Intermodal transportation hub location optimization with governments subsidies under the Belt and Road Initiative

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ABSTRACT

Driven by globalization, the COVID-19 outbreak has severely impacted global transport and logistics systems. To better cope with this globalization crisis, the Belt and Road Initiative (BRI)—based on the concept of cooperation—is more important than ever in the post-pandemic era. Taking the BRI as the background, we design an intermodal hub-and-spoke network to provide reference for governments along BRI routes to improve their cross-border transportation system and promote economic recovery. In the context of the BRI, local governments at different nodes have incentives to subsidize hub construction and/or rail transportation to boost economic development. We consider co-opetition behavior among different levels of government caused by subsidies in this intermodal hub location problem, which we call the intermodal hub location problem based on government subsidies. We establish a two-stage mixed-integer programming model. In the first stage, local governments provide subsidies, then the central government decides the number and location of hubs. In the second stage, freight carriers choose the optimal route to transport the goods. To solve the model, we design an optimization method combining a population-based algorithm using contest theory. The results show that rail subsidies are positively correlated with construction subsidies but are not necessarily related to the choice of hubs. Compared with monomodal transportation, intermodal transportation can reduce costs more effectively when there are not too many hubs and the cost of different modes of transportation varies greatly. The influences of local government competition and hub construction investment on network design and government subsidies are further examined.

1. Introduction

The COVID-19 pandemic was unprecedented in its intensity and geographical scope and heavily impacted global transport and logistics systems. It led to a slowdown in international trade, reducing demand and port throughput. Compared with the pre-COVID-19 era, the volume of cargo and vessel traffic both showed negative growth (Narasimha et al., 2021). Due to the lockdown caused by the pandemic, cargo volume in Shanghai rapidly turned negative in the second quarter of 2022 from positive growth in the first quarter.[1] Esben Poulsson, chairman of the International Chamber of Shipping (ICS), also predicted that global shipping volumes could fall another 30% in the following months.[2]

A fundamental reason for the rapid spread of the pandemic is globalization. Authorities pursued various degrees of lockdown from the early stages of the pandemic, further worsening the global economy. It

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has long been important to understand the threats arising from globalization (disease, war, financial crises, etc.) and to face them head on, not by ending the benefits of globalization but by using international cooperation to control the negative consequences of global-scale interconnectedness (Sachs, 2020). This makes international initiatives based on cooperation, represented by the Belt and Road Initiative (BRI),[3] more important than ever. In fact, the BRI has played an important role in transporting supplies to fight against the pandemic. Since the beginning of the COVID-19 pandemic, trade between China and countries participating in the BRI has increased rather than decreased. Given that the container transport system is a complex network of ports, Guerrero et al. (2022) pointed out that most ports lost connectivity between 2019 and 2020. Yet links between Asian ports, and those between Asia and the rest of the world, have been more resistant, and in some cases have even increased their trading volume.

Nevertheless, the pandemic has continued to cause congestion and inefficiency at transportation *hubs* around the world, increasing the risk of supply chain disruptions and volatility in the transportation market. At the beginning of 2021, the American West Coast ports such as Los Angeles and Long Beach experienced a sharp drop in productivity and severe congestion due to labor shortages. Until the understaffing problem is solved, shipping companies will have to bypass the most congested ports, such as Los Angeles, Singapore and Rotterdam, in the hope of moving shipments to less congested terminals. This highlights the importance of the hub location problem in responding to the pandemic. If we can use the features of the BRI to further strengthen coordination among transportation nodes and optimize the network layout, this may help stabilize supply chains and facilitate global economic recovery. Therefore, the first problem we study is hub location, which is also a fundamental issue of the BRI.

The BRI aims to enhance connectivity between Asia, Europe and Africa for mutual benefit via joint economic development. For instance, the BRI provides a means of rapid transportation to fulfill the energy demands of China and Pakistan, as well as additional economic indicators to boost employment opportunities, promote economic growth and improve welfare (Ullah et al., 2021). By the end of 2021, countries along "the belt" (overland corridors) and "the road" (maritime corridors), such as Russia, Germany, Mongolia and Pakistan, had opened more than 356 international transport routes and had formed six economic corridors.[4] A number of measures are in place to ensure smooth cooperation among countries, such as multilateral mechanisms (G12, APEC, etc.), financial integration (AIIB, PPP, etc.) and intergovernmental cooperation agreements.[5]

However, there are still challenges to cross-border logistics collaboration. Apart from the low level of logistics informatization, major problems along the various corridors of the BRI include inadequate infrastructure and disorderly competition. As shown in Fig. 1, "the belt" (overland corridors denoted by orange lines) and "the road" (maritime corridors denoted by blue lines) are geographically independent of each other. Each transport corridor is connected by hubs (port hubs, railway hubs and combined port/railway hubs known as multimodal hubs) in different countries. A hub is an important node for cargo distribution

and transshipment. As Fig. 1 exhibits, the number of multimodal hubs outside of China is small. Without a unified plan, it is difficult to complete a transshipment from "the belt" to "the road" and vice versa. This hinders the development of efficient and convenient *intermodal transportation*[6] systems. To encourage intermodal transportation, governments in the developed economies of Europe and the United States, and also the Chinese government, have begun to subsidize infrastructure construction and transportation processes (e.g., containerization, transshipment, rail transport). Local government subsidies create competition among local governments and affect how the central government designs the transportation network.[7] This brings us to the second question of government subsidies.

Competition among local governments remains fierce due to *channel encroachment* and *line encroachment*. Channel encroachment refers to competition between different modes of transportation, i.e., "the belt" (railway) and "the road" (maritime), due to different transportation costs and routes. In general, the cost of railway transportation is more than twice that of maritime transportation (ARVIEM, 2018). To attract goods from "the road," i.e., the shipping market, local governments have started to heavily subsidize railway transportation (Barrow, 2018; EDB, 2018). Intuitively, the location of a hub may vary depending on the size of such rail subsidies. Line encroachment is competition between different rail lines within China's Railway Express (CR Express) network caused by inconsistent government subsidies and unreasonable rail line planning. CR Express price competition has gradually morphed into subsidy competition among local governments, as they look to shift more cargo onto their own railways, leaving railway carriers heavily dependent on subsidies. Still, since 2018, the Chinese central government has required local governments to annually reduce their subsidies for CR Express.[8] This has caused panic in the rail industry, which relies heavily on these subsidies. While there is competition among local governments, the overall goal of network design is to minimize overall social spending. This requires collaboration between central and local governments. We examine the influence of co-opetition behavior between central and local governments due to subsidies for hub location and intermodal transportation. We also study the efficiency of intermodal transportation as a way to improve overall social welfare compared with monomodal[9] transportation networks.

Combined with the above practical problems, our research addresses the following research questions:

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[3] This is an open and inclusive economic cooperation initiative proposed by the Chinese government and a global public good jointly created by all parties. For more details, please refer to https://eng.yidaiyilu.gov.cn/.

[4] By March 2020, 138 countries had joined the BRI by signing a Memorandum of Understanding. For the participating countries and BRI documents, please refer to https://www.green-bri.org/countries-of-the-belt-and-road-initiative-bri/and https://eng.yidaiyilu.gov.cn/info/iList.jsp?cat_id=10066. The Silk Road originated in ancient China. For more information on the history of the Silk Road, please refer to http://www.silk-road.com/artl/silkhistory.shtml.

[5] Please refer to https://www.yidaiyilu.gov.cn/wcm.files/upload/CMSydylgw/201904/201904220254037.pdf.

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[6] A means of transport in which goods are carried from end to end by a single and unchanging unit or road vehicle, seamlessly connected by two or more modes of transportation, and in which no handling of the goods occurs during the change of modes of transportation. This is the trend that integrates the BRI, forming a complete intermodal transportation network. However, container sea–rail/rail–rail combined transportation is currently encountering many technical bottlenecks in China. There has not yet been any relevant guidance on transfer locations under intermodal transportation.

[7] The BRI is a top-level cooperation initiative between countries. As an important part of the BRI, infrastructure construction in the form of transportation hubs is the key to changing the way goods are transported and distributed across Eurasia. Such construction is generally planned holistically by the central government, or by a coalition of countries. For more details, please refer to https://lot.dhl.com/5-transport-hubs-paving-the-way-for-the-belt-and-road-initiative/.

[8] The purpose of constructing the CR Express is to reduce the cost of international logistics and promote economic exchanges. CR Express trains are allowed to load/unload goods at various stations along BRI rail routes. To stimulate demand, the Chinese government typically provides large subsidies to encourage the use of rail links. However, a high level of subsidy is not sustainable over the long term. For more details, please refer to https://goodhopefreight.com/china-railway-express.html and https://cbk.bschool.cuhk.edu.hk/the-rise-of-rail-along-chinas-belt-and-road/.

[9] A mode of transportation in which goods are delivered to their destination using a single mode of transportation.
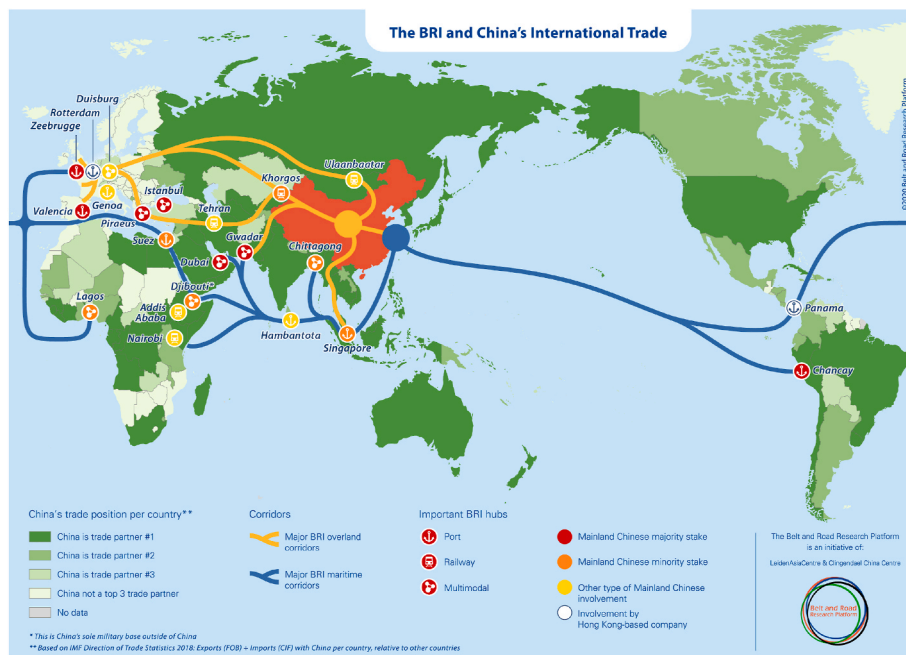
Fig. 1. Routes of the B&R.

1. How can cross-border hub locations be rationally planned to minimize social expenditure?
2. How should governments provide subsidies for hub construction and rail transportation?
3. Is an intermodal network always more efficient than a monomodal network?

In this paper, we propose a new hub location model that considers intermodal transportation and government subsidies. We also consider the co-opetition relationship between two levels of government (local government at each node and central government) in the context of the BRI. The objective of the model is to minimize total social expenditure (excluding government subsidies) borne by private entities, including transportation costs, transshipment costs and hub construction costs. This is a two-stage model. In the first stage, the local and central governments decide on subsidies and hub locations, respectively. To describe the connections between subsidies and hub locations, we propose a novel representation of the influence of subsidy competition between local governments on hub locations based on contest theory. In the second stage, with a given network and subsidies, carriers choose the optimal route and mode to transport the goods. This is a general intermodal transportation issue. Thus, to solve the two-stage model, we design an optimization method combining contest theory with a heuristic algorithm. We also explore the impacts of intergovernmental competition and intermodal transportation on hub location, subsidies and social spending.

The pandemic has exposed the lack of systematic coordination in global logistics, further highlighting the importance of the BRI with cooperation at its core. In a practical sense, this paper, with the BRI as the background, provides reference for governments and maritime/railway policymakers to overcome the impact of the crisis in the post-pandemic recovery phase. Specifically, we suggest how local governments should subsidize rail transportation and hub construction to maximize local economic benefits, and we provide central governments with insights into how to determine the optimal number and location of hubs to minimize total social spending. In a theoretical sense, this research contributes to the literature on intermodal networks by evaluating the impact of co-opetition behavior among multiple network planning decision makers. This enables a closer view of how intermodal networks are affected by competition. The study also redesigns co-opetition governance, considering both horizontal competition between local governments and vertical competition between local governments and the central government.

We find that due to a trade-off between increased construction costs and the economic scale of hubs, central governments should produce a reasonable top-down design for the number and location of hubs based on the subsidies, construction costs, traffic volume and location of each city along the belt and road (B&R). We also find that there is no need for local governments to blindly provide high railway subsidies. However, construction subsidies and railway subsidies should complement each other; otherwise, the initial investment will be wasted. The total cost may increase when rail subsidies are higher. This justifies the requirement to reduce railway subsidies. If the number of hubs is properly designed at the top level, government reliance on railway subsidies and the total cost will be reduced. The results also reveal that intermodal transportation is more effective than monomodal transportation, especially when there are few hubs, and that the cost varies greatly between different modes of transportation[10].

The rest of the paper is organized as follows. Section 2 presents the literature review. There are few studies on the influence of the behaviors of different entities on hub location. Section 3 proposes the intermodal hub location problem and its mathematical formulation. Section 4 presents an optimization method combining a population-based algorithm using contest theory to solve our model. Section 5 analyzes the effects of intermodal transportation, intergovernmental competition and infrastructure investment on network design, and reveals the implications of our results. Section 6 offers concluding remarks. The detailed results and data are provided in Appendices A and B.

2. Literature review

Our study is relevant to three major streams of research: intermodal transportation, the hub location problem and government subsidies.

First, we focus on multimodal and intermodal network planning.

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[10] Data from https://www.beltroadresearch.com/the-bri-and-chinas-international-trade-map/.

These two terms are well established in the context of freight transportation (Willing et al., 2017). Multimodal freight transportation uses at least two transportation modes (e.g., sea and rail), while intermodal transportation is regarded as a special form of multimodality whereby the goods do not change the unit of transportation (e.g., a container). SteadieSeifi et al. (2014) showed that the terms "multimodal" and "intermodal" are used interchangeably in the literature. In this study, we use the term "intermodal" for consistency. In the study of intermodal transportation, in addition to the single objective of minimizing transportation costs, there is a tendency to consider different factors, such as shipment time, energy consumption, risk, container utilization rate and port dynamics, to capture traffic (Srinivasan and Thompson, 1977; Min, 1991; Castillo-Manzano et al., 2013; Gao et al., 2020; Upadhyay, 2020). Thus, multi-objective planning has been widely used in the literature. However, most models focused on single-stage, and the results are solved once and for all. For example, the goal is to find an optimal intermodal routing for a given set of requests and hub locations (Roth-enbächer et al., 2016).

In an intermodal transportation network, the hub plays a critical role because of the functions of transshipment and consolidation. Hub location problems aim to optimize the location of hub facilities in a network.[11] Hub location problems can be further subdivided according to different objectives. For instance, hub median problems minimize total transportation costs (e.g., Yaman, 2009, 2011; Alumur et al., 2012a; Corey et al., 2022); hub center problems minimize the maximum distance/cost between origin–destination pairs (e.g., Meyer et al., 2009); and hub covering problems maximize the total number of served spoke nodes (e.g., Tan and Kara, 2007; Wagner, 2008). To better reflect real-world logistics and transportation systems, a series of studies have sought to bridge the gap between research and reality by eliminating some of the traditional assumptions regarding the structure of a network (Yıldız et al., 2021), adding constraints, such as time limit and hub capacity (Ishfaq and Sox, 2010, 2012; Mohammadi et al., 2011; Alumur et al., 2018), or by considering multiple objectives, including cost, service and environment (Yin et al., 2021). In recent years, another noteworthy issue has been stochastic network design considering uncertainty in demand, revenue and costs or the amount of ship traffic (Alumur et al., 2012b; Peiró et al., 2019; Wang et al., 2019, 2020; Taherkhani et al., 2021). Some studies have also considered the hub location problem in a competitive environment. For example, the behavior of consumers choosing carriers or competition between companies to build hubs have also been examined (Marianov et al., 1999; Sasaki and Fukushima, 2001; Eiselt and Marianov, 2009; Lüer-Villagra and Marianov, 2013; Mahmutogullari and Kara, 2016). These studies have been conducted from the perspective of participants, that is, the parties independently involved in decision-making act to maximize their own interests. In this paper, the network is designed from a holistic perspective to maximize total social benefits (i.e., by minimizing social spending). At the same time, we consider the co-opetition behavior of multiple decision makers.

Hub location is essential in intermodal freight transportation research, which is known as intermodal hub-and-spoke network design (IHSND). An intermodal freight transportation system can be essentially formulated as a hub-and-spoke network. The IHSND problem is fundamentally different from the conventional hub-and-spoke network design (HSND) problem, which has been elaborated in Meng and Wang (2011). The IHSND problem involves various stakeholders, such as the network planner, carriers and hub operators. In recent years, a number of papers have begun to study the decision-making behaviors of other agents that may affect the results of network design. Tawfik and Limbourg (2019)

jointly addressed the intertwined tactical questions of service network design and pricing from the perspective of a freight transport operator. Bouchery et al. (2020) proposed the intermodal hinterland network design games that make it possible to assess the impact of having noncooperative users in intermodal networks.

Most studies have considered only one network planner and addressed the problem from a single perspective through a single-stage model. Nevertheless, in the real world, hub location planning may be determined by more than one entity. For example, in some trans-regional hub location problems, competition and cooperation between local governments may affect the overall design of a network. However, few studies have addressed the process and logic of hub location decision-making. Although some studies have considered competition among hub builders, they have only studied it from a decentralized perspective. For projects that need overall planning, decisions should be made from a holistic perspective. In addition, if a network is designed by different entities, the single-stage model is clearly inadequate to solve this kind of problem. To bridge the gap between research and reality, this paper examines the influence of the co-opetition behavior of multiple network planning decision makers on hub location and intermodal transportation using a two-stage model.

Global transport and logistics systems have been greatly impacted **by the COVID-19 pandemic** (Logunova et al., 2021). Taherkhani et al. (2021) showed that during the pandemic, offshore diesel prices and freight demand fell sharply, but sea freight prices rose. In the context of the BRI, Minárik and Iderová (2021) explored the impact of the pandemic on container transportation costs. In response to the crisis, Huang et al. (2022) studied the issue of locating hub ports to ensure that the container shipping network would be highly reliable in the post-COVID-19 era. Narasimha et al. (2021) proposed that government and maritime policymakers consider long-term support measures, such as the development of sustainable maritime stakeholders and collaboration activities. This makes the BRI, as an international initiative focused on cooperation, all the more important. This paper studies the location of cross-border hubs, which are decided by both central and local governments.

As a lever to regulate or guide the market, governments often intervene to achieve better supply chain performance and social welfare (Yang et al., 2021). This is true across industries, such as manufacturing and remanufacturing (Yu et al., 2018; Zhang and Zhang, 2018), R&D (Yu et al., 2016; Xu et al., 2021) and sustainable development (Cohen et al., 2016; Chen et al., 2019). In recent years, there have been a number of related studies on transportation. Meng et al. (2022) explored the impact of government subsidies/penalties on cooperation between ports and shipping enterprises to reduce emissions. Kundu and Sheu (2019) used a three-stage game-theoretical model to analyze the effect of government subsidies on shippers' mode switching (from maritime to rail) behavior. In maritime transport, Wang and Jiao (2021) studied how government subsidies affect carriers' choices to use low-sulfur fuel oil. Hu et al. (2022) investigated optimal container subsidies for shippers to promote intermodal shipping involving waterways. Tamannaei et al. (2021) examined the effect of government taxes on fuel use on competition between two transportation systems.

The current study mainly focuses on the influence of a single upstream government on the interests of downstream transportation enterprises in an established transportation network, the decisions of which can be analyzed through game theory. In the context of the BRI, government intervention is particularly important, but this may be more complicated than previously discussed. Very limited research has been reported on the effect of government subsidies on network design. Unlike previous research, this paper considers the co-opetition between two levels of government and takes the design of the transportation network as a decision. We innovatively put forward a hub location problem that considers both government subsidies and intermodal transportation.

In Table 1, the studies discussed above are classified according to

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[11] The location of the hubs is determined and spoke nodes are allocated to these hubs. Different policies are used to allocate spoke nodes to different hubs: single, multi, r-, and hierarchical allocation. For more details, please refer to SteadieSeifi et al. (2014). We use hierarchical allocation in this paper.

Table 1
Classification of relevant studies.

Study	Intermodal transportation	Hub location	Government intervention	COVID-19
Srinivasan and Thompson (1977); Min (1991); Castillo-Manzano et al. (2013); Willing et al. (2017); Gao et al. (2020); Upadhyay (2020).	✓			
Marianov et al. (1999); Sasaki and Fukushima (2001); Tan and Kara (2007); Wagner (2008); Eiselt and Marianov, 2009; Meyer et al. (2009); Yaman (2009), 2011; Mohammadi et al. (2011); Alumur et al. (2012a); Lüer-Villagra and Marianov, 2013; Mahmutogullari and Kara (2016); Rothenbächer et al. (2016); Alumur et al. (2018); Peiró et al. (2019); Wang et al. (2019); Wang et al. (2020); Corey et al. (2022).		✓		
Ishfaq and Sox (2010), 2012; Meng and Wang (2011); Alumur et al. (2012b); SteadieSeifi et al. (2014); Tawfik and Limbourg (2019); Bouchery et al. (2020); Yıldız et al. (2021); Yin et al. (2021).	✓	✓		
Cohen et al. (2016); Yu et al. (2016); Yu et al. (2018); Zhang and Zhang (2018); Chen et al. (2019); Wang and Jiao (2021); Xu et al. (2021); Yang et al. (2021); Meng et al. (2022).			✓	
Kundu and Sheu (2019); Tamannaei et al. (2021); Hu et al. (2022).	✓		✓	
Logunova et al. (2021).	✓			✓
Taherkhani et al. (2021); Huang et al. (2022).		✓		✓
Minárik and Iderová (2021); Narasimha et al. (2021).	✓		✓	✓

their research category. By comparison, we summarize the contributions of our study as follows. (i) We make a new attempt to examine intermodal hub location problems with multiple network decision makers: local government at each node and central government. (ii) Co-opetition behaviors between governments due to subsidies are more complicated than those commonly discussed in the literature. Specifically, we consider both horizontal competition between local governments and vertical competition between local governments and the central government. (iii) To characterize the impact of competition on hub location,

we propose a novel representation of local government utility related to government subsidies (inputs) and hub location schemes based on contest theory. (iv) We design an optimization method combining contest theory with heuristic algorithms to solve the problem. (v) Considering both unit subsidies on railway transport lines and fixed subsidies for hub construction, we explore how the subsidization of local governments works in network layout. (vi) We further study the effects of the degree of competition, hub investment and intermodal transportation on social welfare.

3. Problem definition and model

Let us consider a network that includes N cities participating in the BRI, denoted by $I = \{i|1, 2, ..., N\}$. Each city represents a node $i = 1, 2, ..., N$, which is governed by a local government. Node, city and local government correspond to each other, so they can all be denoted by i. Each local government (i.e., provincial government) belongs to the same higher-level government (i.e., the central government). Suppose that there are n_1 cities in China denoted by $I_1 = \{i|1, 2, ..., n_1\} \subseteq I$. First, the local government of each node city determines the subsidies required to maximize its performance; then, based on these subsidies, the central government decides the location of the hub to minimize overall social expenditure (excluding government subsidies) borne by private entities, including construction costs, transportation costs and transshipment costs. Finally, given the location of hubs, carriers choose the optimal intermodal transportation route to minimize their total transportation and transshipment costs. The parameters, sets, decision variables and definitions are shown in Tables 2 and 3. The abbreviations are shown in Table B2 in Appendix B.

3.1. Problem definition

A hub has two main functions. One is distributed control, enabling economies of scale. The other is transshipment, which can enable intermodal transportation. In general, a hub promotes a city's economic development by attracting more goods to pass through it. That is, the construction performance of the local government will be improved. Considering one of the popular modes of infrastructure construction in the BRI, *Public–Private-Partnership* (PPP),[12] hub construction is jointly undertaken by freight companies and governments. Intuitively, a city with higher government input (subsidies) is more likely to be selected as a hub. Thus, hub location planning is related to subsidy decisions. The government subsidies involved in this model can mainly be considered in two parts. The first part of the subsidy is the fixed unit subsidy for hub construction, denoted by μ_i, where $i \in I$. For governments, this part of the subsidy is the input for hub construction. This does not affect the results whether construction subsidy μ_i is provided by local government i or another regional government $j \in I$ and $j \neq i$. The overall objective of the model is to minimize the sum of the construction and transportation costs of private entities excluding government subsidies. The second part of the subsidy is designed to encourage more carriers to transport goods by railway. To achieve this, local government i subsidizes each unit of freight shipped by rail from that node (Barrow, 2018; EDB, 2018) denoted by ε_i. This part of the subsidy is provided to freight carriers by the local government of the departure city of this route. Clearly, ε_i has an impact on the transportation route selected by the carriers and the location of the hub decided by the central government, which in turn

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[12] Under PPP, a government and a company form a partnership of "benefit sharing, risk sharing and whole-process cooperation." In this paper, we consider this kind of mode. Specifically, the private entity, which we refer to as a freight company in this paper, is responsible for hub construction. The government invests in hub construction by offering fixed subsidies to the company. For more details, please refer to http://english.www.gov.cn/archive/statistics/202112/19/content_WS61becb 54c6d09c94e48a272f.html.

Table 2
Parameters/Sets and definitions.

Parameter/Set	Definition
N	The number of cities/nodes in the B&R network.
n_1	The number of cities/nodes located in China in the B&R network.
i	The city/node/local government in the network, $i = 1, 2, ..., N$.
I	The set of cities/nodes/local governments, $I = \{i\|1, 2, ..., N\}$.
j	The city/node/local government in the network other than i, $j \in I$ and $j \neq i$.
I_1	The set of cities/nodes/local governments in China, $I_1 = \{i\|1, 2, ..., n_1\}$, and $I_1 \subseteq I$.
I_1^{-i}	The set of cities/nodes/local governments in set I_1 other than node i.
l	The city/node/local government in China other than i, $l \in I_1^{-i}$.
K	The set of hubs, $K \subseteq I$.
k	The first hub node that passes through during transportation from node i to node j, $k \in K$.
m	The second hub node that passes through during transportation from node i to node j, $m \in K$.
S	The set of transportation modes, $S \varepsilon \{s\|0, 1\}$.
s	$\begin{cases} 1, & maritime, \\ 0, & railway. \end{cases}$
s_{ij}	The transportation mode that exists between any two points i and j in the network, $s_{ij} = 0$, or $s_{ij} = 1$, or $s_{ij} = \begin{cases} 1 \\ 0 \end{cases}$.
s_1	The transportation mode between two nodes i and k.
s_2	The transportation mode between two nodes k and m.
s_3	The transportation mode between two nodes m and j.
U_i	The expected utility of local government i.
γ_i	The output of local government i.
μ_i	The fixed unit subsidy for hub construction at node i.
β_l	The unit impact of competitor l's rail subsidy on local government i's output.
F_i	Total construction cost of the hub at node i.
f_i	The fixed unit cost for hub construction at node i.
M_i	Total construction subsidy offered by the local government at node i.
δ_i	The difference between f_i and μ_i, $\delta_i = f_i - \mu_i > 0$.
HC_i	The unit transshipment cost at node i.
d_{ij}	The distance between node i and node j.
c_{ij}^s	The unit transportation cost by transportation mode s between node i and node j.
V_{ij}	$\begin{cases} 1, & there\ are\ goods\ of\ node\ city\ i\ that\ need\ to\ be\ shipped\ to\ node\ city\ j \\ 0, & otherwise. \end{cases}$
w_{ij}	Freight traffic from origin i to destination j.
M	A large value greater than zero.
f	The total social cost, including hub construction, transportation and transshipment.
f^M	The total social cost under monomodal conditions.
f^I	The total social cost under intermodal conditions.
O	The city of origin.
D	The destination city.
F	The construction cost matrix of hubs.
μ	The fixed subsidy matrix of nodes.
HC	The unit transshipment cost matrix.
D	The distance matrix.
C	The transportation cost matrix.
W	The flow matrix.

Table 3
Decision variables.

Decision Variable	Definition
ε_i	Unit rail transport subsidy offered by local government i.
P	The number of hubs.
y_i	$\begin{cases} 1, & set\ i\ as\ a\ Hub \\ 0, & otherwise. \end{cases}$
$Y_{ij}^{s_1 s_2 s_3}$	$\begin{cases} 1, & transported\ from\ i\ to\ j\ by\ channel\ s_1, s_2, s_3\ separately \\ 0, & otherwise. \end{cases}$
X_{ijkm}	$\begin{cases} 1, & transported\ through\ the\ hub\ (k, m)\ from\ OD\ point\ (i, j) \\ 0, & otherwise. \end{cases}$
Z_{qr}^{ijs}	$\begin{cases} 1, & transported\ from\ q\ to\ r\ by\ channel\ s\ in\ the\ path\ of\ (i\ to\ j) \\ 0, & otherwise. \end{cases}$
y_I	The set of hub locations, $y_I = (y_1, ..., y_i, ..., y_N)$.

affects its own utility. The hub location scheme determined by the central government is $y_I = (y_1, ..., y_i, ..., y_N)$, where y_i is a $0-1$ variable for the hub construction of each node. If node i is selected as a hub, $y_i = 1$; otherwise, $y_i = 0$.

The timing of the game is summarized in Fig. 2. According to the timeline, the problem can be divided into three sub-problems: local government subsidies (at $t = 1$), central government hub location optimization (at $t = 2$), and carrier intermodal transportation (at $t = 3$).

At time $t = 1$, to maximize its utility, each local government decides the amount of subsidy for hub construction μ_i and the function of the rail transport subsidy, which is related to the hub location scheme, presented as $\varepsilon_i(y_I)$ for $i \in I_1$. At present, only Chinese local governments subsidize railway carriers.[13] For a node city outside of China $i \in I - I_1$, there is $\varepsilon_i = 0$. Given that construction subsidies may vary with construction costs and do not affect carrier route selection, we first set μ_i as an exogenous parameter to study the impact of railway subsidies on hub location. We then use sensitivity analysis to study the relationship between construction subsidies and rail subsidies/construction costs.

For a node city in China $i \in I_1$, for a given flow of goods, local governments compete with each other to be selected as a hub and attract more goods through their nodes. It is a contest game.[14] That is, each local government acts as a contestant by exerting effort (i.e.,

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[13] For more details, please refer to https://cbk.bschool.cuhk.edu.hk/the-rise-of-rail-along-chinas-belt-and-road/.

[14] The contest is a game where contestants exert costly and irretrievable effort in order to obtain one or more prizes with some probability (Corchon, 2007). In this study, local government are contestants, subsidies are efforts, and prizes are flow of goods.
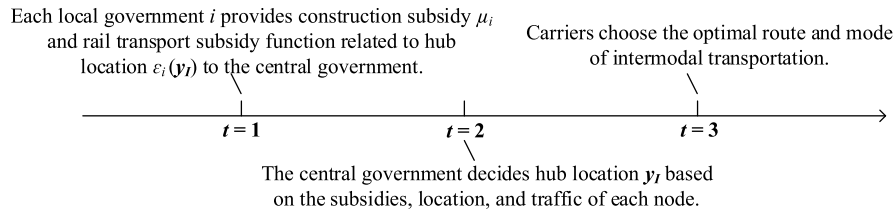
Fig. 2. Timeline of the model.

subsidizing) to win more flows of goods. Referring to contest theory (Corchon, 2007), the expected utility function of each local government can be formulated as follows:

$$U_i = \gamma_i - \varepsilon_i^2, for\ i = 1, 2, ..., n_1, \tag{1}$$

where

$$\gamma_i = \mu_i \left(1 - \sum_{l \in I_1^{-i}} (1 + y_l)\beta_l\varepsilon_l\right)\varepsilon_i. \tag{2}$$

According to contest theory, the subsidy (effort) of each government will affect their respective output and input. For local government i, each additional unit of railway subsidies, will attract more goods to node i, but its investment will gradually increase, making the total cost change in a nonlinear way. Referring to Ewerhart (2016) and Song (2011), the cost function for effort is assumed to be quadratic,[15] i.e., ε_i^2. Local government i's output is denoted as γ_i. Referring to Corchon (2007) and Song (2011), γ_i is expressed by multiplying the factors related to local government i's personal effort and its competitors' efforts, as shown in Equation (2). The effect of personal effort on output γ_i is characterized in two ways. One is the fixed subsidy for unit construction μ_i at each node i. A higher μ_i means that the local government invests heavily in the hub construction of this node, enabling the node to accommodate greater throughput. The output value will increase accordingly. The second is the unit rail subsidy ε_i provided to the carriers. As ε_i increases, more operators are willing to transport goods along this path, which increases the throughput of nodes. However, government investment in other nodes has a negative impact on local output. Specifically, if competitors heavily subsidize, more goods will flow to their nodes, reducing local cargo throughput. For local government i, its competitor located at another node is denoted by $l \in I_1^{-i}$. The set I_1^{-i} represents the set of nodes in set I_1 other than node i. We use $(1 + y_l)\beta_l\varepsilon_l$ to represent the negative effect of each competitor l's effort on the local government i's output. Competitor l's rail transport subsidy is denoted as ε_l, while the unit impact of l's rail subsidy on i's output is denoted as β_l. The unit impact β_l represents the degree of competition between local governments due to rail subsidization. As β_l increases, horizontal competition becomes more intense. In addition to the negative effects of competitors' rail subsidies, the location of hubs matters. It is generally assumed that carriers can only transport goods through hub nodes (Campbell, 1994; Taherkhani et al., 2020, 2021). Intuitively, under the same rail subsidy, the negative impact of a hub node is greater than that of a non-hub node. If l is a non-hub node ($y_l = 0$), then the negative influence of competitor l's

efforts on i's local output is $\beta_l\varepsilon_l$, which depends only on the rail subsidy. If l is a hub node ($y_l = 1$), the adverse effect should be greater,[16] which for simplicity we assume here to be $2\beta_l\varepsilon_l$. For local government i, the negative influences from competitors are summarized as $\sum_{l \in I_1^{-i}} (1 + y_l)\beta_l\varepsilon_l$. We describe the effect of competitors' efforts on local output as 1 minus the summation of the negative impacts.

To maximize its own utility, each local government $i \in I_1$ determines its own effort, which is expressed as the rail transport subsidy function $\varepsilon_i(y_I)$, by solving $\frac{\partial U_i}{\partial \varepsilon_i} = 0$ (see Appendix A for proof). The hub location scheme y_I is an unknown variable at this point. $\varepsilon_i(y_I)$ is a response function with respect to y_I, as shown in Equation (3). No matter where the hub is located later, the subsidy determined under such a formula will maximize the utility of the local government.

$$\varepsilon_i(y_I) = \frac{\mu_i \left(1 - \sum_{l \in I_1^{-i}} (1 + y_l)\beta_l\varepsilon_l\right)}{2}, for\ i = 1, 2, ..., n_1. \tag{3}$$

At time $t = 2$, according to the subsidies (μ_i, ε_i) provided by the local government, the central government selects P nodes as hubs from N nodes to minimize total social spending, including freight companies' hub construction and carriers'/hub operators' transportation and transshipment costs (excluding government subsidies), i.e., the hub location problem. The hub set is represented by $K \in I$. The decision variable is $y_I = (y_1, ..., y_i, ..., y_N)$. The total construction cost of the hub at each node is F_i. The total construction subsidy offered by local government i is M_i. This should be deducted from F_i. Intuitively, a large F_i indicates a city with a high unit construction cost and throughput, whose local government will increase its investment accordingly. Therefore, in our setup, M_i is proportional to unit construction subsidy μ_i and the total throughput of node i. The transshipment capacities at the hubs are assumed to be nonrestrictive (Rothenbächer et al., 2016).

At time $t = 3$, given the location of the hub and the flow of goods (freight traffic, origin and destination are known), carriers choose the optimal route X_{ijkm} and the mode $Y_{ij}^{s_1 s_2 s_3}$ of transportation to minimize their total transportation and transshipment costs. Assume that the network formed between all nodes is fully connected. The mode of transportation between any two nodes may be of two kinds, railway and maritime. The set of transportation modes is represented as $S\varepsilon\{s|0, 1\}$, where $s = 0$ means railway and $s = 1$ means maritime. Considering that each node city is in a different geographical location, the transportation mode between nodes i and j may be limited, and there may be only one way to transport goods, i.e., $s_{ij} = 0$ or $s_{ij} = 1$. However, it is also possible that both modes can be selected, i.e., $s_{ij} = \begin{cases} 0 \\ 1 \end{cases}$. When there is a change in transportation mode at node i—that is, the goods are shipped into a node city by one mode of transportation and then shipped out by another mode of transportation—the internal transshipment cost will occur in

---

[15] Each local government also competes by offering its own rail subsidy function (related to the hub location scheme) to the central government. This is very similar to a supply function competition model. In supply function competition, production costs are generally assumed to be quadratic (Klemperer and Meyer, 1989; Akgun, 2004).

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[16] We can also multiply y_l by a coefficient $\theta > 0$, to represent the different degrees of influence of the hub node on the output of other nodes, i.e., $(1 + \theta y_l)\beta_l\varepsilon_l$. The value of θ will affect the specific value of the subsidy, but it will not affect the interaction between subsidies and hub location. Therefore, we set $\theta = 1$ to simplify the model and calculations.

this node, and the unit transshipment cost is denoted by HC_i. The distance between node i and node j is denoted by d_{ij}. The unit transportation cost by transportation mode s between node i and node j is equal to c_{ij}^s. Note that the effect of carriers' choice of transportation route on the freight rate is not taken into account[17] (Meng and Wang, 2011; Tawfik and Limbourg, 2019; Bouchery et al., 2020). We use V_{ij} to indicate whether there is a flow of goods between node i and node j. If there are goods of node city i that need to be shipped to node city j, then $V_{ij} = 1$; otherwise, $V_{ij} = 0$. Freight traffic from origin i to destination j is represented by w_{ij}. Assume that input and output are strictly positively related.

Assume that goods can only be transported via the hub node from origin city O to destination city D and through at least one hub and at most two hubs. This is a basic assumption of the hub location problem[18] (Campbell, 1994; Ernst and Krishnamoorthy, 1998; Marianov et al., 1999; Ebery et al., 2000; SteadieSeifi et al., 2014; Taherkhani et al., 2020, 2021). Depending on whether O and D belong to the hub set K, there are seven scenarios for optimal path selection, as shown in Fig. 3. In general, the transportation process includes four node cities and three sections of transportation from O to D. The decision variable $X_{ijkm} = \begin{cases} 1 \\ 0 \end{cases}$ represents the transportation route from node i to node j, where $i, j \in I$ and $k, m \in K$. Node i is origin city O, node j is destination city D and nodes k and m are the hubs. If the goods pass through $i \to k \to m \to j$ in sequence, $X_{ijkm} = 1$; otherwise, $X_{ijkm} = 0$. The decision variable $Y_{ij}^{s_1 s_2 s_3} = \begin{cases} 1 \\ 0 \end{cases}$ depicts the mode of transportation from node i to node j. When the goods are transported by (s_1, s_2, s_3) successively in each section, then $Y_{ij}^{s_1 s_2 s_3} = 1$; otherwise, $Y_{ij}^{s_1 s_2 s_3} = 0$. As shown in Fig. 3, if node i or node j is a hub, or only one hub is passed through, some of the four nodes may coincide, and the transport modes between different sections may be the same. Note that if $s_1 = s_2 = s_3$, goods are transported in the monomodal network; otherwise, goods are transported in the intermodal system. The decision variable $Z_{qr}^{ijs} = \begin{cases} 1 \\ 0 \end{cases}$ denotes the mode of transportation for one section on the route from origin i to destination j. If goods are transported by s from node q to node r on route $i \to j$, then $Z_{qr}^{ijs} = 1$; otherwise, $Z_{qr}^{ijs} = 0$.

3.2. Model

Because hub construction is based on local government subsidies, we call this hub location problem the Intermodal Hub Location Problem Based on Government Subsidies (IHLPGS). We then use mixed-integer programming to model this problem. For the central government, the objective in this hub location problem is to minimize the total social cost, i.e., the total construction cost of freight companies and the transportation and transshipment costs of carriers/hub operators.

The IHLPGS is formulated as follows:

$$
\begin{aligned}
\text{Minimize } f = & \sum_{i=1}^{n}(F_i - M_i)y_i + \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\left(\sum_{s=0}^{1}\sum_{q=1}^{n}\sum_{r=1}^{n} c_{qr}^s d_{qr} Z_{qr}^{ijs} \right) + \sum_{i=1}^{n} \\
\times & \sum_{j=1}^{n}\sum_{k=1}^{n}\left[w_{ij}HC_k\left(\sum_{s_1=0}^{1}\sum_{s_3=0}^{1} Y_{ij}^{s_1(1-s_1)s_3} \right) \right] + \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{m=1}^{n}\left[w_{ij}HC_m\left(\sum_{s_1=0}^{1} \right.\right. \\
\times & \left.\left. \sum_{s_2=0}^{1} Y_{ij}^{s_1 s_2(1-s_2)} \right) \right] - \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\left(\sum_{q=1}^{n}\sum_{r=1}^{n} \varepsilon_q d_{qr} Z_{qr}^{ij0} \right)
\end{aligned}
\tag{4}
$$

s.t.

$$
\sum_{i=1}^{n} y_i = P
\tag{5}
$$

$$
w_{ij} \le M * V_{ij} \forall i, j \in I, i \ne j
\tag{6}
$$

$$
\sum_{m=1}^{n}\sum_{k=1}^{n} X_{ijkm} = V_{ij} \forall i, j \in I, i \ne j
\tag{7}
$$

$$
\sum_{s_1=0}^{1}\sum_{s_2=0}^{1}\sum_{s_3=0}^{1} Y_{ij}^{s_1 s_2 s_3} = V_{ij} \forall i, j \in I, i \ne j
\tag{8}
$$

$$
X_{ijkm} \le y_k \;\forall i, j \in I, i \ne j, k, m \in K
\tag{9}
$$

$$
X_{ijkm} \le y_m \forall i, j \in I, i \ne j, k, m \in K
\tag{10}
$$

$$
Z_{ik}^{ijs_1} \le y_k \forall i, j \in I, i \ne j, k \in K, s_1 \in S
\tag{11}
$$

$$
Z_{km}^{ijs_2} \le y_k \forall i, j \in I, i \ne j, k, m \in K, s_2 \in S
\tag{12}
$$

$$
Z_{km}^{ijs_2} \le y_m \forall i, j \in I, i \ne j, k, m \in K, s_2 \in S
\tag{13}
$$

$$
Z_{mj}^{ijs_3} \le y_m \forall i, j \in I, i \ne j, m \in K, s_3 \in S
\tag{14}
$$

$$
X_{ijkm} + \sum_{s_2=0}^{1}\sum_{s_3=0}^{1} Y_{ij}^{s_1 s_2 s_3} - 1 \le Z_{ik}^{ijs_1} \forall i, j \in I, i \ne j, k, m \in K, s_1 \in S
\tag{15}
$$

$$
X_{ijkm} + \sum_{s_1=0}^{1}\sum_{s_3=0}^{1} Y_{ij}^{s_1 s_2 s_3} - 1 \le Z_{km}^{ijs_2} \forall i, j \in I, i \ne j, k, m \in K, s_2 \in S
\tag{16}
$$

$$
X_{ijkm} + \sum_{s_1=0}^{1}\sum_{s_2=0}^{1} Y_{ij}^{s_1 s_2 s_3} - 1 \le Z_{mj}^{ijs_3} \forall i, j \in I, i \ne j, k, m \in K, s_3 \in S
\tag{17}
$$

The first term in Equation (4) is the total cost of hub construction minus the total construction subsidies from local governments, which are borne by the freight companies. The second term is the total transportation cost of goods from origin to destination. The third and fourth terms are the total transfer cost of goods in the hub when its transportation channel switches.[19] The last term is the total amount of local government subsidies for railway goods, which should be deducted from the total cost. Constraint (5) means that the number of hubs equals P. Constraint (6) means that the amount of flow from node i to node j is finite and M is a large value. Constraints (7) and (8) mean that there is only one route and one way of transportation if there is a flow of goods between node i and node j. Constraints (9)–(14) ensure that each cargo flow is routed via hubs from node i to node j. Constraints (15)–(17) state the relationships among decision variables X_{ijkm}, $Y_{ij}^{s_1 s_2 s_3}$ and Z_{qr}^{ijs}.

---

[17] First, this hub location problem aims to minimize the total cost in the intermodal network. The cost paid by the cargo owner is offset by the revenue received by the carrier/hub operator. We also consider the influence of railway transportation subsidies provided by the governments of nodes on freight rates. If we consider both the impacts of government subsidies and cargo owners' route choice on freight rates, it would be difficult to separate their respective effects on the results. From a practical point of view, under the background of the BRI with government participation, the freight rates between the two nodes are relatively stable (uniform rates throughout the journey). In general, the result is not affected by the actions of cargo owners.

[18] One assumption generally made in hub location problems is that the inter-hub network is a complete graph, but the spoke nodes are not always interconnected. Direct shipment between spoke pairs is not allowed and the flow of cargo crosses at most two hubs.

[19] Under intermodal transportation, no handling of goods occurs during the change of transportation modes (as stated in Footnote 5). The transfer cost here is the operating cost for the unchanged unit (e.g., container) when the transportation mode switches.
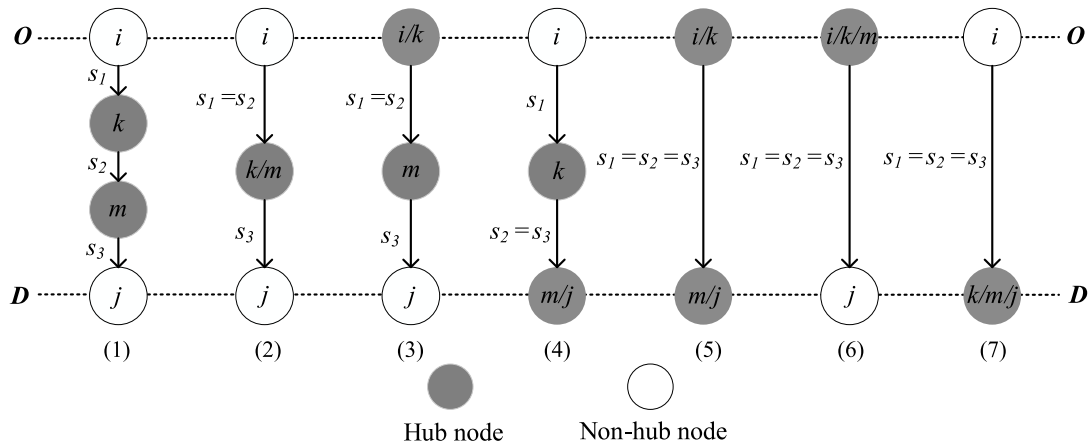
Fig. 3. Seven scenarios for optimal path selection from origin O to destination D.

Specifically, if the goods pass through $i \to k \to m \to j$ in sequence and the transportation mode is (s_1, s_2, s_3), i.e., $X_{ijkm} = Y_{ij}^{s_1 s_2 s_3} = 1$, then $Z_{ik}^{ijs_1} = Z_{km}^{ijs_2} = Z_{mj}^{ijs_3} = 1$; otherwise, $Z_{qr}^{ijs} = 0 \text{ or } 1$.

4. Solution algorithm

The main work to solve this problem includes selecting reasonable intermodal transportation hub nodes, determining the optimal government subsidies and determining the transportation path and mode of each node request. As described in Section 3, under the given hub location scheme, optimal local government subsidies can be determined using contest theory. Thus, we design the Intelligent Location Algorithm Based on Government Subsidies (ILAGS) to solve this problem.

ILAGS is a population-based algorithm. The algorithm uses the genetic algorithm as the framework to solve the location selection scheme. The subsidy strategy can then be obtained by the game method according to the location selection scheme. The transportation path and mode between each node can be solved by the combination enumeration method. For the hub location and government subsidy problem, the optimization goal of the problem is to minimize the total social cost (excluding government subsidies) borne by private entities, including transportation, transshipment and hub construction costs, by determining the optimal location–subsidy scheme under the given constraints.

The overall process of ILAGS is summarized in Algorithm 1, which begins by constructing an initial population P using a randomly generated heuristic. In each iteration, we adopt the steady-state replication strategy for population selection. That is, population P is sorted according to individual fitness values in descending order, and the top 50% of individuals in population P are kept in the new population P_{new}. To generate the other 50% of individuals in population P_{new} and preserve the genetic information of outstanding parents, we use the roulette method to choose parents S_1 and S_2 first. We then apply the crossover operator to generate offspring S_0. Subsequently, there is probability γ to invoke a mutation operator. Finally, we apply the population management procedure to update population P. The crossover operator and mutation operator are the partially mapped crossover operator (PMX) and displacement mutation operator (DM), respectively. Our ILAGS will end when this process is repeated max_iter times.

Algorithm 1. Main Procedure of ILAGS

5. Computational experiments and analysis

In this section, we present computational experiments to analyze the results of IHLPGS. Based on the data we collect, we compare the effectiveness of intermodal and monomodal transportation; then, we examine the problem of rail subsidies and construction subsidies and

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Algorithm 1: Main Procedure of ILAGS

Require: max_iter: the maximum number of iterations
   $P \leftarrow$ **Population_Initialization**();
   $S_{best} \leftarrow Best(P)$;
   while $iter < max\_iter$ **do**
     $P_{new} \leftarrow$ **Population_Management**(P);
     while $|P_{new}| < |P|$ **do**
       Randomly select two parent chromosomes S_1 and S_2 from P;
       $S_0 \leftarrow$ **Crossover**(S_1, S_2);
       $S_0 \leftarrow$ **Mutation**(S_0);
       $P_{new} \leftarrow P_{new} \cup S_0$;
     end while
     $S_{best} \leftarrow Best(P)$;
    $iter = iter + 1$;
   end while
   Return S_{best}: the best solution

---

analyze the influence of horizontal competition among local governments and hub construction on the results using sensitivity analysis.

Our algorithm is coded in C++ programming language, and all experiments are run on a machine with a 3.40 GHz Intel(R) Core(TM) i7-6700 CPU processor and 16 GB of memory. All of the parameters in ILAGS are tuned using the IRACE package (López-Ibáñez et al., 2016), which offers the iterated racing procedure to configure the algorithm automatically. We perform this tuning on 10 randomly generated small-scale instances. The tuning procedure is set to 5,000 executions of ILAGS, each with a time limit of 60 s. The parameter settings are shown in Table 4, which presents both the considered values and the final values.

5.1. Examples

To answer our questions, we collect data from official government documents and international transportation websites to ensure accuracy and usefulness. As mentioned in the Integrated Transport Services Development Plan in the 14th Five-Year Plan[20], the Chinese government will build multilevel integrated transportation hubs to improve intermodal transportation. In this paper, we adopt the standard transportation cost (calculated in US dollars) and flow of containers (40 FT) to calculate the total cost. Referring to "CR Express Construction planning" (2016a), we focus on the 58 cities (shown in Appendix B) in the BRI intermodal transportation network, i.e., the number of nodes N equals 58. The fixed subsidy matrix of nodes ($\boldsymbol{\mu}$) and the construction cost matrix of hubs ($\boldsymbol{F}$) are collected from https://www.mot.gov.cn/tongjishuju/gudingzichantouziwcqk/index.html. The transportation cost matrix ($\boldsymbol{C}$) and the unit transshipment cost matrix ($\boldsymbol{HC}$) are obtained from https://ishare.iask.sina.com.cn/f/bv8HVDh2W6x.html (railway cost), https://www.5688.cn/fcl/cnszn-sgsgp.html (maritime cost) and http://info. jctrans.com/gongju/cx3/2005719109505.shtml (transshipment cost). The distance matrix ($\boldsymbol{D}$) is collected from https://www.huoche.net/tools/gongli/ and https://www.distance-cities.com/. The flow matrix ($\boldsymbol{W}$) is collected from https://comtrade.un.org/. For simplicity, we assume that all negative impact coefficients β_l are the same. As stated in Section 3, this refers to the impact of contestants' subsidies on local government performance (i.e., the subsidy sensing level) and reflects the degree of horizontal competition among local governments caused by railway subsidization.

Monomodal transportation is a special case of the model, as mentioned in Section 3, i.e., when $s_1 = s_2 = s_3$. This ensures that transshipment does not occur during transportation. We compare the two schemes of intermodal and monomodal transportation with different subsidy sensing levels (denoted by β_l) and different numbers of hubs (denoted by P). By comparing the optimal solutions under intermodal and monomodal transportation, we can assess the efficiency of intermodal transportation under different degrees of horizontal competition among local governments and investment in hub construction by the central government.

Table 4
Parameter settings.

Parameter	Description	Considered values	Final value
max_iter	maximum number of iterations	{100, 1,000, 10,000}	1,000
Γ	mutation probability	{0.1, 0.2, 0.3}	0.2

5.2. Intermodal versus monomodal transportation

Considering the influences of both the degree of competition and hub construction, we show the results in Fig. 4. It is easy to see that the cost of intermodal transportation is always lower than that of monomodal transportation. Although there are transshipment charges, intermodal transportation is still economical, especially when the cost of rail transportation is much higher than that of maritime transportation. Intermodal transportation provides carriers with options to reduce their transport costs.

Because the mode of monomodal transportation is a special case of IHLPGS, the degree of competition and hub construction have similar effects on the optimal solution in both cases. As P increases, the total cost first decreases and then increases. The total cost is affected by two factors. One is the incremental cost of hub construction. The other is the reduction in transportation costs brought about by the main functions of the hub, i.e., distribution (when monomodal/intermodal) and transshipment (only when intermodal). If hub construction is insufficient, economies of scale in distribution hubs dominate, and the total cost is therefore reduced. However, when hub construction is excessive, the reduction in scale and the increase in construction costs result in a higher total cost. Thus, the optimal number of hubs created by the central government should be neither too large nor too small. This is related to the degree of competition and the mode of transportation. The optimal number of hubs in a monomodal network is greater than that in an intermodal network. In a monomodal network, a hub only has a distribution function; while in an intermodal network, it also has a transshipment function, which can achieve scale faster. In our experiment, the optimal number of hubs (denoted by P^*) for both intermodal transportation and monomodal transportation is approximately 15.[21] It can be seen from the curves in Fig. 4 that the rate of cost change is higher on the left side of P^* than on the right side, whether under monomodal or intermodal conditions. That is, the cost rise caused by insufficient facilities (i.e., underbuilding) is greater than that caused by excess facilities (i.e., overbuilding). As underbuilding is more costly than overbuilding, the central government should construct more hubs than fewer hubs. However, to some extent, intermodal transportation can compensate for the negative impact of insufficient facilities. It is reasonable to speculate that the transshipment function of hubs plays a greater role in reducing transportation costs when there is underbuilding.

We next discuss the impact of β_l on the total cost. As stated in Section 3, β_l represents horizontal competition among local governments caused by railway subsidies. From Fig. 4, we can see that in both intermodal and monomodal networks, if there is excess construction, the total cost rises when competition is intense (i.e., high β_l). When the number of hubs is large, the total cost tends to be the same under $\beta_l > 0$ and is always higher than the cost without competition (i.e., $\beta_l = 0$). This shows that competition is not conducive to cost reduction when too many hubs are built. However, when few hubs are built, the total cost may be even lower with increased competition (e.g., when $P = 5$, the cost under $\beta_l = 0.8$ is lower than that under $\beta_l = 0.4$ in the intermodal network, and the cost under $\beta_l = 0.4$ is lower than that under $\beta_l = 0$ in the monomodal network). That is, competition can be beneficial when few hubs are built, whether intermodal or monomodal.

Note that maritime costs have been rising since the outbreak of COVID-19, while rail costs have barely changed. We therefore further expand the maritime costs in our experiment (multiplied by 2 and 5). We use $(f^M - f^I)/f^M$ to denote the efficiency of intermodal transportation to reduce costs, using the cost of monomodal transportation as the

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[20] For more details, please refer to https://secure.hkmb.hktdc.com/en/Nzk5NDQ0OTA0/hktdc-research/China%E2%80%99s-14th-Five-Year-Plan-Transportation%2C-Logistics-and-Regional-Development.

[21] This corresponds to one of the 10 key tasks to promote the high-quality development of Chinese logistics in 2019.
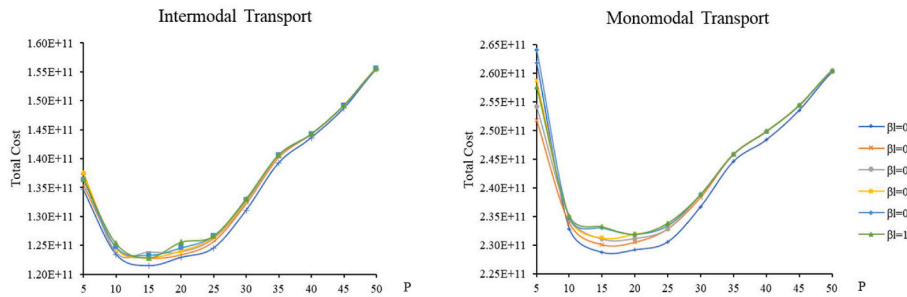
Fig. 4. Total cost under intermodal/monomodal conditions.

benchmark [22]. The results are shown in Fig. 5. As maritime costs rise, the rate of cost reduction declines. The optimal results under IHLPGS gradually converge to monomodal transportation. For a given route, transshipment is not cost-effective if the cost difference between various modes of transportation is not significant. Due to transshipment costs, a carrier may choose monomodal rather than intermodal transportation. At this point, the hub transshipment function has difficulty playing to its advantage in reducing costs. Thus, intermodal transportation is more efficient when the costs of different transportation modes vary greatly. In addition, as the number of hubs increases, the cost reduction rate, i.e., intermodal efficiency, tends to decrease. Specifically, when there are not too many hubs (less than 25 in this experiment), efficiency fluctuates. However, when there are too many hubs, the efficiency of intermodal transportation is greatly reduced. This further verifies our conjecture that intermodal transportation is more effective under underbuilding than under overbuilding.

In summary, a transportation network with hubs can reduce transportation costs due to the economies of scale generated by distribution hubs for both intermodal and monomodal transportation. However, intermodal transportation can further reduce costs due to the transshipment function of hubs. This is more effective when there are not too many hubs and the costs of different modes of transportation vary greatly. We also show that horizontal competition among local governments triggered by rail subsidies is always a disadvantage when there are too many hubs, but could be advantageous when there are few hubs.

5.3. Transportation and construction subsidies

In the previous section, we examine the hub location problem from the perspective of the central government. Next, we look at the subsidization problem from the perspe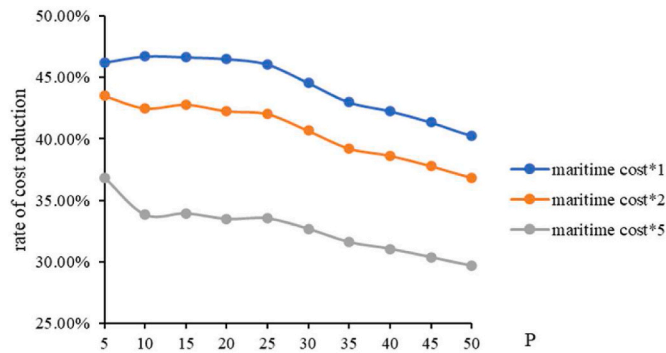ctive of local governments. Two types of subsidies are considered in this paper. One is the unit railway transportation subsidies to carriers to bridge the cost gap between rail and maritime transportation and to encourage more carriers to choose rail transportation. Rail subsidies have enhanced the competitive advantage of rail transportation ("the belt") over maritime transportation ("the road") in channel encroachment, but line encroachment competition between rail lines has intensified. The second type is construction subsidies for freight companies (that undertake hub construction in each node).

5.3.1. Transportation subsidies

First, we examine the factors that influence subsidies for rail transportation. Considering that each node has different construction subsidies and may be selected as a hub, rail subsidies also vary. However, the rail subsidy of each node is affected by the degree of competition and hub construction in the same way. We choose one node to show the results. Fig. 6 depicts the rail subsidy at node 28 (Shanghai, China in this experiment) under different numbers of hubs and different degrees of local government competition in the intermodal network. When there is no competition (i.e., $\beta_l = 0$), the rail subsidy is highest and independent of the number of hubs. Specifically, when the rail subsidies of different local governments do not affect each other, local governments will subsidize railway transportation at the highest level, according to a fixed proportion of the unit construction subsidy (see Appendix A for proof). When there is competition and there are not too many hubs (e.g., less than 35 when $\beta_l = 0.2$), the unit rail subsidy decreases. The greater the competition, the lower the subsidy. That is, fierce competition will reduce local government subsidies for rail transportation. Intuitively, we might think that when competition is intense, local governments would attract more rail freight by lowering transportation rates or raising their unit subsidy. In contrast, we find that the high subsidy sensing level among local governments weakens their incentives to subsidize rail transportation.

In addition, as hub construction gradually improves, the intensity of railway subsidies from local governments will also be slightly reduced. However, if there are too many hubs (P exceeds a threshold, such as 35

Fig. 5. Efficiency of intermodal transportation.

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[22] f^M represents the total cost under monomodal conditions, and f^I represents the total cost under intermodal conditions.
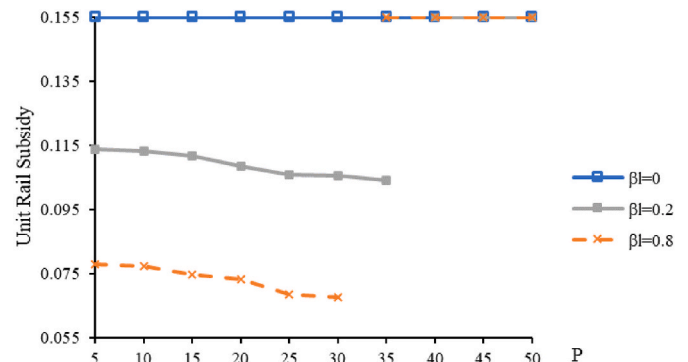

Fig. 6. Unit rail subsidy at Shanghai in the intermodal network.

under $\beta_l = 0.2$), the rail subsidy will jump to the highest level and be in line with subsidies in the absence of competition. As competition intensifies, the threshold moves forward. The influence of hub construction on subsidies can be explained by analogy with that of competition. When the number of hubs is not too large, local governments will compete with each other to be selected as hubs. When P is small, the probability of being selected is low. In such cases, local governments are more focused on their own strategies and less influenced by subsidies from other local governments. This is analogous to a situation where competition is low and subsidies are relatively high. As P increases, so does the probability of being selected. Local governments will pay more attention to the subsidy policies of their competitors. As a result, competition between them will increase, and subsidies will decrease. When P is large enough, the probability of each node being chosen as a hub is high. In such cases, the subsidy provided becomes more critical to being selected, especially for nodes in remote locations and with low cargo flow. Thus, local governments are motivated to offer maximum subsidies as a last resort. The more intense the competition, the greater the local governments are affected by their competitors' decisions. In turn, they offer the highest subsidies earlier. There is little difference in the unit rail subsidy between intermodal and monomodal transportation (shown in Tables A.1–A.2 of Appendix A). However, the threshold of P under monomodal transportation is smaller than that under intermodal transportation. In a monomodal network, local governments will rely more on rail subsidies.

Combined with Figs. 4 and 6, we find that even if subsidies are maximized, the total cost does not necessarily fall (e.g., when $P = 35$, both rail subsidies and total cost under $\beta_l = 0.8$ are higher than those under $\beta_l = 0.2$). However, when there are not too many hubs, the total cost will be cut even when rail subsidies are lower (e.g., when $P = 14$, both rail subsidies and total cost under $\beta_l = 0.8$ are less than those under $\beta_l = 0.2$). We use the impacts of β_l and P on rail subsidies to explain their effects on the total cost (see Section 5.2). As stated above, increased competition will lower rail subsidies when P is not particularly high. The reduction in rail subsidies also changes the central government's choice of hub nodes, especially those providing railway subsidies. When P is small, with an increase in the degree of competition, the hub location plan can be greatly adjusted (there are many other nodes to choose from, and freight may decrease). Thus, lower unit subsidies due to increased competition do not necessarily reduce the total cost when there are few hubs. However, as the number of hubs increases, the range of alternatives shrinks. The reduction in the unit rail subsidy dominates and leads to an overall increase in the total cost. Once P exceeds the threshold, the subsidy reaches its peak (the same as the subsidy when $\beta_l = 0$). When there is competition (i.e., $\beta_l > 0$), hub location and the total cost converge but vary from the results when there is no competition (i.e., $\beta_l = 0$). Due to the negative impact of competition, the total cost is higher under $\beta_l > 0$.

Thus, for the central government, it is reasonable to ask local governments to reduce subsidies for rail transportation. Through effective hub location selection (especially the top-level design of the number of hubs), both local governments' dependence on railway subsidies and the total cost can be simultaneously reduced. In Section 5.2, we show that underbuilding is more costly than overbuilding. However, if there are too many hubs, local governments will rely too much on railway subsidies, resulting in vicious competition. Given the time cost of hub construction and future increases in traffic, a modest increase in the number of hubs is reasonable. In addition, a node with a high rail subsidy will not necessarily be chosen as a hub (e.g., Shanghai, see Tables A.1–A.2 of Appendix A). For the central government, the location of a city and the flow of goods may be more important when choosing a hub, rather than focusing only on subsidies.

5.3.2. Construction subsidies

We next examine the impact of construction subsidies on the total cost and on rail subsidies. For a local government, its construction subsidy is based on construction costs. Due to the different unit costs and throughput in each node, hub construction costs and subsidies also vary. With a certain degree of competition and the appropriate number of hubs, we obtain the change in total cost for different unit construction costs and subsidies (shown in Table A.5 of Appendix A). Clearly, the total cost decreases as the construction cost reduction/construction subsidy increases. For a local government, increasing its construction subsidy will help reduce the total cost. When the hub construction cost of a node is high, the construction subsidy should increase accordingly.

Considering the positive correlation between construction costs and subsidies, we use the difference between unit construction cost f_i and unit construction subsidy μ_i as variables, denoted by δ_i and $\delta_i > 0$. A small δ_i means a high level of subsidy (called subsidy intensity). Fig. 7 shows the influence of subsidy intensity on hub location. As δ_i increases, the optimal number of hubs decreases and the total cost rises. This further proves that the greater the intensity of the construction subsidy, the more favorable it is to reducing costs. When the subsidy is relatively large, the cost increase caused by a shortage of construction is higher than that caused by an excess of construction. That is, underbuilding is more expensive than overbuilding, especially with high subsidies. Considering the time cost of hub construction and future increments of goods, the central government may add hubs. If the construction subsidy is large, the central government may be more aggressive and rapidly expand the number of hubs. Otherwise, the central government should be more conservative and increase the number of hubs on a small scale. In addition, we find that as the construction subsidy increases, the rail subsidy also increases and reaches its maximum level earlier, i.e., the threshold moves forward (shown in Table A6 of Appendix). We speculate that rail subsidies are positively correlated with construction subsidies, which we discuss in the next section.

5.3.3. Relationship between subsidies

From Equations (1) and (2), there is a relationship between rail subsidy ε_i and construction subsidy μ_i. Under different degrees of competition and hub construction, we draw a scatter diagram of the two subsidies on each node, as shown in Fig. 8.

For local governments, subsidies are investments. The more they invest, the more they expect to get back. The construction subsidy can be regarded as preconstruction investment, while the rail subsidy is the operating cost to attract freight flows. Intuitively, there is a trade-off between these two subsidies with limited resources. However, our results show that as the construction subsidy increases, so does the rail subsidy. The local government's upfront construction investment will not reduce future transportation investment. Although subsidies are not the only criteria for choosing nodes as hubs (see Section 5.3.1), construction subsidies and rail subsidies should complement each other. If hub construction at a particular node is costly, leading to a high construction subsidy (see Section 5.3.2), the local government still needs to provide a high subsidy for railway transportation in the later stage; otherwise, the initial investment will be wasted. Furthermore, we find
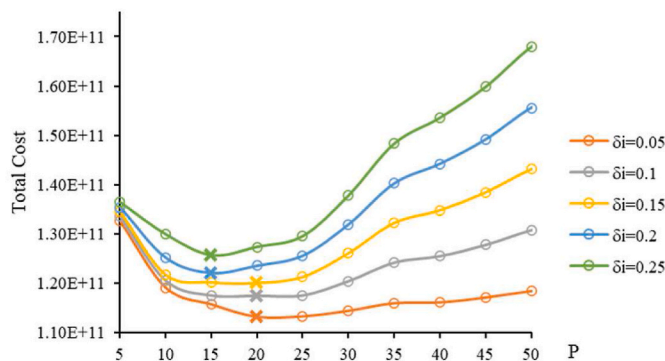

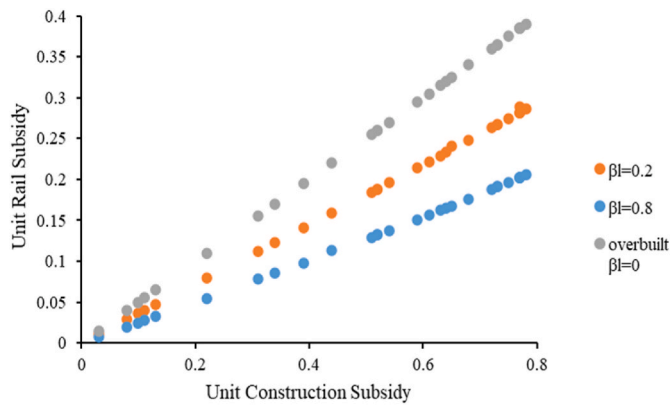**Fig. 7.** Total cost in the intermodal network ($\beta_l = 0.2$).

Fig. 8. Relationship between rail subsidy and construction subsidy in the intermodal network.

that when there are too many hubs or there is no competition, the rail subsidy at each node is always a fixed proportion of the construction subsidy. This result is consistent with the result in Section 5.3.1. As competition becomes more intense, the correlation between the two subsidies decreases. When there are not too many hubs, the number of hubs has little effect on the correlation. The results of monomodal and intermodal transportation are similar.

5.4. Policy recommendations

Based on the above discussion, we put forward policy recommendations for cross-border transportation network design and government subsidies from the perspectives of the central government and local governments, respectively. These recommendations can provide theoretical support for supply chain stability and logistics system recovery in the post-pandemic era, as summarized below.

For the central government:

(i) Network design: The optimal number of hubs should be neither too large nor too small because of the trade-off between construction costs and the scale effect of hubs. Underbuilding is more costly than overbuilding, especially when construction subsidies are high. Considering the time cost of hub construction and future increments of goods, the central government may be more aggressive and rapidly expand the number of hubs when construction subsidies are high; otherwise, it should be more conservative and increase the number of hubs on a small scale.

(ii) The impact of subsidies: Encouraging local governments to increase subsidies for hub construction may help reduce the total cost. Higher rail subsidies, however, may increase the total cost. It is reasonable to ask local governments to reduce subsidies for rail transportation.

(iii) The impact of competition: When there are too many hubs, horizontal competition between local governments is always detrimental to cost reduction, but can be beneficial when there are few hubs.

(iv) The impact of intermodal transportation: Intermodal transportation is more efficient in reducing costs when the costs of different transportation modes vary greatly or there is underbuilding. The optimal number of hubs in a monomodal network should be higher than that in an intermodal network.

For the local government at each node:

(i) Offering a high rail subsidy will not necessarily result in being chosen as a hub. However, if the initial investment (construction subsidy) is high, the rail subsidy should also be high.

(ii) When the rail subsidies of different local governments do not affect each other (no horizontal competition), or there are too many hubs, the highest subsidy for railway transportation should be given in accordance with a fixed proportion of the unit construction subsidy.

(iii) When there are not too many hubs, as the perceived subsidy levels rise (competition becomes fierce), local governments should reduce their railway subsidies.

6. Conclusions

This paper investigates the hub location problem considering intermodal transportation and government subsidies (i.e., IHLPGS). This is a crucial issue of the BRI, which has strengthened co-opetition between governments in global transport networks during the COVID-19 pandemic. The overall goal of the problem is to reduce the total social cost of private entities, including hub construction, transportation and transshipment costs. Each local government along the B&R is faced with the issue of how to improve local economic benefits through subsidies (investments) for rail transportation and hub construction, as hub location planning is related to subsidization. Viewing the complexity of co-opetition behavior between governments caused by subsidies, we establish a two-stage MIP model and propose ILAGS, which combines a population-based algorithm with contest theory, to solve this problem. We carry out comprehensive computational experiments on various data collected from international transportation websites.

By comparing intermodal and monomodal transportation, we find that a hub's distribution function will create sufficient economies of scale to reduce transportation costs, whether such a hub is part of an intermodal network or monomodal network. However, due to the transshipment function of hubs, intermodal transportation is able to further reduce costs. This is more effective when there are not too many hubs and the costs of different modes of transportation vary greatly. We also analyze the effects of the degree of competition and hub construction on the results. The number of hubs makes a great difference in the total cost. In our setup, underbuilding is more costly than overbuilding, especially when construction subsidies are high. If there are too many hubs, rail subsidies from local governments will reach their highest levels, leading to vicious competition. Horizontal competition among local governments has a great impact on rail subsidies. As competition is stiffer, rail subsidies are lower. We show that competition is always a disadvantage when there are too many hubs, while it can be an advantage when there are few hubs.

We also look at subsidies from the perspectives of central and local governments. The results show that the total cost is lower under high-intensity construction subsidies. However, even if rail subsidies are maximized, the total cost will not necessarily fall. For the central government, it makes sense to ask local governments to reduce rail subsidies. If the number of hubs is properly designed at the top level, the government can rely less on rail subsidies and the total cost can be reduced. In addition, we find that rail subsidies are positively correlated with construction subsidies but are not necessarily related to the choice of hubs. For local governments, there is no need to blindly provide high railway subsidies. However, construction subsidies and railway subsidies should complement each other; otherwise, the initial investment will be wasted.

This study contributes to the literature on intermodal networks by evaluating the impact of competition between nodes arising from hub construction and/or rail transportation subsidies. The results of our study are also important for both governments and maritime/railway policymakers as they shed light on how a transportation system reacts to the co-opetition behavior of multiple network planning decision makers. Identifying supply chain cooperation and competition may help governments and maritime/railway policymakers reconsider the design of transport networks and formulate corresponding incentive mechanisms.

In the future, we will investigate some additional perspectives. First,

we will extend our model by relaxing general assumptions of the hub location problem, such as allowing goods to flow through more than two hubs, or stopovers. As the different impacts of hub nodes and non-hub nodes on local output are simplified in this model, we will further study the specific difference in impact and the influence of size difference on the results. We will also consider the influence of shippers' choice behavior on transportation rates. Effective solutions will then be developed to deal with more complex problems. Another interesting research direction would be to investigate a stochastic network design considering uncertainty in demand, costs or the amount of ship traffic.

Declaration of competing interest

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

Data availability

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

Acknowledgments

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2022.106414.

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