeholders. We show that the decision framework of a logistics company can be expressed using an MILP model. Compared to the meta-heuristic algorithms such as genetic algorithm, the solution method using MILP model as in this research can provide optimum solutions if the solution time is acceptable. However, one disadvantage of this method is that the solving time will increase significantly as the instance size increases usually. Such a model would be a decision-support tool for logistics companies to find a good transportation plan with containerization considerations. It is also easy to extend the model to solve problems in the interests of governments and customers.

From the perspective of logistics companies, the introduction of bulk containerization technology into multimodal transport networks can reduce the total logistics cost under certain conditions of unit containerization cost, unit transshipment cost, and unit container usage cost. Compared with the delivery of all cargos in bulk, containerized cargos may involve more transshipment at ports that reduce the scale of road and railway transportation. Thus, the overall cost can be decreased because of the high cost-efficiency of shipping.

In addition to monetary benefits, containerization technology can also improve utility in terms of the environment and service time. First, a high leakproof level of containers can reduce the amount of cargo spilling during transportation and transshipment. Next, although the number of transshipments could be higher with containerization, the total carbon emissions can be decreased owing to the lower emissions per unit of transshipment and less truck transportation. Third, containerization can shorten the logistics cycle time because of the higher robustness of transshipment operations to weather conditions, higher efficiency in transshipment operations, and the priority of container ships on the right-of-way at navigation locks. Therefore, the public, as well as customers, can benefit from the implementation of containerization technology in hinterland logistics networks.

6.1. Directions of future study

We would like to suggest several directions of future study on the cargo containerization. First, the amount of cargo containerization is influenced by the green performance of vessels. As more and more emission control areas have been established on waterways, the scrubbers would be helpful to reduce the pollutant emission of vessels that may promote the utilization of cargo containerization. Hence, it would be fruitful to explore how the installation of scrubbers influence the cargo containerization. Second, the utilization of the cargo containerization technology may influence the benefits of different stakeholders in supply chains, such as logistics companies, customers, and governments. Therefore, it would be interesting to develop game models of these stakeholders by considering this technology in the shipping market. Third, permanent modification of bulk cargo's vehicles to deliver containers may fail to prove efficient in the real world. The demand of the containerization can be variable that may not deserve a permanent increment of the container vehicle capacity. As a consequence, we would like to suggest the trip sharing strategy under which the bulk cargo transportation and the empty container repositioning are combined to save the costs of both sides.

Data availability

Data will be made available on request.

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