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Hierarchical Multimodal Hub Location With Time Restriction for China Railway (CR) Express Network

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ABSTRACT Known as the Belt and Road Initiative, China Railway(CR) Express is a cross-continent railway container transport mode between China and Europe, and plays an important role for connecting China and Eurasia market to boost the regional economy. In order to balance cargo flow and improve transport efficiency, this paper proposes a hierarchical multimodal hub location problem with time restriction for CR Express network. A mix integer programming is formulated and derived, and some results are concluded based on our observation and investigation on CR Express. The results illustrate the rail hub location in China with different rail hub number input, and the hinterland of every hub is explored as well. The rail hubs tend to cover more regions first and then be spatially agglomerative in the central and western regions of China. Moreover, we find that the city Wulanchabu that is located in Inner Mongolia Province has the largest hinterland range, and that strong competition among hubs exists in central and western of China, especially for Zhengzhou, Xi'an, Chongqing and Chengdu.

INDEX TERMS China Railway Express, hierarchical hub location, mix integer programming, multimodal transport, belt and road initiative.

I. INTRODUCTION

In 2013, Chinese present Xi Jinping put forward "the Silk Road Economic Belt" and "Twenty-First Century Maritime Silk Road" initiative in his speeches, respectively, which are known as two main parts of "the Belt and Road" initiative (hereinafter referred as "B&R" Initiative). "B&R" Initiative is a blueprint for China to explore good cooperation with new trade partners and to boost regional economic, involving a few of new trade and investment initiatives. Improving and reconfiguring transport and logistics networks along the trade corridors and connectivity among participating countries, through the land-based route and the sea-going route together, are primary goals of the initiative [1]. Fig. 1 shows the sketch map of "B&R" initiative including two main routes. As for the land-based route, Chinese government has strongly supported a new cross-continent rail transport mode, which is called China Railway Express (hereinafter referred to CR Express).

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FIGURE 1. The Belt and Road Initiative sketch map. ***Source:*** Xinhua News Agency.

CR Express plays an important role for "the Silk Road Economic Belt" developing. In 2011, the first CR Express run from Chongqing of China to Duisburg of German, via Alashankou port of China, Kazakhstan, Russia, Belarus, Poland etc. Nowadays, relying on the Siberia Continental Bridge and the new Eurasian Continental Bridge, CR Express

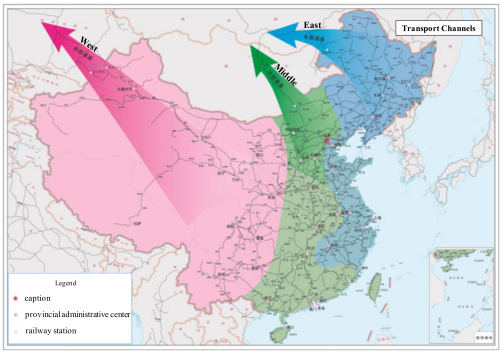

FIGURE 2. Three transport channels of CR Express. *Source:* China CR Express planning document.

has generated the west, the middle and the east transport channels within China and Eurasia markets, which is illustrated as Fig. 2. CR Express has two main characters; the first is the one-fifth of air transport cost, and the second is the one-third of maritime transport time. Featuring the shorter transport time and the reasonable fee, on one hand, CR Express has run from 56 cities of China and reached 49 cities of 15 European countries. Fig. 4 shows CR Express origin cites from 2011 to 2017. On the other hand, the total trains CR Express run increases continuously. According to statistics from China National Development and Reform Commission, CR Express has run 8225 trains in 2019 and has reached cumulatively 20000 trains by the end of 2019, also with a better balance of westbound (China to Europe) and eastbound (Europe to China) transport than this situation in the initial stage.

CR Express has developed dramatically and its international influence has grew rapidly with the content of ''B&R'' initiative, however, there are some problems and challenges with regard to the transport network emerging. Different CR Express origin cites of China has different situations. Some of them could attract sufficient cargoes and result in the supply shortage because of excellent location or good transport organization capability. For this situation, cargo owners need to wait for a long time, which weakens the transport efficiency advantage of CR Express. Meanwhile, some of origin cities of China struggle to operate CR Express with low load of railway transport, which causes the transport resources wasting. Moreover, with development of CR Express during more than 9 years, stakeholders pay more attention to operation quality than the total running trains. A better transport network structure for CR Express could not only generate a good balance of cargo flows but also increase transport efficiency, therefore, this paper develops a hierarchical hub location problem with time restriction for CR Express based on our observations and investigations in reality.

This paper is organized as follows. Related and recent literatures are reviewed in Section II. The detailed hierarchical hub location problem with time restriction for CR Express is proposed in Section III. Section IV formulates a mixed integer programming model for the problem and give the solution algorithm. Section V presents a numerical results and analysis. In Section VI, this paper in concluded and some future research is provided.

II. LITERATURE REVIEW

Problems with the content of ''B&R'' initiative has attracted more and more attentions of scholars since it was put forward, and most of the existing researches are related to the framework, economic opportunities, trade impact of this initiative [2]–[4]. Also, some researchers focus on the field of transport and logistics management with ''B&R'' initiative and point the importance of transport infrastructure to economic growth of involving areas [5]. Then, there are more and more researches discuss transport infrastructure related problems, especially problems of maritime transport [6], such as transport corridors [7], transport network [8], [9], and port competition [10]. Recently, with the increasing of international influence of CR Express, there is a trend to discuss problems with this new cross-continent railway container transport mode or railway transport with the content of ''B&R'' initiative. In order to solve the fierce hinterland competition between neighboring cities in the same region, Du and Shi proposed a incomplete information dynamic game model to discuss the government subsidy for CR Express from perspective of governments [11]. Also, Jiang *et al.* discussed the current and the prospective spatial-temporal hinterland pattern of CR Express for IT products and auto accessories two types of cargos in order to recognize cargo flow of network [12]. Shao *et al.* proposed a framework international cooperation relationship between China and other countries to evaluate the priority of transnational high-speed railway construction projects in the ''B&R'' surrounding region [13]. Similar to our problem, Zhao *et al.* combined complex network theory and TOPSIS method to select candidate nodes, and explored the optimal consolidation centers for CR Express by a mix integer programming [14]. However, this existing research focus more on the transport infrastructure in China and ignore the link between China and ''B&R'' initiative involving countries. CR Express is an cross-continent container railway transport mode, and it is of importance to consider cargo flow between China and other countries, therefore, this paper explore the hierarchical hub location for CR Express from the perspective of network considering trade interactions between China and involving countries.

There is a large body of literature discussing hub location and facility location problems. The hub location problem firstly proposed by O'Kelly [15], which explored the hub location and the allocation of demand nodes to hubs in a given origin-destination network. Then, O'kelly formulated a cost minimizing hub location problem, which could be seen as the first model in the field of hub location problem research [16]. Campbell presented integer programming formulations for four types of discrete hub location problems [17]: the p-hub median problem with minimizing total transport cost [16], [18]–[20], the uncapacitated hub location problem with

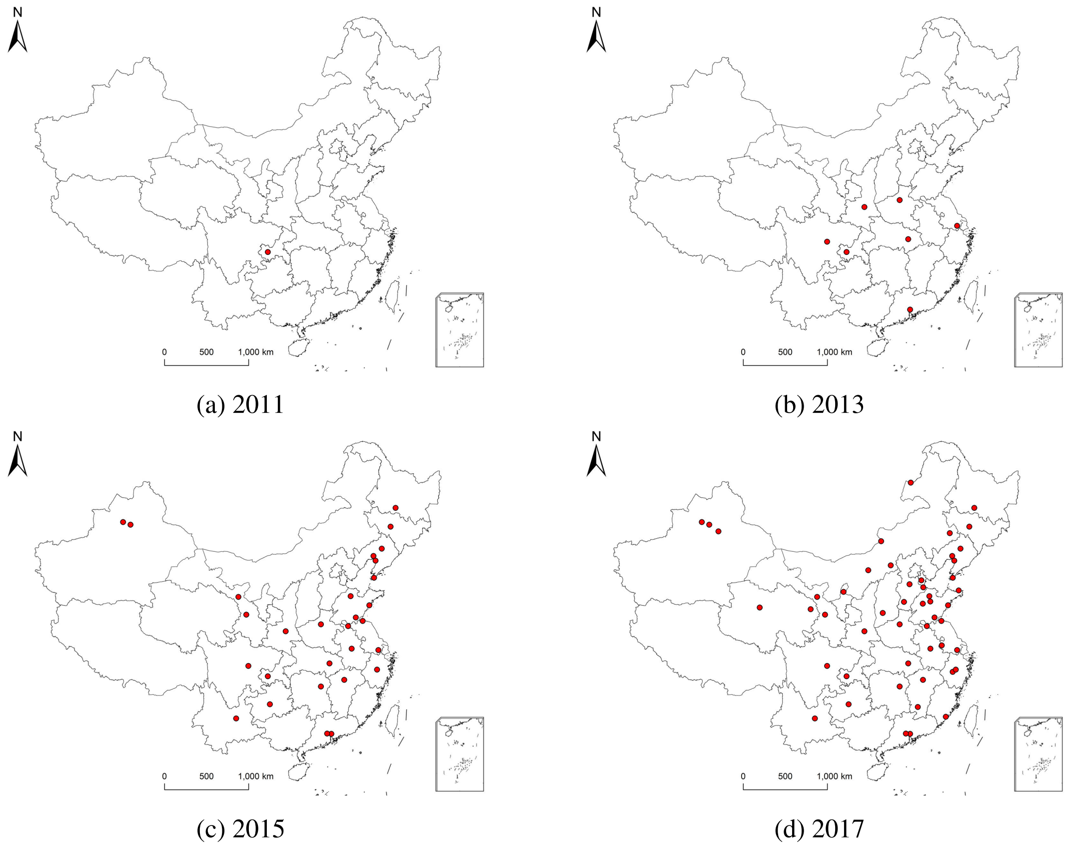

FIGURE 3. CR Express origin cities in China, 2011-2017.

minimizing total transport cost and fixed setup cost [21], [22], p-hub center problems with minimizing the maximum transport cost [23] and hub covering problems with minimizing number of hubs [24]. The fist two types of hub location problems has been discussed more by scholars. From the allocation perspective, hub location problem usually could be classified by two types, which are single allocation hub location problem [25], [26] and multiple allocation hub location problem [27], [28]. The difference is that cargo flow from one demand node could be allowed to more than one hubs in multiple allocation hub location problem but single allocation hub problem not.

Recently, relaxing the complete network assumption, many scholars tend to consider hub location problem involving different network structure. Hierarchical hub location problem is a kind of them. In the hierarchical network, cargo flow from origin node to destination node may visit more than one types of nodes or hubs [29]–[31]. It is the hierarchical multimodal hub location when cargo is transported by more than one mode [32], such as road-rail multimodal, road-air multimodal etc. Moreover, hub location problem with "time-definite" delivery has been investigated more and more by researcher in recent years with more requirements for service quality from customers [33], [34]. For the problem in this paper, transport network efficiency and service quality are very important points for CR Express network, therefore, in this paper, we formulate a hierarchical multimodal hub location with time restriction and present the solution algorithm, and present results for CR Express emphasizing the time restriction requirements and minimum total transport cost.

III. PROBLEM DESCRIPTION

In order to make the hierarchical multimodal hub location for CR Express network more clear, in this section, we make descriptions for CR Express network structure and operation process.

Fig. 4 shows the sketch of CR Express network structure, which contain three types of nodes, three main transport channels and multiple transport mode. Three types of nodes are demand nodes like node 1, 2, 7, CR Express rail hubs like node 3, 6, and gateway nodes like node 5. Three transport channels generate relying on the three gateway nodes in reality, which are Alashankou port, Erlianhot port, and Manzhouli port, to complete cargo transport between China and Europe. As for the multimodal transport, cargoes are transported by CR Express between two rail hubs via a gateway node, and cargoes are transported between demand node and rail hub by road, rail, even air transport mode. Moreover, the allocation principle between nodes are multiple

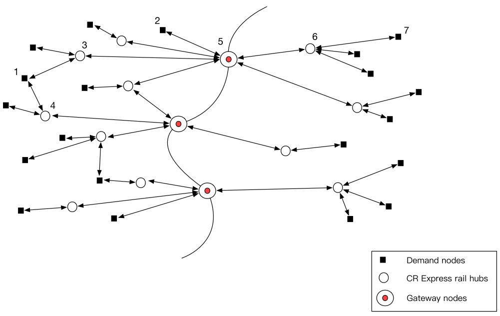

FIGURE 4. Illustration of CR Express network structure.

allocation. For instance, cargo flow from demand node 1 are partially allocated to rail hub 3, and others are allocated to rail hub 4; the allocation between rail hubs and gateway nodes are the same. Therefore, the CR Express network is a hierarchical multimodal transport network with multiple allocation principle. Cargo flow from a demand node to another need to visit two rial hubs and one gateway node, or one rail hub and one gateway node. The first category occurs in most situation. There is a bit difference for the second category, which is cargo flow from demand nodes in China may visit a gateway node directly not pass any rail hub, and then destined to demand nodes in Europe via one European rail hub.

Total transport time of CR Express is always an important factor for cargo owners while choosing cross national transport mode. In order to improve market competitiveness, the transport time of CR Express has been shortened for several times due to better organization and optimization. Therefore, in this paper, considering transport time restriction, we formulate a hierarchical multimodal hub location problem for CR Express with minimizing total cost, in order to explore rail hubs location in China and hinterland allocation.

IV. PROBLEM FORMULATION AND SOLUTION ALGORITHM

In this section, we introduce a mathematical formulation for CR Express network hub location problem based on above descriptions. The parameters and variables are shown as following.

Sets

N, Set of demand nodes, where $i, j \in N$;

H, Set of candidate rail hubs, where $H \subseteq N$, $k, m \in H$;

L, Set of candidate gateway nodes, where $L \subseteq H$, $l \in L$;

Parameters

w_{ij}, Total transport demand from node i to j, where $i, j \in N$;

O_i, Total cargo flow from node i, where $i \in N$;

D_i, Total cargo flow to node i, where $i \in N$;

t_{ik}, Road transport time from node i to rail hub k, where $i \in N$, $k \in H$;

t_{klm}, Railway transport time from rai hub k to rail hub m via gateway node l, where $k, m \in H$, $l \in L$;

t_{lm}, Railway transport time from gateway node l to rail hub$m$, where $i \in N$, $m \in H$;

t_{mj}, Road transport time from rail hub$m$ to node j, where $j \in N$,$m \in H$;

ht_k, Cargo process time atr rail hubs, where $k \in H$;

ht_l, Cargo transfer time at gateway nodes, where $l \in L$;

wt_k, Cargo waiting time at rail hubs, where $k \in H$;

wt_l, Cargo waiting time at gateway nodes, where $l \in L$;

T, Time restriction for cargo from node i to node j, where $i, j \in N$;

p_H, Number of rail hubs;

p_L, Number of gateway nodes;

c_{ik}, Unit road transport cost from node i to rail hub k, where $i \in N$, $k \in H$;

c_{mj}, Unit road transport cost from rai hub m to node j, where $m \in H$, $j \in N$;

c'_{kl}, Unit CR Express transport cost from rail hub k to gateway node l, where $k \in H$, $l \in L$;

c'_{lm}, Unit CR Express transport cost from gateway node l to rail hub m, where $l \in L$, $m \in H$;

d_{ik}, Road transport distance from node i to rail hub k, where $i \in N$, $k \in H$;

d_{mj}, Road transport distance from rail hub m to node j, where $m \in H$, $j \in N$;

d'_{kl}, CR Express transport distance from rail hub k to gateway node l, where $k \in H$, $l \in L$;

d'_{lm}, CR Express transport distance from gateway node l to rail hub m, where $l \in L$, $m \in H$;

Decision variables

x_k, 0-1 variable, node k is selected as a rail hub when $x_k = 1$, where $k \in H$;

y_l, 0-1 variable, node l is selected as a gateway node when $y_l = 1$, where $l \in L$;

a^i_k, Cargo flow origin from node i via rail hub $k$where $i \in N$, $k \in H$;

b^i_l, Cargo flow origin from node i to gateway node l directly, where $i \in N$, $l \in L$;

f^i_{kl}, Cargo flow from node i firstly visiting rail hub $k$and then to gateway node l, where $i \in N$, $k \in H$, $l \in L$;

g^{ij}_{lm}, Cargo flow from node i to node j via gateway node l and rail hub m, respectively, where $i, j \in N$, $m \in H$, $l \in L$;

v^{ij}_m, Cargo flow from node i to node j via rail hub m, where $i, j \in N$, $m \in H$;

Based on our observation and investigation on CR Express network, we organize and group the constrains of mathematical formulation as follows.

A. HIERARCHICAL HUB LOCATION AND MULTIPLE ALLOCATION CONSTRAINS

$$\sum_{k \in H} x_k = p_H \tag{1}$$

$$\sum_{l \in L} y_l = p_L \tag{2}$$
$$O_i = \sum_{j \in N} w_{ij} \quad \forall i \in N \tag{3}$$
$$D_j = \sum_{i \in N} w_{ij} \quad \forall j \in N \tag{4}$$
$$a_k^i \leq x_k(O_i - \sum_{l \in L} b_l^i) \quad \forall i \in N,\ \forall k \in H \tag{5}$$
$$b_l^i \leq y_l(O_i - \sum_{k \in H} a_k^i) \quad \forall i \in N,\ \forall l \in L \tag{6}$$
$$g_{lm}^{ij} \leq x_m D_j \quad \forall i, j \in N,\ \forall m \in H \tag{7}$$
$$x_k \in [0, 1] \quad \forall k \in H \tag{8}$$
$$y_l \in [0, 1] \quad \forall l \in L \tag{9}$$
$$a_k^i,\ b_l^i,\ g_{lm}^{ij} \geq 0 \forall i \in N,\ \forall k, m \in H,\ \forall l \in L \tag{10}$$

Constrains Eq. (1) and Eq. (2) presents the number of selecting rial hubs and gateway nodes are p_K and p_L, respectively. Total transport demand of every demand nodes are calculated by Eq. (3) and Eq. (4). Eq. (5), Eq. (6) and Eq. (7) describe the allocation between nodes, which is cargo flow from demand nodes only could be allocated to rail hubs or gateway nodes. Eq. (8) and Eq. (9) define two 0-1 variables, and Eq. (10) is the non-negative constrains.

B. CARGO FLOW ROUTING CONSTRAINS

$$O_i = \sum_{k \in H} a_k^i + \sum_{l \in L} b_l^i \quad \forall i \in N \tag{11}$$
$$D_j = \sum_{i \in N} \sum_{m \in H} v_m^{ij} \quad \forall j \in N \tag{12}$$
$$\sum_{i \in N} a_k^i = \sum_{i \in N} \sum_{l \in L} f_{kl}^i \quad \forall k \in H \tag{13}$$
$$\sum_{i \in N} \sum_{j \in N} \sum_{l \in L} g_{lm}^{ij} = \sum_{i,j \in N} v_m^{ij} \quad \forall m \in H \tag{14}$$
$$\sum_{i \in N} \sum_{k \in H} f_{kl}^i + \sum_{i \in N} b_l^i = \sum_{i \in N} \sum_{j \in N} \sum_{m \in H} g_{lm}^{ij} \quad \forall l \in H \tag{15}$$
$$a_k^i,\ b_l^i,\ f_{kl}^i,\ g_m^{ij},\ v_m^{ij} \geq 0 \quad \forall i, j \in N,\ \forall k, m \in H,\ \forall l \in L \tag{16}$$

The above set of constrains are to route cargo flow and to ensure flow balance in the network. Eq. (11) ensures all cargoes from demand nodes could be transported to rail hubs or gateway nodes. Similarly, Eq. (12) describes cargo flow destined to demand nodes. Eq. (13) and Eq. (14) ensure cargo flow balance at rail hubs; Eq. (15) is cargo flow balance constrain for gateway nodes. Eq. (16) is the non-negative constrain.

C. TRANSPORT TIME RESTRICTION CONSTRAINS

$$wt_k = \frac{1}{\alpha - r_k} \quad \forall k \in H \tag{17}$$
$$wt_m = \frac{1}{\beta - r_m} \quad \forall m \in H \tag{18}$$
$$wt_l = \frac{1}{\gamma - r_l} \quad \forall l \in L \tag{19}$$
$$r_k = \sum_{i \in N} x_k a_k^i \quad \forall k \in H \tag{20}$$
$$r_m = \sum_{i \in N} \sum_{j \in N} \sum_{l \in L} x_m g_{lm}^{ij} \quad \forall m \in H \tag{21}$$
$$r_l = \sum_{i \in N} \sum_{k \in H} y_l(b_l^i + f_{kl}^i) \quad \forall l \in L \tag{22}$$
$$\alpha,\ \beta,\ \gamma,\ x_k,\ x_m,\ a_k^i, y_l,\ g_{lm}^{ij},\ b_l^i,\ f_{kl}^i \geq 0 \quad \forall i, j \in N,\ \forall k, m \in H,\ \forall l \in L \tag{23}$$

Eq. (17)-Eq. (23) formulate waiting time at rial hubs and gateway nodes. In this paper, we assume cargo arrival at rail hubs and gateway nodes are poisson process with rate parameter r. Eq. (20)-Eq. (22) are mathematical calculation formulations for arrival container amounts at rail hubs and gateway nodes, respectively. Moreover, we assume that handling time at rail hubs of China, rail hubs of Europe, gateway nodes obey negative exponential distribution with parameter α, β, γ, therefore, waiting time are expressed as Eq. (17)-Eq. (19). Eq. (23) is the non-negative constrain.

Total service time for CR Express contains inland transport time by road, cross-continent railway transport time, handling time and waiting time at every nodes. The following set of constrains present the time calculation and time restriction constrains. Eq. (24) and Eq. (25) express two kinds of total transport time including inland transport time and CR Express transport time; Eq. (26) and Eq. (27) are cargo total handling time calculation; cargo total waiting time are presented as Eq. (28) and Eq. (29). Eq. (30) and Eq. (31) are time restriction constrains for CR Express transport total service time.

$$T_1 = t_{ik} + t_{klm} + t_{mj} \quad \forall i, j \in N,\ \forall k, m \in H,\ \forall l \in L \tag{24}$$
$$T_1' = t_{il} + t_{lm} + t_{mj} \quad \forall i, j \in N,\ \forall m \in H,\ \forall l \in L \tag{25}$$
$$T_2 = ht_k + ht_l + ht_m \quad \forall k, m \in H,\ \forall l \in L \tag{26}$$
$$T_2' = ht_m + ht_l \quad \forall m \in H,\ \forall l \in L \tag{27}$$
$$T_3 = wt_k + wt_l + wt_m \quad \forall k, m \in H,\ \forall l \in L \tag{28}$$
$$T_3' = wt_m + wt_l \quad \forall m \in H,\ \forall l \in L \tag{29}$$
$$sgn(a_k^i) * sgn(f_{kl}^i) * sgn(g_{lm}^{ij}) * (T_1 + T_2 + T_3) \leq T \quad \forall i, j \in N,\ \forall k, m \in H,\ \forall l \in L \tag{30}$$
$$sgn(b_l^i) * sgn(g_{lm}^{ij}) * (T_1' + T_2' + T_3') \leq T \quad \forall i, j \in N,\ \forall m \in H,\ \forall l \in L \tag{31}$$

D. OBJECTIVE FUNCTION

The objective function for the problem in this paper is to minimize total cost. Total transport cost contains road transport costs, rail transport costs, and handling costs. However, handling costs are not in our consideration because we assume handling cost is the same in every nodes and there are almost same handling costs for all cargoes. Therefore, objective function for this model is as Eq. (32), as shown at the bottom of this page.

As listed below, a mix integer programming formulation of hierarchical multimodal hub location with time restriction for CR Express contains objective function Eq. (32) and a set of constrains Eq. (1)-Eq. (31). In worst case, $|N| = |H| = |L| = n$, the model has $O(n^3)$ binary variables and $O(n^3)$ continuous variables. We make some constrains linear before solving the problem to improve solving algorithm efficiency.

Firstly, constrains Eq. (4) and Eq. (5) illustrate that cargo flow from demand node i could be only allocated to rail hubs or gateway nodes, and cargo flow between two demand nodes is not allowed. To simplify the formulation, for all $a_k^i \leq 0$, $b_l^i \leq 0$, $g_{lm}^{ij} \leq 0$, we write these two constrains as $a_k^i \leq x_k O_i$ and $b_l^i \leq y_l O_i$ to express the same meaning. Due to x_k, y_l are 0-1 variables and a_k^i, b_l^i, O_i are continuous variables, there are $O(n^n)$ constrains in the formulation; therefore, we introduce an infinity constant M and make these two constrains linear by inequality Eq. (33) and Eq. (34).

$$\begin{cases} a_k^i \leq O_i + (1 - x_k)M \\ a_k^i \leq x_k M \\ a_k^i \geq -x_k M \end{cases} \tag{33}$$

$$\begin{cases} b_l^i \leq O_i + (1 - y_l)M \\ b_l^i \leq y_l M \\ b_l^i \geq -y_l M \end{cases} \tag{34}$$

Similarly, Eq. (7) could be written as inequality Eq. (35).

$$\begin{cases} g_{lm}^{ij} \leq D_j + (1 - x_m)M \\ g_{lm}^{ij} \leq x_m M \\ g_{lm}^{ij} \geq -x_m M \end{cases} \tag{35}$$

Regarding transport time restriction constrains, Eq. (17)-Eq. (19) are exponential, and we solve them based on piecewise linearization method. Piecewise linearization method is a method for analyzing nonlinear systems by making the nonlinear characteristics approximately linear; that is, dividing the nonlinear curve into several segments and using straight lines to approximately replace every nonliear curve. Piecewise linearization can be divided into uniform piecewise linearization and non-uniform piecewise linearization, and the difference is mainly about the calculation accuracy and efficiency. Since the calculation is exponential in our model, a non-uniform piecewise linearization method is used to ensure the calculation accuracy as well the calculation efficiency.

The linear measure of constrains Eq. (20)-Eq. (22) is similar to that of Eq. (5)-Eq. (7). Taking Eq. (20) as an example, it could be expressed as inequality Eq. (36).

$$\begin{cases} r_k \leq \sum_{i \in D} x_k + (1 - x_k)M \\ r_k \geq \sum_{i \in D} x_k - (1 - x_k)M \\ r_k \leq x_k M \\ r_k \geq -x_k M \end{cases} \tag{36}$$

With regard to the linearization of constrain Eq. (30), $a_k^i, f_{kl}^i, g_{lm}^{ij} \leq 0$ for all $i, j \in N$, $k, m \in H$, $l \in L$, thus, $sgn(a_k^i)$, $sgn(f_{kl}^i)$, $sgn(g_{lm}^{ij})$ could be regarded as 0-1 variables and $(T_1+T_2+T_3)$ is continuous variable. Let $\Phi(\cdot) = sgn(a_k^i) * sgn(f_{kl}^i) * sgn(g_{lm}^{ij}) * (T_1 + T_2 + T_3)$, and Φ could be presented as Eq. (37), as shown at the bottom of this page. The process for Eq. (31) is similar.

V. NUMERICAL ANALYSIS

Rial hubs in China for CR Express and hinterland allocation are explored based on data that we observe and investigate in reality in this Section. We firstly introduce principles for candidate nodes selection.

A. DATA SETTING

CR Express transport network nodes involve nodes in China and nodes in Europe. We select candidate nodes, respectively, based on different principles for nodes in different regions. Firstly, we select candidate nodes in China based on such criteria: (1) cities have been operated CR Express, such as Chengdu, Wuhan, etc.; (2) national circulation cities planned in circulation cities design document or main cities pointed in CR Express planning document by Chinese government, such as Shanghai, Yiwu, etc.; (3) municipality or provincial capital like Huhehot. Moreover, we exclude Beijng, and cites located in Hainan province and Tibet in consideration of various reasons. Beijing is political center of China and has put

$$\begin{aligned} C = &\sum_{i \in N} \sum_{k \in H} a_k^i d_{ik} c_{ik} + \sum_{i \in N} \sum_{l \in L} b_l^i d_{il} c_{ik} + \sum_{i \in N} \sum_{k \in H} \sum_{l \in L} f_{kl}^i d'_{kl} c_{kl} \\ &+ \sum_{i \in N} \sum_{j \in N} \sum_{m \in H} \sum_{l \in L} g_{lm}^{ij} d'_{lm} c_{lm} + \sum_{i \in N} \sum_{j \in N} \sum_{m \in H} v_{mj}^{ij} d_{mj} c_{mj} \end{aligned} \tag{32}$$

$$\begin{cases} \Phi \leq (T_1 + T_2 + T_3) + (3 - sgn(a_k^i) - sgn(f_{kl}^i) - sgn(g_{lm}^{ij}))M \\ \Phi \geq (T_1 + T_2 + T_3) - (3 - sgn(a_k^i) - sgn(f_{kl}^i) - sgn(g_{lm}^{ij}))M \\ \Phi \leq sgn(a_k^i)M, \quad \Phi \geq -sgn(a_k^i)M \\ \Phi \leq sgn(f_{kl}^i)M, \quad \Phi \geq -sgn(f_{kl}^i)M \\ \Phi \leq sgn(g_{lm}^{ij})M, \quad \Phi \geq -sgn(g_{lm}^{ij})M \end{cases} \tag{37}$$

TABLE 1. Selection of candidate nodes in China.

Province or municipality	City
Shanghai	Shanghai
Tianjin	Tianjin
Chongqing	Chongqing
Hebei	Shijiazhuang, Baoding, Huanghua, Xingtai
Shanxi	Taiyuan, Linfen
Liaoning	Shenyang, Dalian, Yingkou, Panjin
Jilin	Changchun, Tongliao
Heilongjiang	Haerbin
Jiansu	Nanjing, Lianyungang, Suzhou, Nantong, Xuzhou
Zhejiang	Hanghzou, Yiwu, Jinhua
Anhui	Hefei
Fujian	Xiamen, Fuzhou
Jiangxi	Nanchang, Ganzhou
Shandong	Jinan, Qingdao, Weihai, Zibo, Linyi, Boxing
Henan	Zhengzhou
Hubei	Wuhan
Hunan	Changsha
Guangdong	GUanghzou, Dongguan
Sichuan	Chengdu
Guizhou	Guiyang
Yunnan	Kunming
Shanxi	Xi'an
Gansu	Lanzhou, Wuwei
Qinghai	Xining
Inner Mongolia	Huhehot, Erlianhot, Manzhouli, Baotou, Chifeng, Wulanchabu
Guangxi	Nanning
Ningxia	Yinchuan
Jinjiang	Urumqi, Korla, Golmud, Kuitu, Shihezi, Alashankou

TABLE 2. Selection of candidate nodes in Europe.

Country	City
Germany	Hamburg, Duisburg, Schwarzschild, Munich, Nuremberg
England	London
Netherlands	Rotterdam, Tilburg
France	Paris
Italy	Rome
Switzerland	Berne
Spain	Madrid
Belgium	Antwerp
Poland	Warsaw, Rhodes, Marasevic
Sweden	Stockholm
Czech Republic	Prague, Pardubice
Denmark	Copenhagen
Hungary	Budapest
Ireland	Dublin
Greece	Athens
Austria	Vienna
Finland	Helsinki

forward truck restriction policy. It is not possible to transport a large volume of container cargo in Beijing urban area. With regard to Hainan province and Tibet, container transport links between these two areas with other provinces of China is slightly weak because of the geographical location. Therefore, we select 61 cities in China as candidate nodes based on the above principles, which is showed as Table 1.

CR Express service for economy and trade development between China and Eurasia market, and we select candidate nodes in Europe mainly based on import and export trade between China and Europe. There are two steps for selection. The first step is filtering top 15 European countries according to import amount and export amount with China in 2016-2018. The top 15 countries could almost represent the situation because the import and export amount of these countries account for more than 85% of the total. Then, from countries we select at the first step, we determine cities by two criteria: (1) cities have been operated CR Express; (2) national caption. Finally, we select 25 cities as candidate nodes in Europe, which shown as Table 2.

Moreover, other parameter setting and data sources are as following. Data on road transport distance determined through Google API interface, and data on CR Express transport based on our investigations to China railway authority.

TABLE 3. Solving results of CR Express rail hubs in China.

p_K	Rial hubs location	Optimal Objective function	Time(s)
10	Chongqing, Shanghai, Zhengzhou, Wuhan, Haerbin, Dalian, Wulanchabu, Urumqi, Guangzhou, Kunming	4233.5	982
11	Chongqing, Shanghai, Zhengzhou, Wuhan, Haerbin, Dalian, Wulanchabu, Urumqi, Guangzhou, Kunming, Xi'an	4232.5	1038
12	Chongqing, Shanghai, Zhengzhou, Wuhan, Haerbin, Dalian, Wulanchabu, Urumqi, Guangzhou, Kunming, Xi'an, Lianyungang	4231.7	1132
13	Chongqing, Shanghai, Zhengzhou, Wuhan, Haerbin, Dalian, Wulanchabu, Urumqi, Guangzhou, Kunming, Xi'an, Lianyungang, Changsha	4230.9	1327
14	Chongqing, Shanghai, Zhengzhou, Wuhan, Haerbin, Dalian, Wulanchabu, Urumqi, Guangzhou, Kunming, Xi'an, Lianyungang, Changsha, Chengdu	4230.4	1653
15	Chongqing, Shanghai, Zhengzhou, Wuhan, Haerbin, Dalian, Wulanchabu, Urumqi, Guangzhou, Kunming, Xi'an, Lianyungang, Changsha, Chengdu, Qingdao	4229.8	1989

TABLE 4. Solving results of hinterland of every CR Express rail hub.

Rial hub location	Hinterland province or municipality
Chongqing	Chongqing, Sichuan, Guizhou, Hunan, Hubei, Guangxi
Shanghai	Shanghai, Zhejiang
Zhengzhou	Henan, Hebei, Hubei, Hunan, Anhui, Shandong, Jiangsu
Wuhan	Jiangxi, Fujian, Anhui, Hunan
Haerbin	Heilongjiang, Jilin
Dalian	Liaoning, Jilin
Wulanchabu	Inner Mongolia, Beijing, Tianjin, Hebei, Shanxi, Liaoning, Jilin, Heilongjiang, Ningxia, Gansu, Qinghai
Urumqi	Xinjiang, Qinghai, Gansu, Ningxia
Guangzhou	Guangdong, Fujian, Guangxi
Kunming	Yunnan, Guanxi
Xi'an	Shanxi, Gansu, Sichuan, Henan, Hubei
Lianyungang	Jiangsu, Anhui, Shandong
Changsha	Jiangxi, Fujian
Chengdu	Sichuan, Guizhou, Yunnan, Guangxi
Qingdao	Shandong, Jiangsu

We calculate transport time according to transport distance and speed, and we set speed of road transport speed and CR Express speed 100km/h and 120km/h,respectively. Moreover, based on facts we observed, we consider the handling time at rail hubs and gateway nodes are 0.5 day and 1 day, respectively. With regard to cost parameter, it is estimated that unit road transport cost is 0.7$/TEU and unit rail transport cost is 0.5$/TEU. The time restriction factor is taken as 13 days when total transport distance is less than 10000 kilometers, and adding 1 day with every 1000 kilometers increasing.

B. RESULTS ANALYSIS

We run our model based on CR Express data on a server with 2.7 GHz Intel Core i5 processor and 8GB of RAM operating under MacOs system we use the optimization software GUROBI version 9.0.1.

Table 3 shows hub location and objective function value with different hubs number.

In 2, the first column is the number of rail hubs, which is the input of model; the second column is the rail hub location we solved; the third column is the optimal minimum total transport cost; the last column is CPU requirement time by gurobi. Without considering operation costs, Table 3 reflects the relationship between minimum total transport cost and number of rail hubs. Minimum total transportation cost decreases with the number of railway hub increasing, but the decline rate is getting slower. Moreover, observing rail hubs location selected, the network tends to cover all area of China from spatial perspective while the number of rail hubs is small; however, the distribution of rail hubs tends to be agglomerative in the central and western regions of China and the coastal areas. Gathering in central and western regions is because of good geographical location. For instance, Chongqing, Zhengzhou, etc. have a good accessibility to most of regions in China. The reason for gathering in the coastal areas is due to high economic development and openness degree, therefore, considering cooperation with ports and developing sea-rail transport services might be the potential opportunities for CR Express.

Taking the scenario of 15 rail hubs as an example, we conclude the hinterland of every hub, which seen as Table 4. From the table, there is still a strong competition among hubs in central and western regions because of overlapping hinterland, especially competition for Zhengzhou, Xi'an, Chongqing and Chengdu. Therefore, it is important and necessary to put forward some regional coordination developing mechanism for governments. Moreover, Wulanchabu has a large hinterland. The reason for this, on one hand, Wulanchabu is located in Neimeng and is very close to Beijing-Tianjin-Heibei region, SHanxi province, etc.; one the other hand, Wulanchabu has a good accessibility to the middle channel Erlianhot port and the east channel Manzhouli port in CR Express network.

VI. CONCLUSION

CR Express is a cross-continent railway transport mode between China and Europe, and plays an important role for connecting China and Eurasia market to boost regional economy. In order to improve the efficiency and balance cargo flow of CR Express network, in this paper, we propose a hierarchical multimodal hub location problem with minimizing total transport cost considering transport time restriction. The aim of this paper is to explore rail hubs and relevant hinterland allocation in CR Express network. A mixed integer programming is derived and some variables and constrains linearization method is proposed.

Based on our observation and investigation on CR Express, we solve the problem efficiently by software GUROBI. Moreover, We test and compare results of different hubs number input, and the results show that the minimum total transportation cost decreasing with rail hubs number increasing but the decline getting slower. The network tends to cover all area of China from spatial perspective while the number of rail hubs is small; however, the distribution of rail hubs tends to be agglomerative in the central and western regions of China and the coastal areas. Another finding is that Wulanchabu that is located in Inner Mongolia Province has the largest hinterland range. Also, there is still a strong competition among hubs in central and western regions because of overlapping hinterland, especially competition for Zhengzhou, Xi'an, Chongqing and Chengdu.

In this paper, we consider road-rail multimodal transport mode in CR Express, network design considering other multimodal transport like maritime-rail transport could be explored in the further to find more development opportunities for CR Express.

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