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Research Article

Evolution of the China Railway Express Consolidation Network and Optimization of Consolidation Routes

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China Rail Express (CRE) is the international container train line that runs between China and Europe. Since the implementation of China's Belt and Road initiative, CRE has developed rapidly. As most CRE trains travel directly from source to destination without load consolidation, CRE faces issues such as an insufficient cargo supply, a low load factor, and a low profit margin. To address these problems, we analyzed the selection of potential consolidation centers and the optimization of consolidation routes to these centers from the perspective of complex network evolution. First, we constructed rules for generation and evolution of the complex network. Next, we generated logistics connection topology networks for CRE from 2013 to 2017 using those rules. We then optimized the consolidation routes based on the network structures formed from those rules. Chongqing, Xi'an, Chengdu, Zhengzhou, Shenyang, Lanzhou, Urumqi, and Tianjin were selected as potential consolidation centers. We conclude with a sensitivity analyses and a discussion of management implications for CRE.

1. Introduction

China's Belt and Road Initiative (BRI) is an ambitious program to connect Asia with Africa and Europe via land and maritime networks. The initiative aims to improve regional integration, thereby increasing trade and stimulating economic growth. China Rail Express (CRE) is an important component of BRI, as it implements international container trains between China and Europe. CRE has developed rapidly since the first line, YuXinOu, commenced operations in 2011. In March 2015, China's government proposed the "Vision and action to promote the construction of the Silk Road Economic Belt and the Maritime Silk Road in the 21st Century" program. This program confirmed CRE's important role in creating an international land-based logistics channel for the Silk Road Economic Belt. In October 2016, the "CRE construction and development plan (2016–2020)" was proposed. It was the first top-level design of CRE development, and identified development targets for CRE over the next 5 year. In May 2017, President Xi Jinping's keynote speech at the BRI International Cooperation summit stated that cooperation agreements with the railway departments of the countries involved in BRI were necessary.

CRE has grown rapidly, from 17 trains per year in 2011 to 6363 in 2018 (Figure 1). By late 2017, 59 Chinese cities operated CRE terminals that were directly linked to 49 cities in 15 European countries. This shows strong international success and promising development prospects for CRE.

Despite CRE's rapid development and strong momentum, its operating mode is primarily point-to-point (direct transportation between source and destination) rather than representing an optimized network. CRE faces issues such as an insufficient cargo supply, a low load factor, a low profit margin, and high pressure upon the government to subsidize its operations. These issues have seriously weakened its economics and international competitiveness in long-distance cross-border transportation, and has thereby restricted its development. This, in turn, has affected the BRI implementation strategy. To address these issues, scholars have proposed the idea of cargo consolidation [1] and begun to apply it in practice. On

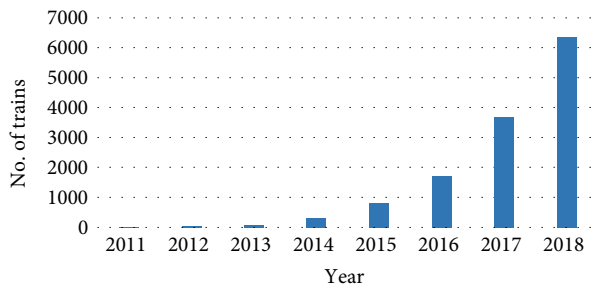


Figure 1: Trend of CRE train volume from 2011 to 2018.

20 December 2017, the first test train set out from the Urumqi consolidation center to follow the Chengdu–Urumqi–Tilburg route.

Although consensus exists on the benefits of CRE consolidation, selection of consolidation centers remains a difficult problem. If CRE consolidates cargo, the resulting logistics relationships would lead to the evolution of a complex network that includes operational nodes, consolidation centers, and routes between the nodes and the centers. This complex network can be called the CRE consolidation network (CRECN). In the CRECN, each node transfers cargoes to a consolidation center, where cargo from multiple smaller trains is unloaded and consolidated in an integrated train that carries the combined load to its destination.

With the increasing number of cities served by CRE, spatial interactions among the nodes of this network have become more complex. The network structure that formed during the early stages of the network's evolution will have sustained impacts on the subsequent evolution and optimization of the network. Both in theory and in practice, choosing suitable consolidation centers that can support continuous evolution of the CRE logistics network is a thorny problem.

To address this problem, we analyzed two issues in the present study: (1) How should the CRECN form and evolve? (2) Given CRECN's evolution, which locations are most suitable for consolidation centers?

In this paper, we provide several novel contributions to the literature. First, most previous studies have used mixed-integer programming methods to solve the problem of selecting locations for consolidation centers, and assumed that all nodes were fully connected, while ignoring the actual characteristics of the network structure and the issue of accessibility between nodes (i.e., whether an efficient path exists between pairs of nodes). We instead constructed the CRECN network using the 0–1 programming method to determine the optimal consolidation points and routes based on the constructed network. During this analysis, we also considered the impact of the network structure on selection of the consolidation routes. Second, previous research studied the CRE network using only a cross-sectional perspective, and did not consider the lock-in effects that result from the existing network structure that has evolved over time. In this paper, we explore the structural evolution of an optimal CRECN from 2013 to 2017, and clarify the laws that have governed this evolution.

The remainder of this paper is organized as follows. Section 2 presents the literature review. Section 3 describes the rules used to generate the complex network and generates the CRECN network in each year of the study period. Section 4 optimizes the consolidation routes based on the network structures formed in Section 3. Section 5 performs a sensitivity analysis. Section 6 discusses management implications and offers conclusions.

2. Literature Review

The literature review in this paper focused on two main aspects: CRE consolidation, and the characteristics of hub-and-spoke transportation networks.

2.1. CRE Consolidation. To understand the implementation of BRI, an increasing number of scholars have explored CRE. For example, Rodemann and Templar [2] identified the factors that enabled and inhibited Eurasian rail freight from six perspectives: political, economic, social, technical, legal, and environmental. With the development of CRE, a number of operational issues were revealed, such as unbalanced flows of freight in opposite directions (e.g., trains returning to their origin without carrying a load), high costs, and the limited market potential for competitiveness [3]. Consolidation of cargoes from multiple origins could solve these and other problems.

Scholars have studied the problems and opportunities of consolidation operations. Ye et al. [4] built a game model that included a railway company, a freight forwarder, and a shipper. They identified the optimal consolidation mode, and used several CRE consolidation centers, including Yuxinou, Zhengxinou, and Rongou, as examples to analyze the feasibility of the consolidation scheme. Fu et al. [5] focused on the general situation for seven train paths between China and Europe and established a value model with four appraisal indexes. They selected the optimal train path through comparison of the index values, and argued that the trains should be consolidated in the future. Zhao et al. [1] constructed railway, highway, and national road networks for 27 selected pre-candidate cities, and then used the TOPSIS model to comprehensively evaluate the flows within and between these networks. They selected five cities as the optimal consolidation centers using mixed-integer programming. Li et al. [6] studied the problem of grain backhaul distributions by CRE for trains from Europe and Central Asia. They selected 23 distribution nodes for imported grain based on a qualitative approach, then evaluated the importance of each node for freight transport by the railway, highway, and waterway networks using complex network theory. Using the improved-entropy TOPSIS model, they selected six cities as the final distribution centers. Dong et al. [7] analyzed the conditions of the CRE international transit hubs, including sufficient hinterland, an important position with respect to the main international logistics routes, excellent cargo-handling capacity, the conditions of land port operation, and the implementation of a free port policy. They further analyzed the feasibility of the Xi'an International Land Port as a CRE transit hub, and found that this port could reduce the operating costs and travel time. Wang et al. [8] used a "hub-and-spoke" organizational model

Table 1: Summary and comparison of the research literature.

Main characteristics of previous studies	Representative studies	Research perspectives
Evaluation of a node's importance using an indicator system	[2, 5, 7, 28, 29]	The indicator evaluation mostly analyzed the network as sublevels. It should instead consider the network as a functional whole
Evaluation of a fully connected CRE network	[1, 4, 6]	In practice, the CRE network is not fully connected, and does not represent a scale-free network
Evaluation of the CRE network with a focus on static analysis, primarily considering a cross-sectional view of the network structure	[1, 6, 8]	In practice, the CRE network is dynamic. The emerging network structure will lead to lock-in and path dependence, and will therefore significantly affect the network's future evolution

to identify the economic hinterlands of different border ports, and identified a number of transport hubs (including Harbin, Zhengzhou, and Lanzhou).

2.2. Hub-and-Spoke Transportation Networks. During the last decade, complex network theory has been widely used in transportation and logistics research. Scholars have explored railway networks [9, 10], shipping networks [11–13], air transport networks [14, 15], and urban traffic [16, 17]. Numerous studies have discussed the topological structures and behaviors of different transport networks. Hub-and-spoke (HS) networks have received much attention. HS networks offer many benefits, such as traffic flow consolidation, high coverage of a region by the network, and simplified operations [18].

As a typical network topology for freight consolidation, HS networks have been widely adopted in different transportation sectors. O'Kelly [19] first described the concept of HS networks, and formulated the p-hub model as a quadratic integer program. Hsiao and Hansen [20] developed a city-pair air transportation demand model and applied it to the HS air transportation network of the United States. Zheng et al. [13] studied a linear HS shipping network design problem and developed a mixed-integer programming model with nonconvex multi-linear terms. Meng and Wang [21] considered an intermodal HS network design problem with multiple stakeholders and container types, and solved the problem using a mathematical program with equilibrium constraints model.

Several studies have examined railway networks based on an HS structure. Jeong et al. [22] studied the HS network transportation problem for railway freight, and formulated a linear integer programming model whose objective function included both the typical operating cost and the costs due to transit time. They found that cities in France and Germany were the most important hubs in the European rail network. Lulli et al. [23] designed a service network based on real HS railway operations in Italy. Researchers have noted that HS networks have the features of scale-free networks [24, 25], and analyzed the impacts of these features on network robustness [26] and operating performance [27].

2.3. Summary and Research Problem. As a new type of railway network, the CRE has been studied by many researchers. However, research gaps remain.

The first research gap relates to the two main methods that have been used to study CRE consolidation issues. The first is based on a comprehensive appraisal of indices that describe the node importance. This method analyzes the node and group characteristics as sublevels of the network, but cannot consider the network as a whole. The second method confirms the pre-candidate points and then solves the consolidation route by mixed-integer programming. This method treats the default CRECN network structure as fully connected, but does not consider the actual network structure and accessibility between nodes (i.e., whether a feasible path exists).

The second research gap arises from the fact that most previous studies have focused on static analysis, and have considered the network structure via a cross-sectional analysis at a given point in time. However, in reality, the nodes of the CRECN did not join the network at the same time. The network structure that formed during the early stages of the network's evolution will have a sustained impact on the subsequent evolution and optimization of the future network (e.g., lock-in effects). Our literature review found no dynamic analysis of the formation and evolution of the CRECN structure.

Table 1 summarizes the key features of this previous research.

In the present study, we attempted to fill the abovementioned research gaps. In reality, although CRE has operated every year since 2013, most CRE trains have traveled directly between points. This has led to issues such as insufficient cargo to fill each train, a low load factor, and a high operating cost. In this paper, we adopted consolidation methods to solve or mitigate these problems. We designed the CRECN and optimized it to improve the existing transportation network, which is dominated by direct transportation between source and destination, to achieve more load consolidation. We adopted the following steps in our research framework:

Step 1. We constructed the CRECN network generation rules. Based on these rules, we generated the logistics connection topology network in 2013. At this time, only the logistics connections had formed, and the consolidation paths had not yet been determined.

Step 2. We optimized the logistics connection topology network developed in Step 1 to minimize the total network cost. The consolidation paths and the CRECN in 2013 were confirmed.

Step 3. We used the CRECN in 2013 as original network to generate the network in 2014 based on the network generation rules.

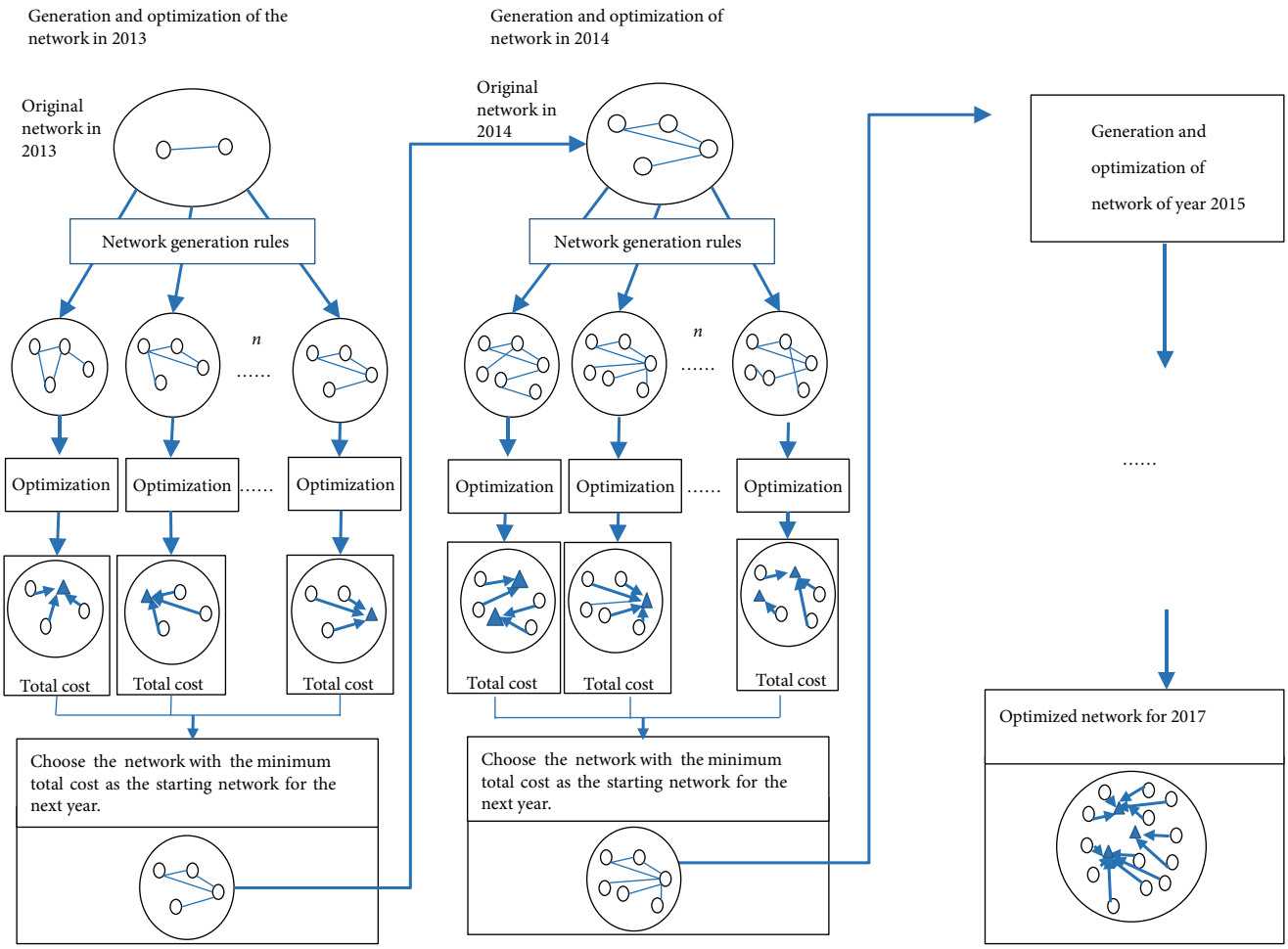


Figure 2: Framework for evolution of the transportation logistics network.

Step 4. We repeated steps 2 and 3 until we evolved and optimized the CRECN of 2017. Figure 2 illustrates this framework.

3. Generation of the CRECN

3.1. Structural Analysis of the CRECN Topology

3.1.1. Hybrid HS Network. CRECN is a complex system with strong comprehensiveness, a complex connection structure, and high requirements for spatial integrity. Each city that belongs to the railway network becomes a network node in the CRECN, and the edges represent the logistics connections between nodes. This complex network has three main characteristics:

(1) CRECN is spatially and temporally stable, but exhibits continuous evolution.

(2) The train operations are influenced by economics, politics, and geography. The connection relationships between nodes are intermediate between following a series of strict rules and randomness.

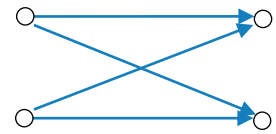
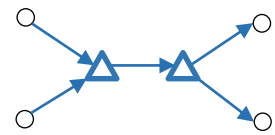
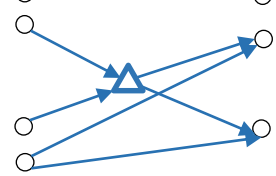
(3) Based on factors such as market demand and export distances, the CRECN is a weighted complex network.

Different transportation modes (e.g., direct vs. consolidation) between nodes in the CRECN can form different connection relationships and different network topologies, as shown in Table 2.

Among the actual and potential CRE transportation modes shown in Table 2, direct transportation is currently the main mode, but this mode requires a higher market demand to ensure full loads, which leads to a shortage of goods for some trains and low full load rates. Trunk–branch transportation can gather cargo from lower-level shippers, yielding scale benefits, but its flexibility is insufficient. In contrast, a consolidation network (a hybrid HS network) can both provide scale benefits through load consolidation and ensure that nodes that have sufficient freight can operate direct lines to allow fast transportation without the delays created by consolidation operations. In this mode, consolidation centers are selected and each branch line train travels to these centers, where its cargo is consolidated with cargo from other trains before transportation along a trunk line. Thus, it forms a complex transportation network. This kind of hybrid HS network is more suited to the needs of CRE.

3.1.2. Properties of a Scale-Free Network. A scale-free network is a type of network in which most nodes of the network only

Table 2: Transportation modes and network topological structures.

Transportation mode	Characteristics	Network topological structure	Network graphic
Direct transportation	No transshipment on the way, fast travel speed, Higher proportions of train cars with no load	Point-to-point network	
Hub-and-spoke transportation	High proportion of train cars that carry a load, Potentially poor timeliness of transportation	HS network	
Consolidation transportation	High proportion of train cars that carry a load, Reduced overall transport time	Hybrid HS network	

connect with a few other nodes, and few nodes connect to a large number of nodes. The network degree distribution (i.e., the probability of each node having a given number of connections with other nodes) follows a power-law distribution. Scale-free networks are widely used in transportation network analysis because they appear to be common in real-world networks and facilitate the dynamic addition and removal of nodes [30, 31]. Based on theory and practice, the CRECN should have scale-free network properties. The CRECN that we examined in the present study has three main attributes:

First, it is a specific rail freight network. Several scholars have analyzed the topological characteristics of rail freight networks. Li and Cai [32] presented an empirical analysis of the statistical properties of the CRE network, which consisted of 3915 nodes (train stations) and 22 259 edges (railway lines between nodes), and found that the network followed power-law distributions for both degrees and weighted degrees.

Second, the CRECN is a kind of hybrid HS network, and therefore is scale-free [24].

Third, given the practical requirements of the CRECN topological structure, it should have the following properties:

(1) The operating nodes are most likely to assemble at the existing nodes with mature conditions, which will lead to a disparity of node degrees and the "Matthew effect" of node degree distribution (i.e., "the rich get richer").
(2) The CRECN exhibits dynamic growth as more cities join the CRE network each year.
(3) Some consolidation centers have a high degree of connectivity within the CRECN.

Hence, the CRECN's hybrid HS structure should have the properties of a scale-free network, and should be suitable for our analysis of the CRE network's evolution.

3.2. Generating the Scale-Free Network in Each Year. In a hybrid HS network, nodes should connect to hubs along paths that form the spokes of the network. Reasonable connection rules are the foundation of a successful network, as they constrain or promote the evolution of the whole network, and play a decisive role in determining the network's structure and characteristics. Barabási and Albert [32] proposed that the scale-free properties of complex networks be reduced to two simple mechanisms: growth and priority connection. The Barabási–Albert free-scale network model has been extended in many ways, such as adding nonlinear priority connections, node aging and death, and random reconnection and removal of edges. Here, we use the extended Barabási–Albert model [33], and use it to define the annual rules that govern the evolution of the network by considering the characteristics of a hybrid HS network to form the CRECN model.

3.2.1. Node Growth Rule. In a network with m nodes, a new node is added with a certain probability p_0 and connects with m_0 existing nodes. At most, only one edge is connected between any two nodes. The greater the value of p_0, the greater the possibility of adding new nodes, and the faster the growth of the network through the addition of new nodes. The order of new nodes in each year depends on the first operating time of CRE in the node. When operations commenced earlier, the node will join the network earlier. Wang et al. [34] argued that the distance between the newly joined node and existing nodes in the network would negatively affect the connection relationship between them. Hence, we assumed that the connection between newly joined nodes and existing network nodes would be based on two factors: the degree of the existing nodes (i.e., the number of nodes they connect to) and the distance between the nodes. The connection probability is:

$$p(i) = \frac{d_i/l_{ij}}{\sum_i d_i/l_{ij}}, \tag{1}$$

where j represents a newly joined node, i represents an existing node in the network, and l_{ij} represents the spatial distance between nodes i and j, which is the railway distance in the present context.

3.2.2. Priority Connection (Edge Growth) Rule. Based on the rule for node growth, we define the probability that two existing nodes are connected as $1 - p_0$, and repeat the connection process m_0 times. Obviously, the larger p_0, the

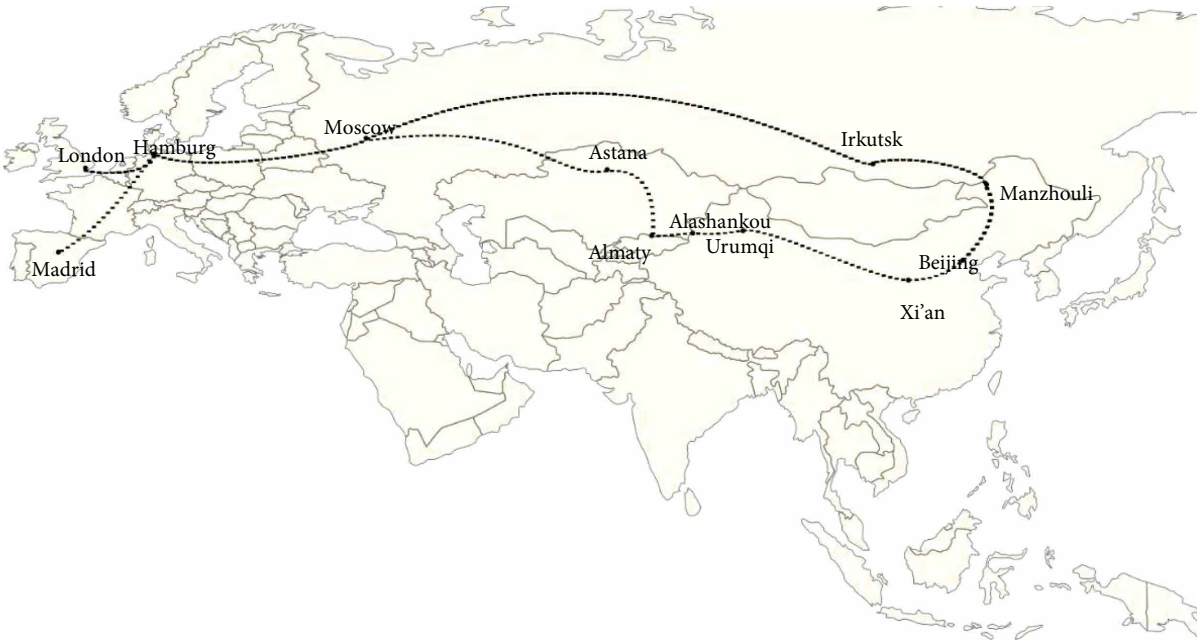


Figure 3: CRE transportation routes from China to Europe.

lower the probability of node connection and the slower the edge growth. The extended Barabási–Albert network treats the degree as the edge weight, and ignores connections between existing nodes with close economic ties. Hence, a connection between two nodes should be represented by a variable that combines distance and the market's demand for cargo. Many scholars have applied the economic gravity model to the field of logistics, and found that the closer the economic connection between two cities, the more easily transportation and logistics connections will form [35, 36]. As CRE is a long-distance logistics system, the economic gravity model is suitable for describing the relationship between cities in the CRE network. We therefore defined the connection probability between existing nodes based on the economic gravity model:

$$p(ij) = \frac{F_{ij}}{\sum_{ij} F_{ij}}, \tag{2}$$

where F_{ij} denotes the economic gravity between nodes i and j, which is calculated as follows:

$$F_{ij} = G\frac{G_i G_j}{{l_{ij}}^2}, \tag{3}$$

where G is the gravity parameter, which is generally set to 1, and G_i and G_j represent economic variables that describe the connection between the two cities. Since export products are the objects transported by CRE, we used the volume of foreign trade as a proxy for these variables.

3.2.3. Network Evolution Rule. To ensure the consistency and continuity of the CRECN's evolution over time, we used the network structure in year t as the starting point for evolution of the network in year $t + 1$. In 2011 and 2012, only Chongqing and Wuhan operated CRE trains. Thus, Chongqing (Node 1) and Wuhan (Node 2) were connected, and the initial network for 2013 grew from these two nodes.

To reduce the impact of randomness on the results, we conducted r experiments for each simulation period, and selected the results of the experiment with the lowest cost as the results of the current simulation.

4. Selection of CRE Consolidation Centers and Consolidation Routes

4.1. Problem Description. To establish the optimization model, we made several assumptions based on the actual operation of CRE. These related to exit paths (routes by which cargo left the country), transportation modes (direct vs. consolidation), and operating costs.

4.1.1. Exit Lines. Although the routes and destinations of CRE are quite different, most of the routes pass through one important city: Moscow. We therefore chose Moscow as the destination of the CRECN in this analysis. The exit ports are Manzhouli, Erlianhot, and the Alashan Pass/Khorgas. Few CRE trains operate along the central route, and the frequency of operation is unstable. Thus, we have only considered the eastern route and the western route (Figure 3).

4.1.2. Transportation Mode. We assumed that each node of the CRECN will not transport cargo directly to its destination, but will instead transport cargo to only one consolidation point (or a direct train). For simplicity, we assumed that the consolidation point will only operate direct trains to Moscow, and will not transport cargo to a second consolidation point, although this is a possible option in future research. Since all the nodes in the CRECN have operated CRE trains in the past, we assumed that all cargo will be consolidated by rail, without accounting for highway, waterway, or other multimodal

Table 3: Parameters and variables used in the CRECN model.

Symbol	Definition
Sets	
I	Set of CRE origin nodes, indexed by i
J	Set of CRE consolidation centers, indexed by j
M	Set of CRE corridor gateways (i.e., ports of exit between China and Europe), indexed by m
D	Set of Destination nodes, indexed by d, which is Moscow
Parameters	
f	The unit setup cost of the consolidation centers
μ	The unit value of time
δ	Maximum daily cargo-handling ability of the consolidation center
l_{ij}	Rail distance between nodes i and j
q_i	Annual freight volume of node i
p_1	Cargo cost (CNY/t-km) before consolidation
P_2	Cargo cost (CNY/t-km) after consolidation
Decision variables	
a_j	Binary variable. If node j is selected as a consolidation center, then $a_j = 1$; otherwise, $a_j = 0$
b_{ij}	Binary variable. If origin nodes i consolidates to node j, then $b_{ij} = 1$; otherwise, $b_{ij} = 0$
c_{jmd}	Binary variable. If corridor gateway m is selected as an exit point in the route from consolidation center j to destination d, $c_{jmd} = 1$; otherwise, $c_{jmd} = 0$

transport modes. Such additional transportation modes could be added to our model in future research.

4.1.3. Operating Costs. The operating costs for a consolidation center included loading, sorting, and unloading to produce a single unified unit price for transport of cargo.

4.2. Notation. All the parameters and variables using in the model are defined in Table 3.

4.3. The CRECN Optimization Model. Based on the abovementioned assumptions, we constructed the optimization model. The objective function was to minimize the total cost (TC) of the transportation network:

$$\begin{aligned}\text{Min}\, TC = &\sum_{i\in I}\sum_{j\in J}\mu \max\left\{0, \frac{365}{q_i b_{ij}/q} - 1\right\} q_i b_{ij} + \sum_{i\in I}\sum_{j\in J} p_1 l_{ij} q_i b_{ij} \\ &+ \sum_{j\in J}\mu \max\left\{0, \sum_{i\in I}\left(q_i b_{ij} - \delta\right)\right\} \frac{\max\left\{0, \sum_{i\in I}\left(q_i b_{ij} - \delta\right)\right\}}{\delta/365} \\ &+ \sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\sum_{d\in D} p_2 c_{jmd} l_{jmd} q_i b_{ij} a_j + \sum_{j\in J} f a_j,\end{aligned} \tag{4}$$

s.t.

$$\sum_j b_{ij} = 1,\ \forall i, \tag{5}$$

$$b_{ij} \neq b_{ji},\ \forall i, j, i \neq j, \tag{6}$$

$$b_{ij} \leq a_j, \forall i,\ j, \tag{7}$$

$$\sum_m c_{jmd} = 1,\ \forall j,\ d, \tag{8}$$

$$c_{jmd} \leq a_j,\ \forall j,\ m,\ d, \tag{9}$$

$$a_j \in \{0, 1\},\ \forall j, \tag{10}$$

$$b_{ij} \in \{0, 1\},\ \forall i,\ j, \tag{11}$$

$$c_{jmd} \in \{0, 1\}, \forall j,\ m,\ d, \tag{12}$$

$$i \in I,\ \forall i, \tag{13}$$

$$j \in J,\ \forall j, \tag{14}$$

$$m \in M,\ \forall m, \tag{15}$$

$$d \in D,\ \forall d. \tag{16}$$

The objective function includes the waiting cost at start node i, the freight cost from node i to consolidation center j, the waiting cost at the consolidation center, the freight cost from consolidation center j through exit node m to the destination, and the total setup cost of the consolidation centers. Equation (5) ensures that each starting point must and can only be connected to one consolidation center. Equation (6) ensures that the CRECN is a one-way network (i.e., we only consider exports, not two-way flows of cargo), that the consolidation is only in one direction, and that there is no reverse relationship. Equation (7) ensures that the consolidation route is from origin node i to consolidation center j. Equation (8) ensures that only one exit point should be selected for each consolidation center j. Equation (9) ensures that the exit route is started from consolidation center j.

Figure 4 illustrates a model for the process of cargo consolidation with n origins, j consolidation centers, two corridor gateways (i.e., the eastern and western routes), and one destination (Moscow).

Based on data from the research literature [1], the cargo weight transported by a single train is 1500 t, the unit freight

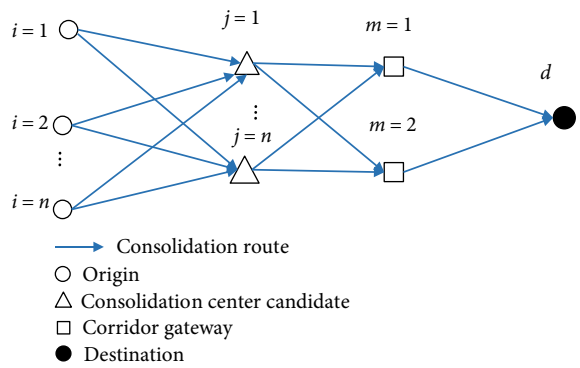


Figure 4: Flows of cargo in the CRECN. Abbreviations: i = shipment origin; j = consolidation center; m = corridor gateways; d = destination.

before consolidation is $p_1 = 0.1$ CNY/t-km, the unit freight after consolidation is $p_2 = 0.3$ CNY/t-km, the unit waiting cost is $\mu = 150$ CNY/t-day, and $\delta = 780$ trains/year. The setup cost of the consolidation center is 2×10^9 CNY, and its depreciation is averaged over 20 years.

4.4. Genetic Algorithm Design. Each node can send a train directly to a destination, or to a consolidation center with a connection. This may be treated as a 0–1 programming problem with constraints in a discrete network. The discrete network design problem has been shown to be NP-hard, and is difficult to solve using exact methods [37]. We therefore used a heuristic method to solve the model. Genetic algorithms (GAs) have seen a number of applications in solving NP-hard programming problems [21]. Hence, we chose a GA to solve the problem. The GA process is shown in the Appendix.

4.5. Results

4.5.1. Topological Structure of CRECN in Each Year. Based on the network evolution rules designed in this paper, p_0 is a key parameter for the generated network structure. As p_0 represents the growth rate of the number of nodes in the network, increasing p_0 will increase the number of nodes faster. We used the following expression to describe p_0 in each year:

$$p_{0t} = \frac{n_t}{\sum_t n_t}, \tag{17}$$

where n_t represents the number of newly operating CRE nodes in year t. In addition, $m_0 = 1$. The trade data used in this paper were obtained from the "China Urban Statistics Yearbook." The railway data were obtained from the China Railway Customer Service Center Web site (http://www.12306.cn).

To mitigate the influence of the randomness of network generation on the network topology, we used repeated experiments, and selected the optimal value of TC from the results. We let $r = 30$, which means 30 simulations were performed for each year. The best of these simulations was chosen as the network structure for that year. We implemented the network evolution rules using MATLAB 2016 (https://www.mathworks.com), and simulated the CRECN's evolution. We ran the simulations on a computer equipped with an Intel Core i7-7500U CPU running at 2.70 GHZ and with 8 GB of RAM, and the calculation time was 104.4 s for 2013 (2 nodes at the start of the simulation), 245.2 s for 2014 (7 nodes), 364.3 s for 2015 (15 nodes), 991.1 s for 2016 (27 nodes), and 1556.4 s for 2017 (39 nodes). The calculation time increased rapidly as the network grow. Figure 5 illustrates the evolution of the CRECN.

During the evolution of the network, the network density in the central and eastern regions increased significantly. This is because China's industrialized areas are mainly concentrated in the central and eastern regions, and these industries are the main cargo source for CRE. Some regional subnetworks formed in the northwest, northeast, and southwest.

Figure 6 shows the network node degree's probability distribution and cumulative probability distribution at the end of the simulation in 2017. The node degree's probability distribution followed a power law, with a significant and moderately strong regression. This means that the CRECN conforms to the properties of a scale-free network. As the CRECN evolved, a number of pivotal nodes continued to emerge, for which the degree was significantly higher than that of ordinary nodes. Although the network generation rules considered both the node degree and distance (as a weighting factor), the Matthew effect was strong. As the CRECN evolved under the hybrid HS network rules, it continued to show scale-free properties. Pivotal nodes with a high degree were more likely to be selected as consolidation centers.

4.5.2. Effectiveness of GA. In our analysis, we set the population size to 500, specified 20 000 generations of evolution, and used a mutation probability of 0.016. Taking 2017, which has the largest number of network nodes, as an example, the fitness converged at around 8000 generations (Figure 7).

4.5.3. Selection of Consolidation Centers and Routes. Optimizing the total cost of the CRECN revealed the optimal CRECN routes and the associated consolidation centers (Table 4). The final consolidation centers in 2017 were Chongqing, Xi'an, Chengdu, Zhengzhou, Shenyang, Lanzhou, Urumqi, and Tianjin. Cargoes that pass through Shenyang and Tianjin leave China through the Manzhouli port of entry, and the remaining centers exit though the Alashan Pass/Khorgas (Figure 8).

We compared the total cost of point-to-point network, which represents the realistic CRE network, and CRECN. As shown in Figure 9, the total cost of CRECN is much less than the point-to-point network, which confirms the effectiveness and rationality of the CRECN.

The evolution of the CRECN shows four overall results.

First, the locations of the consolidation centers and CRE terminal cities show obvious regional characteristics. Based on the distribution of the node degree in the final network, Xi'an and Zhengzhou are the two nodes with the largest degree. These two cities are located in central China. This superior geographical location enables the cities to gather cargoes from many regions. Based on the distribution of the cargo sources, the cargoes that are transported to these two consolidation centers come primarily from eastern, central, and southern China. There are nine cities in the coastal areas of eastern and southern China that have CRE rail terminals, but they are too far from the exit ports to function as consolidation centers.

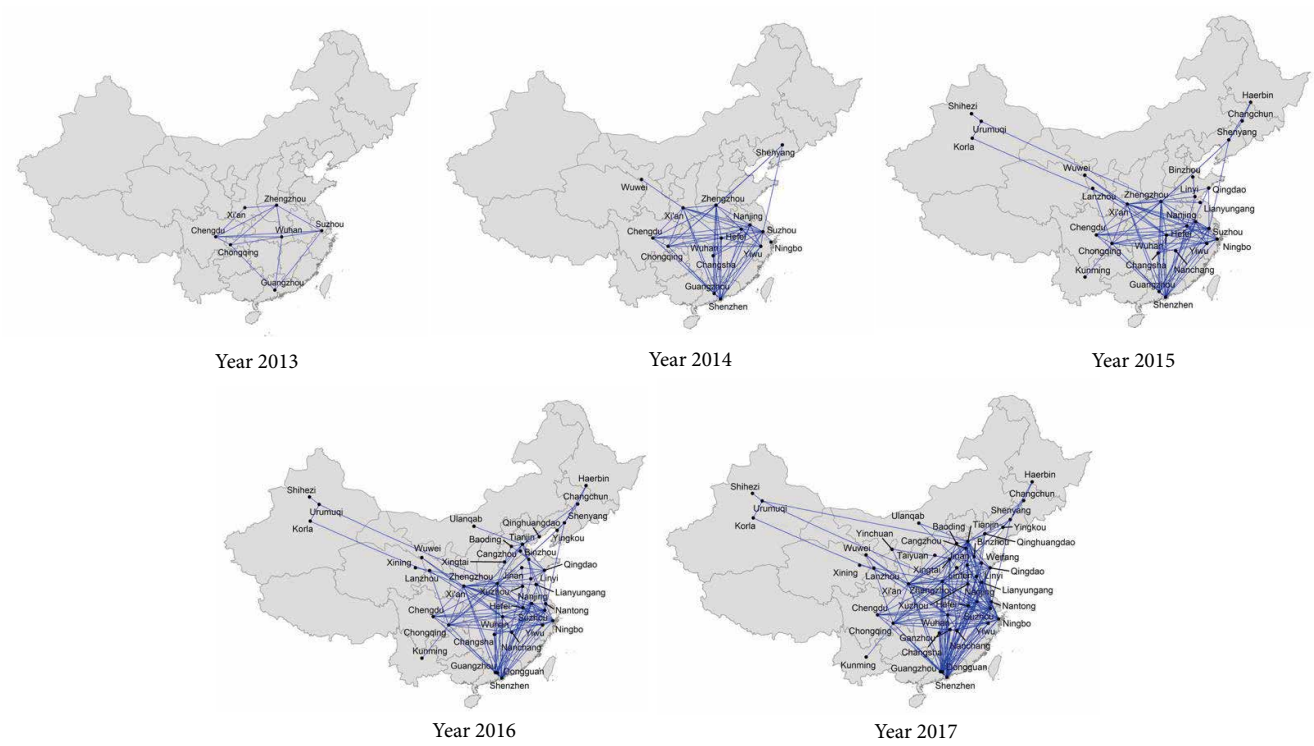


Figure 5: Evolution of the CRECN network topology.

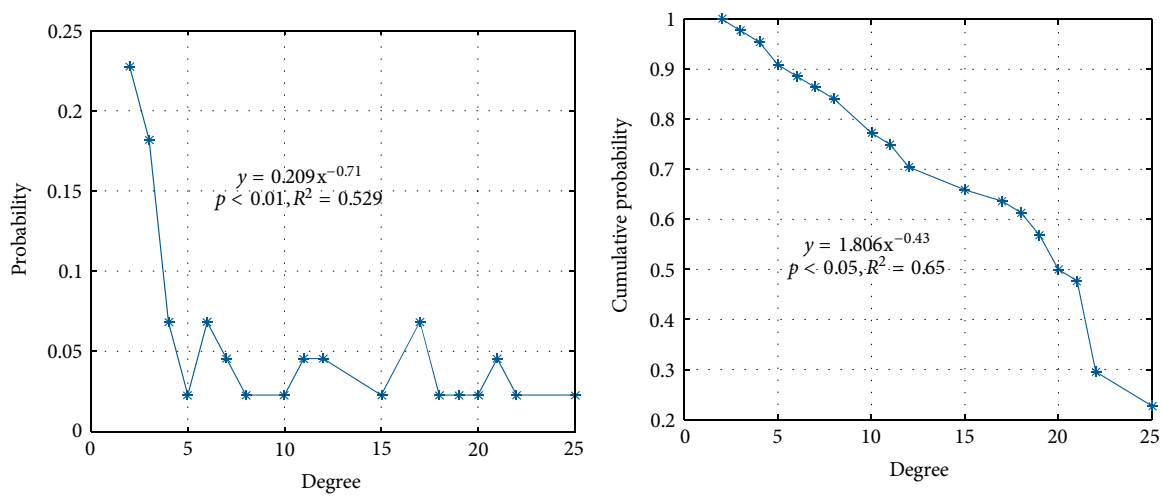


Figure 6: CRECN node degree probability distribution and cumulative probability distribution for 2017.

Hence, their cargoes will be consolidated in Zhengzhou and Xi'an, in central China, and then transported to Europe.

Chongqing and Chengdu are located in southwestern China. They will gather cargoes from southwestern and southern China. Chengdu will operate direct trains for its plenitude of cargoes. Tianjin, located in northern China, will collect cargoes from northern China and its CRE trains will exit through Manzhouli. Shenyang is the consolidation center for northeastern China. Its main cargo sources are the three northeastern provinces, and its cargoes will also exit through Manzhouli. Urumqi is too far from the main sources of cargoes to form an effective economic link with those sources. However, Xinjiang Province is too far from central China. and it is unreasonable to consolidate cargoes in reverse by moving them from west to east. Therefore, Urumqi will remain a necessary consolidation center, and will gather its cargoes largely from Xinjiang Province. Lanzhou should be a sub-consolidation center in northwestern China because of its small economic gravity for cities in the surrounding areas and its proximity to Xi'an.

Second, some nodes will operate direct trains without consolidation. The evolution of the CRECN shows that the nodes that will operate direct trains generally possess two characteristics. First, these nodes joined the network later,

Table 4: Selection of consolidation routes and the corresponding consolidation centers.

Year	Start nodes	Consolidation center
2013	Chengdu, Guangzhou	Chongqing
	Wuhan, Suzhou, Xi'an	Zhengzhou
2014	Chongqing, Wuhan, Chengdu, Suzhou, Guangzhou, Hefei, Shenzhen, Nanjing, Wuwei	Xi'an
	Yiwu, Shenyang, Changsha	Zhengzhou
2015	Lanzhou, Kunming, Nanchang	Chongqing
	Wuhan, Chengdu, Suzhou, Guangzhou, Hefei, Shenzhen, Nanjing, Wuwei, Ningbo, Qingdao, Linyi	Xi'an
	Yiwu, Changsha, Lianyungang	Zhengzhou
	Shenyang, Changchun	Harbin
	Korla, Shihezi	Urumqi
		Binzhou
2016	Lanzhou, Kunming, Nanchang, Jinan	Chongqing
	Wuhan, Suzhou, Guangzhou, Hefei, Shenzhen, Wuwei, Ningbo, Qingdao, Linyi, Xuzhou	Xi'an
		Chengdu
	Yiwu, Changsha, Lianyungang, Xining, Xingtai	Zhengzhou
	Changchun, Harbin, Yingkou	Shenyang
	Dongguan, Nantong	Nanjing
	Korla, Shihezi	Urumqi
	Binzhou	Cangzhou
	Baoding, Qinhuangdao, Ulanqab	Tianjin
2017	Kunming, Nanchang, Ganzhou	Chongqing
	Wuhan, Suzhou, Guangzhou, Hefei, Shenzhen, Nanjing, Ningbo, Qingdao, Linyi, Xuzhou, Xingtai, Baoding, Cangzhou, Taiyuan, Yinchuan	Xi'an
		Chengdu
	Yiwu, Changsha, Lianyungang, Dongguan, Xining, Linfen, Weifang	Zhengzhou
	Changchun, Haerbin, Yingkou	Shenyang
	Wuwei	Lanzhou
	Korla, Shihezi	Urumqi
	Binzhou, Jinan, Qinhuangdao, Nantong, Ulanqab	Tianjin

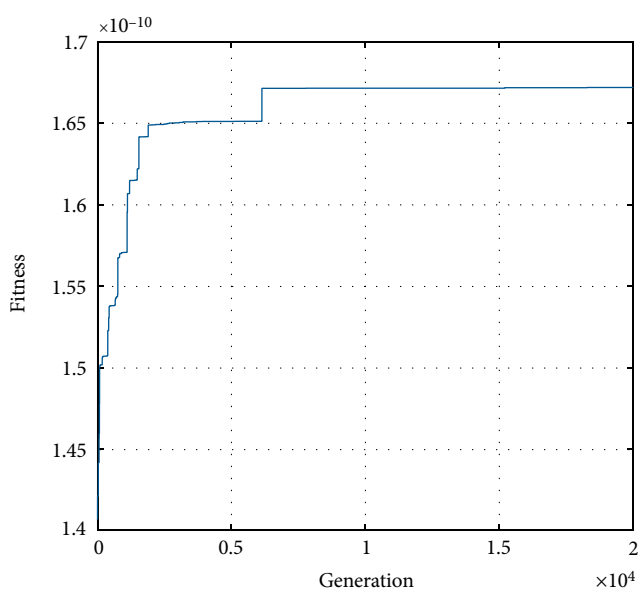


Figure 7: Convergence of the genetic algorithm using data from 2017 as an example.

such as Ningbo in 2014 and Binzhou in 2015. These nodes have not formed sufficient logistics connections with other nodes, and can therefore only operate direct trains. However, as the CRECN continued to evolve, the connections between these nodes and other nodes increased, and they shifted from direct trains to consolidation trains. The second characteristic is that some nodes have a high freight volume, such as Chengdu in 2016 and 2017. The freight volume that passes through Chengdu was not large before 2016 and the consolidation mode is better. However, with increasing freight volume, consolidation will actually reduce its operating efficiency and increase operating costs. Thus, direct trains are becoming more suitable for cargoes that pass through Chengdu. Therefore, this node will evolve from consolidation trains to direct trains.

Third, the average cost and average freight cost show a downward trend since 2013 (Figure 10). With the evolution of the CRECN, the network will be continuously optimized, thereby reducing both costs. This also means that, along with the continuous implementation of CRE, we will need to periodically adjust and optimize the consolidation paths.

Fourth, consolidation modes should be flexible. Figure 8 shows that some nodes have issues related to reverse consolidation. That is, the direction of consolidation (west to east) is the opposite of the ultimate transportation direction (from east to west), which greatly increases the transport cost. For example, the cargoes from Yinchuan

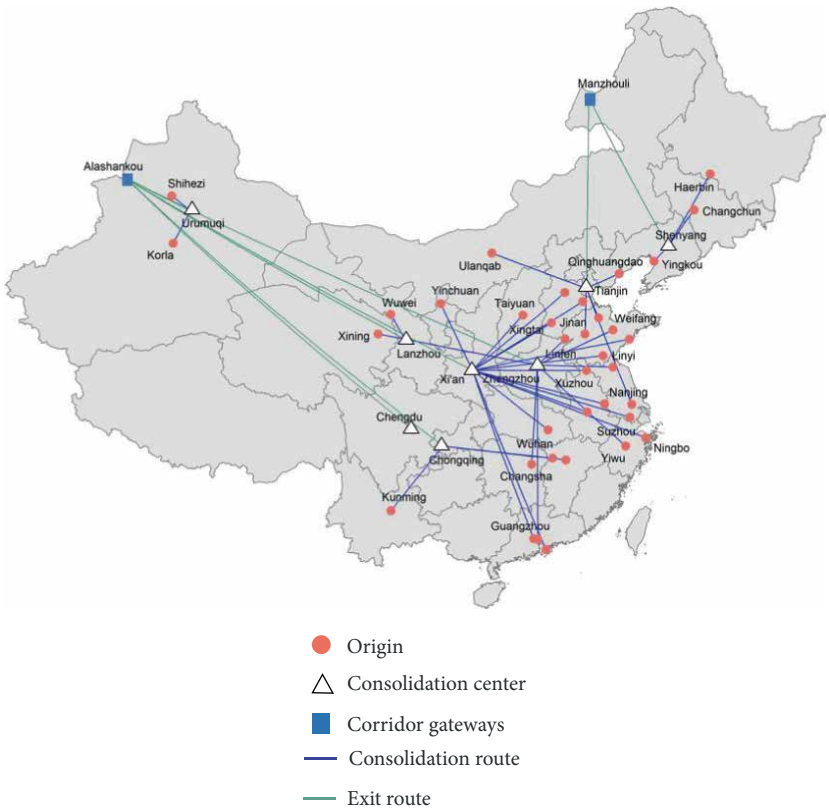


Figure 8: The optimal CRECN in 2017.

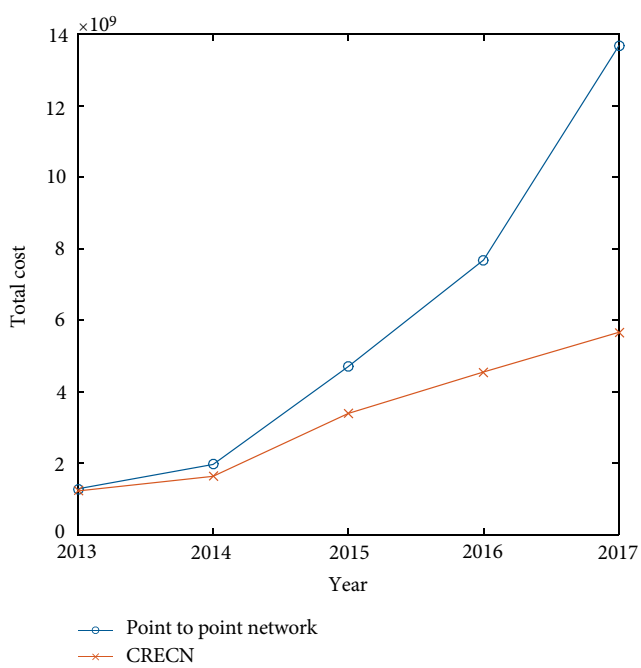


Figure 9: Total cost comparison between point-to-point network and CRECN.

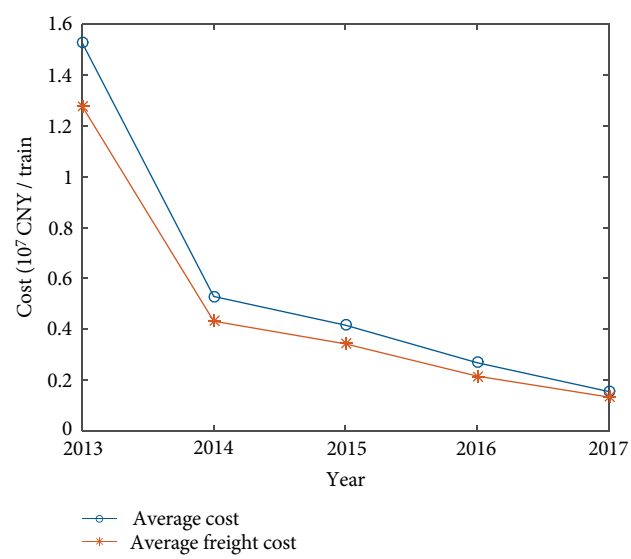


Figure 10: Average annual costs and average freight costs for the CRECN.

must be transported eastward to Xi'an for consolidation, then go west again from Xi'an. After passing through Yinchuan again, the train then exits China to the west. Therefore, the consolidation mode may shift. After consolidation, the main mode is a direct train to western destinations, but the drop-and-hook mode can be used when appropriate. In the drop-and-hook mode, the consolidation train stops briefly at a drop-and-hook station along its direct route, where it picks up cargo that could not be efficiently delivered to the consolidation center, then continues its

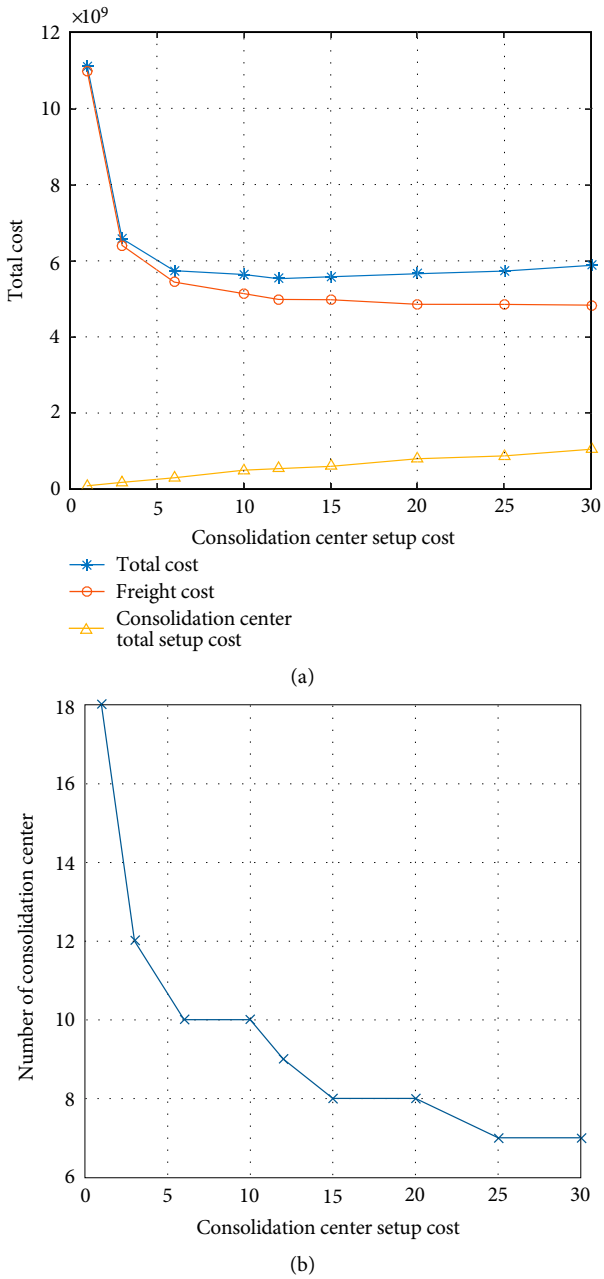


FIGURE 11: Impacts of the setup cost per consolidation center on the (a) total cost (*TC*) of the CRENC and (b) optimal number of consolidation centers.

journey. This ensures sufficient cargoes for the consolidation center while also reducing operating costs by avoiding reverse consolidation.

5. Sensitivity Analysis

To explore the factors that affect the site selection results, we conducted a sensitivity analysis for the effects of several parameters. The sensitivity analysis was based on the 2017 network, which had the largest number of network nodes in our analysis.

5.1. Consolidation Center Setup Cost. The setup cost of a consolidation center is proportional to its processing capacity. To simplify the problem without losing generality, we assumed that $f = a\delta$, where $a > 0$. We can therefore calculate a as $a = f/\delta = 256\,410$ CNY/TEU. Figure 11 shows that with an increasing setup cost, the total setup cost increases (Figure 11(a)) and the number of consolidation centers decreases (Figure 11(b)). The cargo-handling capacity also increases, leading to a reduction in waiting time that reduces the risk of penalty costs from delayed shipments and reduces total transportation costs (see Section 5.3 for more details). As a result of these two factors, the total cost initially decreases and then increases. Since there is an optimal setup cost for consolidation centers, which minimizes the total cost, bigger is not necessarily better. Choosing the correct scale for each consolidation center can reduce the total cost of the network more effectively.

5.2. Freight. Our analysis considered the impacts of changes in freight volume before and after consolidation. Before consolidation, increasing the freight volume decreased the consolidation distance (Figure 12). That is, the higher the freight before consolidation, the closer together the consolidation centers will be. The number of consolidation centers and the total cost will increase with increasing freight volume before consolidation. As p_1 increases, the freight cost also increases, while waiting cost decreases for the increasing number of consolidation centers.

An increasing freight cost after consolidation increases the consolidation distance and decreases the number of consolidation centers (Figure 13(a)). At the same time, the total cost and freight cost increase, but the total setup cost decreases (Figure 13(b)).

This analysis shows that the geographical scope of the consolidation center is significantly affected by freight costs. It also illustrates the role of subsidies in CRE operations, since subsidies decrease the cost to the customer (an important incentive) and guarantee profitable operation of CRE until it can become self-financing. If consolidation occurs close to the source of cargoes, the freight shipments should rise after accounting for the consolidation subsidies. This suggests that at least in the short term, regional governments should use subsidies more often.

Table 5 lists the subsidy policies that have been implemented by certain CRE nodes. Many nodes subsidize overseas freight. Most of these nodes are close to the source of their cargoes and are suitable for overseas freight subsidies. Because Zhengzhou is far from the source of its cargoes, it subsidizes domestic freight heavily. This kind of subsidy also greatly improves the attractiveness of Zhengzhou as a consolidation center.

5.3. Value of Time (VOT). The value of time (VOT) for cargoes reflects their sensitivity to delivery time. Figure 14 shows that with increasing VOT, the number and total cost of the consolidation centers increases. As VOT increases, congestion at the consolidation centers also increases, thereby increasing the handling time. To reduce congestion, the number of

Table 5: Local subsidy policies under CRE (TEU, twenty-foot equivalent unit).

Node	Subsidy policy
Chongqing	Subsidize CRE cargoes to make the cost competitive with the current overseas sea freight rate; the freight price is about 4.5 CNY per kilometer.
Chengdu	3500 USD per TEU
Xi'an	600 000 CNY per train, equivalent to 11 000–15 000 CNY per TEU.
Lanzhou	6000 CNY per TEU. Lanzhou also provides free short-term stopovers and loading services, and provides advances on the national export tax rebate.
Zhengzhou	Depends on price of sea freight, but Zhengzhou offers free cargo collection within a radius of 1500 km.
Urumqi	All services at the rail station are free, and fees for customs supervision, warehouse handling, and short-distance transport are reduced.

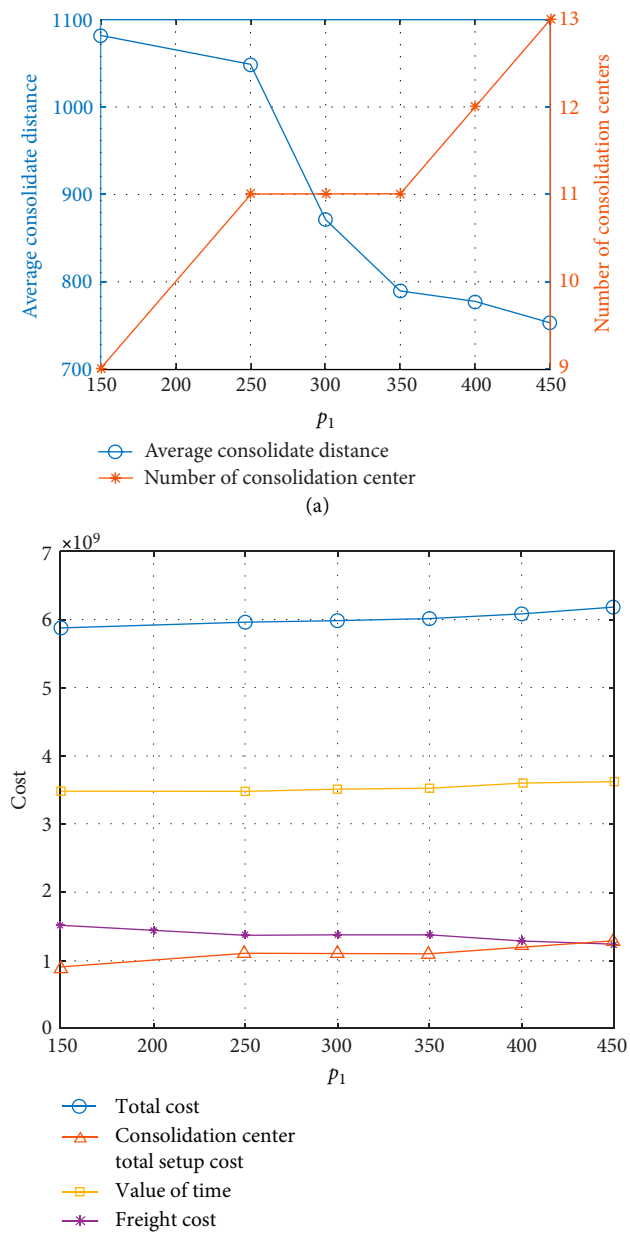


Figure 12: Impacts of freight cost before consolidation (p_1) on (a) the average consolidation distance and number of consolidation centers, and (b) the total cost (TC), freight cost, and consolidation center setup cost.

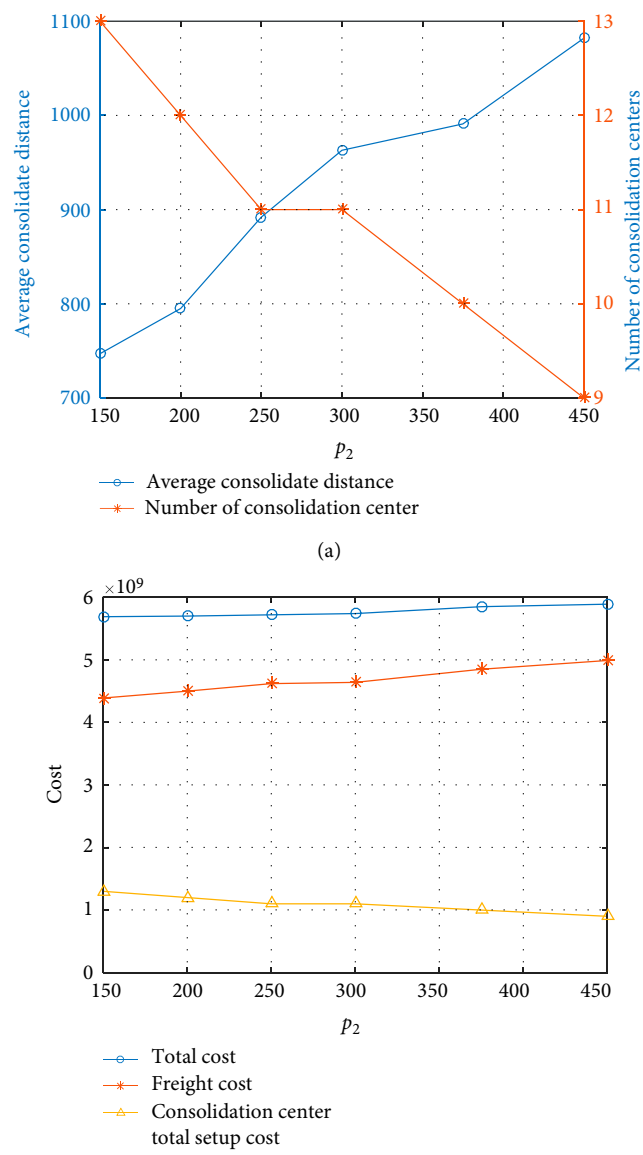


Figure 13: Impacts of freight cost after consolidation (p_2) on (a) the average consolidation distance and number of consolidations centers and (b) the total cost (TC), freight cost, and consolidation center setup cost.

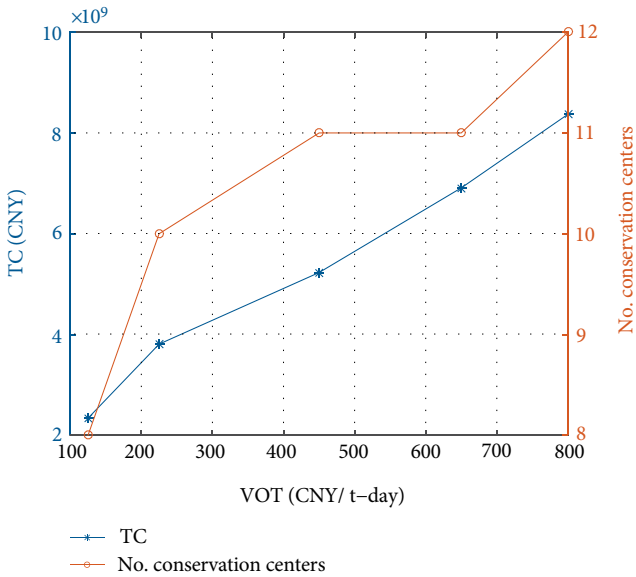


Figure 14: Impact of the value of time (VOT) on total cost (TC) and the number of consolidation centers.

Table 6: Additional consolidation centers that should be added as the value of time (VOT) increases.

VOT (μ, CNY/t-day)	Additional consolidation centers
125	Chongqing, Wuhan, Chengdu, Zhengzhou, Xi'an, Urumqi, Shenyang, Tianjin
225	Chongqing, Wuhan, Chengdu, Zhengzhou, Xi'an, Lanzhou, Urumqi, Shenyang, Tianjin
450	Chongqing, Chengdu, Zhengzhou, Xi'an, Changsha, Hefei, Lanzhou, Urumqi, Shenyang, Tianjin, Xuzhou
650	Chongqing, Wuhan, Zhengzhou, Xi'an, Changsha, Urumqi, Shenyang, Tianjin, Xuzhou, Xingtai, Cangzhou
800	Chongqing, Wuhan, Chengdu, Zhengzhou, Xi'an, Lanzhou, Urumqi, Shenyang, Tianjin, Xuzhou, Cangzhou, Qinhuangdao

consolidation centers must increase, which increases TC. Table 6 shows the additional consolidation centers that should be added to counteract the cost increase.

The transport capacity of CRE is about 1500t per train. The transportation time from China to Europe ranges from 12 to 15 days. Compared with marine transportation, CRE is more suitable for cargoes with high VOT and high unit value, such as electronics products. At present, the main cargoes of CRE are light industrial, daily, and mechanical products. The timeliness requirement for these products is relatively low. As the CRE market grows, the VOT for the cargoes will increase over time. It will be necessary to increase the number of consolidation centers, or operate direct trains to reduce the waiting time at consolidation centers and reduce the associated costs.

6. Conclusions

China Rail Express will become an increasingly important economic link between China and Europe, so optimizing its structure to lower costs and make the network self-financing is essential. To support this evolution, we combined two innovations: a hybrid hub-and-spoke network (CRECN) and genetic algorithms to identify optimal consolidation centers capable of reducing total transportation costs and optimizing the network's efficiency. This allowed a time series analysis rather than the cross-sectional analysis performed in most previous studies. However, our results were constrained by lock-in (e.g., the Matthew effect) and path dependence. The optimal CRECN was a scale-free network, and should reduce operating costs.

We identified eight optimal consolidation centers and routes to these centers in the overall CRE network by accounting for its rules-based evolution. Our sensitivity analysis showed that the consolidation center setup cost, freight cost, and value of time affected the optimal location and number of consolidation centers. These results provide management recommendations, such as adjusting the value of CRE subsidies until the CRECN becomes self-financing and adding additional consolidation centers or drop-and-hook nodes to reduce congestion.

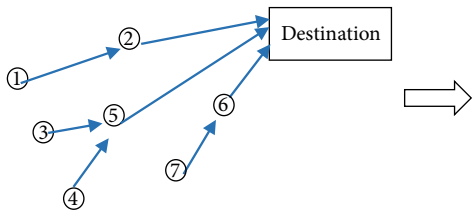
This paper has several limitations. First, the network was generated based on the cities that already participate in CRE, leading to lock-in effects. In future research, it will be necessary to determine whether this problem must be solved or whether the current centers are truly optimal. Second, the CRECN only considered the railway network, and did not consider multimodal transport using highways and waterways. The integration of multiple transport networks will permit additional cost savings, and should be the target of future research.

Appendix

The Genetic Algorithm (GA) Process

We used the Matlab2016 software to implement our genetic algorithm.

(1) Encoding. In the optimal model, the decision represents the consolidation routes for each node, so we encoded the GA's chromosomes as arrays of nodes in length. We used the natural number coding rule. Based on the order from left to right, each position represents the corresponding node. The number of the location represents the consolidation route from the node. For example, Figure 15 shows that chromosome 2255566 represents cargo transport from node 1 to node 2 for consolidation, from node 2 to node 2 itself during consolidation



Start node number	1	2	3	4	5	6	7
Chromosome	2	2	5	5	5	6	6

Figure 15: Coding of the genetic algorithm.

(i.e., node 2 accounts for direct trains within the node), node 3 goes to node 5 for consolidation, and so on for all nodes in the network. The number of each location is assigned based on the complex network that is formed by the paths among the nodes. Since CRECN is a one-way network, it is impossible for the chromosomes to exhibit $a_i = j$ and $a_j = i$, simultaneously.

(2) Population Initialization. According to the coding rules for the seeds, a large number of seeds were randomly generated to form the initial population. The size of the population equals the number of individuals in the population (here, the number of nodes), and the size of the population directly affects the computational efficiency and convergence of the genetic algorithm. We set the population size to 500, with evolution for 20 000 generations.

(3) Selection. The selection process was based on a fitness function that equaled the reciprocal of the total cost function:

$$F(x) = \frac{1}{TC(x)}, \tag{A.1}$$

We adopted roulette selection. We retained the first 50% of population and crossed them with the second 50%.

(4) Crossing. The corresponding positions of the two chromosomes were crossed.

(5) Generating Variants. By means of translocation mutation, we randomly selected two sites on each chromosome to exchange positions.

(6) Recalculating the fitness and iterating steps 3, 5, and 6.

(7) Termination of the Algorithm. The number of iterations was preset at 20000 generations. When the algorithm completed the specified number of iterations, the algorithm stopped, and provided the final result.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

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Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Authors' Contributions

Laijun Zhao and Zhaolin Cheng were contributed equally to this work.

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