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Research Article

Research on the Optimization of Cross-Border Logistics Paths of the "Belt and Road" in the Inland Regions

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Taking logistics time, logistics cost, and carbon emissions as optimization objectives, air transportation is included in the cross-border logistics paths optimization of multimodal transportation. Considering the scale effect of transportation, a multiobjective optimization model of cross-border logistics paths including road, water, railway, and air is constructed. The problem of cross-border logistics paths along the "Belt and Road" regions for cities in inland is studied via the NSGA-II method. The research results show that Chengdu and Xi'an should bear a large number of cross-border air transportation and be constructed as the national airport-type logistics hub. The foreign destinations of cross-border air transportation are distributed in different regions, mainly in Eastern Europe and Eastern Central Europe. The optimization result shows that if there is a 1-fold increase in logistics cost, the logistics time can reduce by 1.37 folds after the cross-border air transportation joins in the model. Such a result has effectively guided the transition from cross-border water transportation to cross-border air transportation.

1. Introduction

The "Belt and Road" is a major national initiative for China's opening up. It aims to promote trade development through the interconnection between China and the countries along the "Belt and Road." Efficient cross-border logistics can promote international transaction processing and accelerate the development of international trade [1]. In China, the economic development of different regions is unbalanced, and the level of logistics development in the inland regions is generally slow. To a certain extent, although the "China Railway Express" has strengthened the cross-border logistics capacity of inland regions to the west, its function is still very limited. Taking the western region of China as an example, according to the "Belt and Road Trade Cooperation Big Data Report" released by the State Information Center, the cross-border transportation in the region to the "Belt and Road" countries are mainly by water transportation and road transportation, which account for about 78% of the total exports of freight, while air transportation and railway transportation account for about 15% and 4% of the total exports of freight respectively. Inland regions of China are excessively relying on water transportation of coastal ports and highly polluted road transportation. This not only hinders the development of cross-border logistics and trade but also has a negative impact on the trade of the whole "Belt and Road" initiative. Therefore, based on the existing transportation facilities, inland regions effectively organize cross-border logistics according to their transportation conditions, which is the key to improve the level of interconnection between China and the countries along the "Belt and Road."

Cross-border logistics has the characteristics of long-distance transportation, usually using multimodal transportation [2–5]. At present, the theoretical research of cross-border multimodal transportation mainly focuses on road-sea multimodal transportation, road-rail multimodal transportation, and road-rail-sea multimodal transportation. These researches are optimized by developing a mathematical model. According to different optimization objectives, they can be classified into two categories as follows:

One is to construct a single-objective optimization model to minimize logistics costs. For example, some scholars not only consider transportation cost but also consider transit costs, storage costs, and transportation scale effects when constructing an optimization model [6–8]. Among them, Zhang et al. [6] put forward a basic framework to solve the problem of multimodal transportation paths optimization, which provided a solid foundation for future research. These studies did not consider logistics efficiency and environmental factors, thus, time and carbon emission restrictions are absent in their models. However, with the trend of high-quality economic development, logistics efficiency and environmental factors have become important objectives of cross-border logistics transportation. Scholars have further studied the optimization model, including adding the time window constraint into the optimization model [9–11] or adding logistics time and carbon emissions to logistics costs for optimization [12–15]. Moreover, some scholars have studied models under uncertainty [16–18].

The other one is to construct a multiobjective cross-border logistics optimization model that includes logistics cost, logistics time, and carbon emission [19–21]. It is difficult for single-objective optimization model to balance logistics time, logistics cost, and carbon emission [19]. Due to the release of low-carbon policy, some scholars have focused on the optimization of cross-border logistics paths under low-carbon policy [22–24]. The optimization conclusion of the above literatures is that the proportion of road-sea multimodal transportation and road-rail-sea multimodal transportation is much higher than that of road-sea multimodal transportation. Such a result indicates that it is important for supporting road-rail multimodal transportation and road-rail-sea multimodal transportation to construct the dry ports. We can find that the exploration of air transportation on cross-border multimodal transportation is absent in the existing theoretical studies.

In December 2018, the logistics hub policies were published by relevant departments of the Chinese government. In September 2019 and October 2020, there are 23 cities and 22 cities respectively that became national logistics hubs. Among these cities, there are 13 dry port-type national logistics hubs, 14 seaport-type national logistics hubs, and 3 airport-type national logistics hubs. Since the inland cities in China are far away from seaports, air and railway transportation are important ways for them to carry out cross-border logistics. However, inland cities in China mainly build dry port logistics hubs, while the existing airport-type national logistics hubs are only Beijing, Zhengzhou, and Shenzhen. Therefore, the importance of air transportation in inland cities and the impact of air transportation on cross-border logistics along the “Belt and Road” need to be explored.

This study incorporates air transportation into the theoretical framework of cross-border multimodal transportation. Taking logistics cost, logistics time, and carbon emission as the optimization objectives, a cross-border logistics path optimization model including water, railway, air, and road is constructed. This study not only improves the theory of multimodal transportation but also provides decisions for cross-border logistics transportation and airport-type national logistics hubs construction in inland regions.

2. Construction of Cross-Border Logistics Paths Optimal Model

2.1. An Abstract Description of Cross-Border Transportation Problems. The cross-border transportation, consisting of different types of transportation nodes, is to transport cargoes from the domestic source of supply to the foreign destination. As shown in Figure 1, the different types of transportation nodes are represented by different graphics, including the domestic source of supply $i\,(i \in I)$, domestic dry port $d\,(d \in D)$, domestic airport $a\,(a \in A)$, domestic seaport $p\,(p \in P)$, foreign dry port $d'\,(d' \in D')$, foreign airport $a'\,(a' \in A')$, foreign seaport $p'\,(p' \in P')$, and foreign destination $j\,(j \in J)$. Among them, the channels between the nodes represent different transportation modes, including road transportation, railway transportation, air transportation, and water transportation. The railway transportation involves both domestic railway transportation and cross-border railway transportation. The channels between different transportation nodes have resulted in multiple paths of multimodal transportation.

As shown in Figure 1, four multimodal transportation modes can be selected for cross-border transportation of cargoes from the domestic source of supply i to foreign destination j.(1) The cargoes are transported first from the domestic source of supply i to domestic seaport p through road transportation, then to foreign seaport p' through water transportation, and finally to the foreign destination j through road transportation. This mode is the road-sea multimodal transportation. (2) The cargoes are transported first from the domestic source of supply i to domestic dry port d through road transportation, then to domestic seaport p through railway transportation, and then to foreign seaport p' through water transportation, and finally to the foreign destination j through road transportation. This mode is road-rail-sea multimodal transportation. (3) The cargoes are transported first from the domestic source of supply i to domestic dry port d through road transportation, then to foreign dry port through cross-border rail transportation, and finally to the foreign destination j through road transportation. This mode is the road-rail multimodal transportation. (4) The cargoes are transported first from the domestic source of supply i to domestic airport a through road transportation, then to foreign airport a' through air transportation, and finally to the foreign destination j through road transportation. This mode is the road-air multimodal transportation.

When cargoes are transported from domestic source of supply i to foreign destination j, there are not only four multimodal transportation modes to select but also many

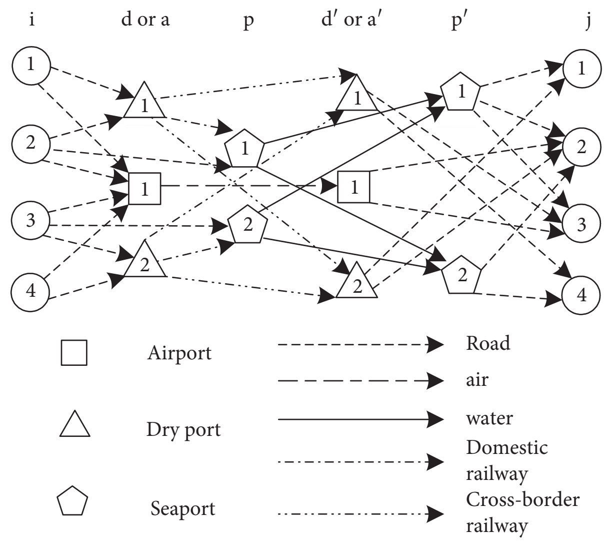

Figure 1: Abstract description of cross-border transportation problems.

Table 1: Model parameters.

Unit freight	c_{rd}	The road transportation unit cost	Fixed costs	F_d	The fixed fees for services provided by the dry port d
	c_{rl}	The railway transportation unit cost		F_a	The fixed fee for the service provided by the airport a
	c_{sea}	The water transportation unit cost		F_p	The fixed fees for services provided by the seaport p
	c_{ra}	The air transportation unit cost	Freight volume	q_{ij}	The freight volume from the source i to the destination j
Carbon emission	co_{rd}	The unit carbon emission factor of road transportation		$B[m]$	The freight volume discount factor
	co_{rl}	The unit carbon emission factor of railway transportation			
	co_{sea}	The unit carbon emission factor of water transportation	Storage time	t_p	The storage time in the domestic seaport p
	co_{ra}	The unit carbon emission factor of air transportation unit carbon		t_d	The storage time in the dry port d
	r_e	Carbon tax value		t_a	The storage time in the domestic airport a
Transport distance	l_{id}	The road distance from domestic source i to dry port d		$t_{d'}$	The storage time in the foreign dry port d'
	l_{ip}	The road distance from domestic source i to domestic seaport p		$t_{a'}$	The storage time in the foreign airport a′
	$l_{p'j}$	The road distance from the foreign seaport p' to the foreign destination j		t_p	The storage time in the foreign seaport $p\prime$
	$l_{d'j}$	The road distance from the foreign dry port d' to the foreign destination j	Transport speed	v_{ra}	The air transportation speed
	l_{dp}	The railway distance from the dry port d to domestic the sea port p		v_{rl}	The railway transportation speed
	$l_{aa'}$	The air distance from the domestic airport a to foreign the airport a'		v_{sea}	The water transportation speed
	$l_{dd'}$	The railway distance from the dry port d to the foreign dry port d'		v_{rd}	The road transportation speed
	$l_{pp'}$	The water distance from the domestic seaport p to foreign the seaport p'			

different cross-border logistics paths in each mode. Every cross-border logistics path is accompanied by logistics costs, logistics time, and carbon emissions. The purpose of cross-border logistics paths optimization is to find out the best cross-border logistics paths from the numerous logistics paths corresponding to the four multimodal transportation modes, so as to implement the optimization of logistics costs, logistics time, and carbon emissions.

2.2. A Bi-Objective Mixed-Integer Programming Model for Cross-Border Logistics Path Optimization. According to the method in the literature [14], this study converts emission into carbon tax costs and incorporates them into logistics costs. A bi-objective (logistics cost and logistics time) mixed-integer programming model is constructed in this study on the basis of the four multimodal transportation in Figure 1.

2.2.1. Model Parameters and Variables. Set the decision variables as follows: $X_{\mathrm{ipp}'j}$ as the road-sea multimodal transportation mode decision variable, $X_{\mathrm{idp}'j}$ as the road-rail-sea multimodal transportation mode decision variable, $X_{\mathrm{idp}'j}$ as the road-rail multimodal transportation mode decision variable, and $X_{\mathrm{iaa}'j}$ as the road-air multimodal transportation mode decision variable. These decision variables are binary variables. If a certain multimodal transportation mode is adopted, the corresponding decision variable is 1; otherwise, the decision variable is 0. In addition, the related parameters need to be selected including unit transportation cost, carbon emissions, transportation distance, fixed cost, storage time, transportation speed, and freight volume. The specific parameter symbols and meanings are listed in Table 1.

2.2.2. Model Objective Function. As for cross-border logistics paths optimization, there are two objective functions including cross-border logistics cost and cross-border logistics time in the bi-objective mixed-integer programming model.

Cross-border logistics costs consist of transportation costs, fixed costs at each port, and carbon tax costs converted from carbon emissions during transportation. Considering the scale effect of railway transportation, the growth rate of total transportation costs will slow down as freight volumes increase. Therefore, a constant unit transportation cost can be equivalently considered as a decrease in freight volume. Based on the size of freight volume, the decreased freight volume can be divided into three intervals with different discount factors, which is expressed as the original freight volume multiplied by the discount factor of the corresponding interval [25]. Therefore, the cost objective function is constructed as follows:

$$\begin{aligned}
\min f_1 = &\sum_{i,j,p,p'} q_{\mathrm{ij}} X_{\mathrm{ipp}'j}\Big(\big(C_{\mathrm{rd}} + \mathrm{co}_{\mathrm{rd}} \times r_e\big)\big(l_{\mathrm{ip}} + l_{p'j}\big) + \big(C_{\mathrm{sea}} + co_{\mathrm{sea}} \times r_e\big) l_{pp'}\Big) \\
&+ \sum_{i,j,d,p,p'} X_{\mathrm{idpp'}j}\Big(q_{\mathrm{ij}}\big(\mathrm{z}C_{\mathrm{rd}} + \mathrm{co}_{\mathrm{rd}} \times r_e\big) l_{\mathrm{id}} + \big(C_{\mathrm{sea}} + \mathrm{co}_{\mathrm{sea}} \times r_e\big) l_{\mathrm{pp}'} \\
&+ \big(C_{\mathrm{rd}} + \mathrm{co}_{\mathrm{rd}} \times r_e\big) l_{p'j}\Big) + q_{\mathrm{ij}} B[m]\big(\mathrm{co}_{\mathrm{rl}} + \mathrm{co}_{\mathrm{rl}} \times r_e\big) l_{\mathrm{dp}}\Big) \\
&+ \sum_{i,j,d,d'} X_{\mathrm{idd}'j}\Big(q_{\mathrm{ij}}\big(C_{rd} + \mathrm{co}_{\mathrm{rd}} \times r_e\big)\big(l_{\mathrm{id}} + l_{d'j}\big) + q_{\mathrm{ij}} B[m]\big(\mathrm{co}_{\mathrm{rl}} + \mathrm{co}_{\mathrm{rl}} \times r_e\big) l_{\mathrm{dp}}\Big) \\
&+ \sum_{i,j,a,a'} q_{ij} X_{\mathrm{iaa}'j}\Big(\big(C_{\mathrm{rd}} + \mathrm{co}_{\mathrm{rd}} \times r_e\big)\big(l_{\mathrm{ia}} + l_{a'j}\big) + \big(C_{\mathrm{ra}} + \mathrm{co}_{\mathrm{ra}} \times r_e\big) l_{\mathrm{aa}'}\Big) \\
&+ \sum_{a,d,p}\big(y_d F_d + y_a F_a + y_p F_p\big).
\end{aligned} \tag{1}$$

The first part of the objective function of the road-sea multimodal transportation is the transportation cost and carbon tax cost. The second part is the transportation cost and carbon tax cost of the road-rail-sea multimodal transportation which has the scale effect. The third part is the transportation cost and carbon tax cost of the road-rail multimodal transportation which has the scale effect. The fourth part is the transportation cost and carbon tax cost of the road-air multimodal transportation. The last part is the fixed cost at each port, and the binary variables including y_a, y_d, and y_p indicate whether the airport, dry port, and seaport provide services respectively.

Cross-border logistics time consists of transportation time and storage time at each port. The transportation time is the distance between two logistics nodes divided by the speed. Therefore, the time objective function is constructed as follows:

$$\min f_2 = \left(\sum_{a,a\prime,d,d\prime,p,p'} X_{\mathrm{ipp}'j} \left(\frac{\left(l_{\mathrm{ip}} + l_{p'j}\right)}{v_{\mathrm{rd}}} + \frac{l_{\mathrm{pp}'}}{v_{\mathrm{sea}} + t_p + t_{p'}} \right) \right.$$

$$+ X_{\mathrm{idpp}'j} \left(\frac{\left(l_{\mathrm{id}} + l_{p'j}\right)}{v_{\mathrm{rd}}} + \frac{l_{\mathrm{dp}}}{v_{\mathrm{rl}}} + \frac{l_{\mathrm{pp}'}}{v_{\mathrm{sea}} + t_d + t_p + t_{p'}} \right)$$

$$+ X_{\mathrm{idp}'j} \left(\frac{\left(l_{\mathrm{id}} + l_{d'j}\right)}{v_{\mathrm{rd}}} + \frac{l_{\mathrm{dd}'}}{v_{\mathrm{rl}} + t_d + t_{d'}} \right)$$

$$\left. + X_{\mathrm{iaa}'j} \frac{\left(\left(l_{\mathrm{ia}} + l_{a'j}\right)/v_{\mathrm{ra}} + l_{\mathrm{aa}'}/v_{\mathrm{rl}} + t_a + t_{a'}\right)}{24} \right). \tag{2}$$

The first part of the objective function is the transportation time of the road-sea multimodal transportation and the storage time of domestic and foreign seaports. The second part is the transportation time of the road-rail-sea multimodal transportation and the storage time of domestic, foreign seaports, and domestic dry ports. The third part is the transportation time of the road-rail multimodal transportation and the storage time of domestic and foreign dry ports. The fourth part is the transportation time of the road-air multimodal transportation and the storage time of domestic and foreign airports.

2.2.3. Constraint Conditions. The constraint conditions that must be met by the variables in the model are as follows:

$$\sum_{d,a,p,d',a',p'} \left(X_{\mathrm{ipp}'j} + X_{\mathrm{idpp}'j} + X_{\mathrm{idp}'j} + X_{\mathrm{iaa}'j}\right) = 1, \forall i \in I; j \in J. \tag{3}$$

$$X_{\mathrm{idp}'j} \le y_d, \forall i \in I; j \in J; d \in D; d' \in D'. \tag{4}$$

$$X_{\mathrm{iaa}'j} \le y_a, \forall i \in I; j \in J; a \in A; a' \in A'. \tag{5}$$

$$X_{\mathrm{ipp}'j} \le y_p, \forall i \in I; j \in J; p \in P; p' \in P'. \tag{6}$$

$$X_{\mathrm{idpp}'j} \le y_p, \forall i \in I; j \in J; p \in P; p' \in P'; d \in D. \tag{7}$$

$$X_{\mathrm{idpp}'j} \le y_d, \forall i \in I; j \in J; p \in P; p' \in P'; d \in D. \tag{8}$$

$$y_a, y_d, y_p, X_{\mathrm{idp}'j}, X_{\mathrm{iaa}'j}, X_{\mathrm{ipp}'j}, X_{\mathrm{idpp}'j} \in \{0, 1\}. \tag{9}$$

Among them, constraint conditions (3) indicate that only one multimodal transportation mode can be used for cross-border transportation. Constraints conditions (4) to (8) indicate that multimodal modes passing through this port can be adopted only after the corresponding seaport, airport, or dry port has been passed through. Constraint condition (9) indicates that the variables in the constraint are binary variables.

3. The Solution to the Optimization Model of Cross-Border Logistics Path: Genetic Algorithm

In the bi-objective mixed-integer programming model for cross-border logistics path optimization, the two optimization objectives of logistics cost and logistics time cannot be optimized at the same time. Therefore, how to balance the importance of these two optimization objectives is the key to obtain the optimal cross-border logistics paths. Following the method of solving multiple objective functions in the existing literature [22, 26, 27], the genetic algorithm is used to find the Pareto optimal solution of logistics cost and logistics time in this study. In the solution process, this study adopts the NSGA-II algorithm [28] that ensures the diversity of the population and high computational efficiency. This algorithm cannot directly calculate the fitness of the chromosomes to select the optimal solution like the single-objective algorithms, while it is used to select the optimal solution by calculating the nondominated sorting level and crowding distance of each chromosome. The optimal solutions are further optimized by genetic operations and repeated until the solutions are obtained that outperform other chromosomes in both objectives within a specified maximum number of generations. The optimal solutions are called the Pareto optimal solution sets. The specific process is as follows:

3.1. Chromosome Encoding and Decoding of Cross-Border Logistics Paths. In this study, the chromosome is encoded by integer coding. Each chromosome represents a cross-border logistics path with 8-bit codes. The first part of the chromosome is the code of multimodal transportation mode, and the second part is the code of passing through ports. The specific coding structure is shown in Figure 2.

The first part of the chromosome consists of the first four codes, representing different multimodal transportation modes. They are road-sea multimodal transportation, road-rail-sea multimodal transportation, road-rail multimodal transportation, and road-air multimodal transportation, successively. The code is taken as an integer from 0 to 1. If the multimodal transportation mode is selected, the code is 1, otherwise, the code is 0. Since only one multimodal mode can be selected for each cross-border logistics path, only one of the 4-bit codes is 1.

The second part of the chromosome consists of the last four codes that represent the number of the port passed through. They are domestic dry port or airport, domestic seaport, foreign dry port or airport, and foreign seaport, successively. Since dry port and airport do not appear in the same multimodal transportation mode, they are represented by the same location code. The second part of the code is taken as the number of the different ports (m_1, m_2, m_3, and m_4) or 0. If any port is passed through, the corresponding code is the number of this port, otherwise, the code is 0. The second part of the chromosome is determined by the first part of the chromosome. For example, in the road-sea multimodal transportation mode, the code representing the

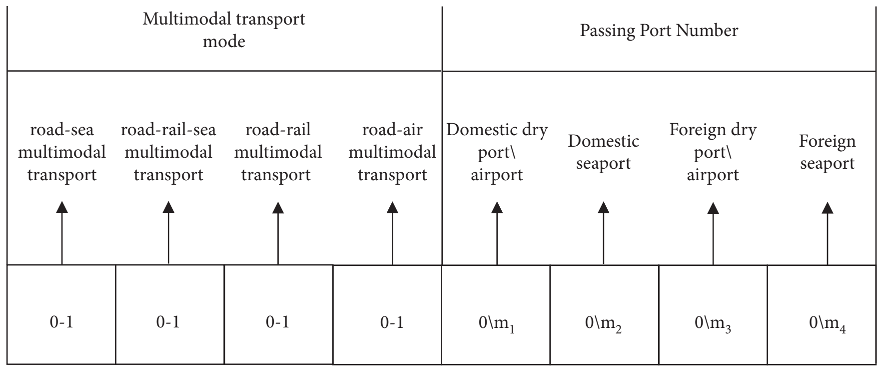

Figure 2: Chromosome coding.

seaport is the port number, while the code representing the other ports is 0. The specific decoding process is given in Figure 3.

As shown in Figure 3, based on the first part of the chromosome, it is known that the chromosome is a road-sea multimodal transportation mode. From the second part of the chromosome, the cargoes are transported through road transportation from the source of supply to the domestic seaport 3, then through cross-border water transportation to the foreign seaport 4, and finally through road transportation to destination.

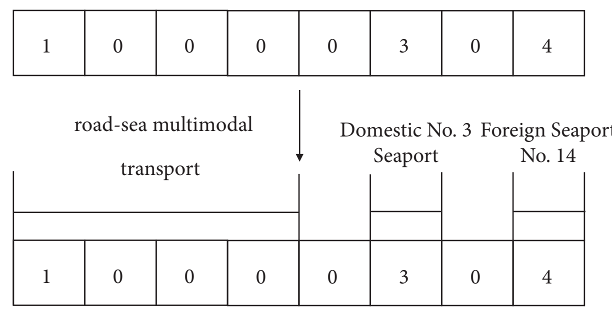

Figure 3: Chromosome decoding.

3.2. NSGA-II Algorithm Process

3.2.1. Nondominated Sorting and Calculating Crowding Distance. The code is initialized to obtain the initial population of cross-border logistics paths. The two objective function values are calculated for each cross-border logistics path in the population. Such a result indicates that each logistics path is sorted nondominated, and the logistics paths with the least dominated rank are selected from them. Moreover, the crowding distance of logistics path in the same rank is calculated to ensure the diversity of the population. As shown in Figure 4, the crowding distance of any logistic path is the difference between two adjacent logistic paths, and the crowding distance of node n can be calculated by equations (10)–(12) [29]. Equations (11) and (12) indicate the difference between the node $n+1$ and the node $n-1$ in the objective function (1) and the objective function (2), respectively. After finishing the sorting and the calculation of crowding distance for all logistics paths, the logistics paths with the least dominant sorting and the largest crowding distance are selected as the candidate populations.

$$\text{The crowding distance of node } n = \Delta f_1 + \Delta f_2. \quad (10)$$

$$\Delta f_1 = f_1(n+1) - f_1(n-1). \quad (11)$$

$$\Delta f_2 = f_2(n+1) - f_2(n-1). \quad (12)$$

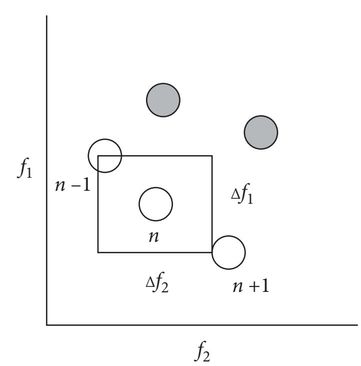

Figure 4: Crowding distance for node **n**.

3.2.2. Select. The tournament selection algorithm is used to simulate the elimination system [13] in this study. A certain number of cross-border logistics paths are randomly selected from the population for comparison every time, and the cross-border optimal logistics path is selected to join the next-generation population. This operation is repeated until the size of the next-generation population reaches the number that needs to be selected.

3.2.3. Crossing and Mutation. Based on the set crossover and mutation probabilities, some cross-border logistic paths in the new population are selected for crossover and mutation. Then crossover and mutation should follow the coding rules in 2.1, otherwise the logistics path will be discarded. The SBX [30] (simulated binary crossover) and polynomial mutation [25] are adopted to further increase the diversity of the population, enhance the local search ability, and speed up the convergence.

```
Input: Number of individuals in the population, NUM; Maximum evolutionary generation, G;
Output: The population that completes the optimization is the pareto optimal solution;
/* Initial population */
while g = 0. g ≤ G do
population: = population + offspring;/* Father and son merged */
levels: = ndSort (population, NUM);/* Non-dominant ranking */
distance: = crowdis (population, levels);/* Calculate the crowded distance */
population, FitnV: = argsort (lexsort ([dis-levels]));/*Calculate fitness */
until number of population < NUM
return population
/* Start to evolve */
offspring: = population|selecting (population, FitnV, NUM)|;/*Select individuals to participate in evolution */
offspring: = recOper (offspring);/* Simulated binary crossover */
offspring: = mutOper (offspring);/* Polynomial mutation */
population: = reinsertion (population, offspring);/*Reinsert to get a new generation of population */
g: = g + 1
end do
return population
```

Algorithm 1: NSGA-II algorithm.

3.2.4. Elitism Strategy. When generating the cross-border logistics path population of the offspring, the elitism strategy is introduced to ensure that the optimal solution is obtained [28]. This strategy combines parental population with offspring population to compete together. This results in an increased space of the selected logistics path, and hence it is helpful to improve more optimal solutions for the next generation.

3.2.5. Algorithm Pseudocode. Based on the above algorithm design, the specific steps of NSGA-II algorithm are shown in Algorithm 1.

4. The "Belt and Road" Cross-Border Logistics Path Optimization Program

4.1. Freight City and Model Parameter Selection. Considering the optimization of the "Belt and Road" cross-border logistics paths in inland regions, this study focuses on the key regions including the urban agglomeration in the middle reaches of the Yangtze River, Chengdu–Chongqing urban agglomeration, and Zhongyuan Urban agglomeration. Among these regions, 14 cities such as Yibin, Baoji, Daqing, and Luoyang are selected as domestic sources of supply. According to indicators such as economic aggregates and trade levels of foreign cities along the "Belt and Road," 11 cities, including Tashkent, Nur-Sultan, and Moscow, are selected as foreign destinations. According to the government policy issued in 2018, 10 cities such as Zhengzhou, Chengdu, and Xi'an are selected as both domestic dry ports and domestic airports, and 6 cities such as Shanghai, Dalian, and Lianyungang are selected as domestic seaports. At the same time, 10 cities such as Lodz, Almaty, and Moscow are selected as foreign dry ports or foreign airports, and 6 cities such as Haiphong are selected as foreign seaports based on the total economic volume and infrastructure of the overseas cities along the "Belt and Road." Due to good trade development and a high level of logistics development, some cities such as Moscow and Tashkent are both destinations and hub ports, as listed in Table 2.

According to the literatures [23, 31, 32] and the actual data collected, various parameters, such as the transportation costs, carbon emission factor, and speed, are set as listed in Tables 3 and 4 (1 yuan = 0.1547 $) [33]. Then the average storage time in dry ports, airports, and seaports is 12 h, 12 h, and 24 h, respectively [31]. The fixed fees for services provided by seaports, dry ports, and airports are 2,000yuan, 2,000 yuan, and 1,500 yuan, respectively [32].

4.2. Experimental Results and Analysis. Considering the parameter setting in the relevant literatures [34, 35] and the result of our tests, the algorithm parameters are set as follows: the population number is 2000, the maximum number of iterations is 500, the probability of crossover is 0.9, the probability of mutation is 0.01, and the distribution indexes of SBX and polynomial mutation are both 20. Based on the above model parameters and algorithm parameters, the model is programmed by Python to obtain the Pareto optimal solution sets for the cross-border logistics paths. Taking the cross-border logistics paths from Baoji to New Delhi as an example, its optimal Pareto solution sets are shown as star-shaped points in Figure 5.

According to the method for obtaining Pareto satisfactory solutions in the literature [22], the percentage changes of logistics cost and logistics time for the five Pareto solutions are analyzed in Figure 5. Among them, the solution indicated by the arrow is the Pareto satisfactory solution. The characteristic of this solution increasing the least logistics costs can save the most logistics time. The logistics path corresponding to this Pareto satisfactory solution is Baoji-Changsha-Guangzhou-Mumbai-New Delhi (road-rail-sea multimodal transportation). The logistics cost of this path is 232,304.24 yuan and the logistics time of this path is 18.09 days. Similarly, the optimal cross-border logistics

Table 2: Source, destination, and port hub.

Domestic sources of supply	Daqing, Tongliao, Luoyang, Xiangyang, Xinyang, Zunyi, Huaihua, Yibin, Zhaotong Yulin, Baoji, Shangrao, Changzhou, Jiaxing
Domestic dry ports/airports	Harbin, Zhengzhou, Changsha, Chengdu, Kunming, Xi'an, Nanjing, Hangzhou, Chongqing, Guiyang
Domestic seaports	Dalian, Lianyungang, Qingdao, Guangzhou, Tianjin, Shanghai
Foreign dry ports/airports	Tashkent, Almaty, Moscow, Rhodes, Tehran, Minsk, Riga, Prague, Istanbul
Foreign seaports	Haiphong, Mumbai, Abbas, Mersin, Odessa, Gdynia, Riga
Foreign destination	Tashkent, Nur, Sultan, Moscow, Warsaw, Tehran, Minsk, Riga, Prague, Ankara, New Delhi, Hanoi, Kiev

Table 3: Transportation mode parameters.

Mode of transportation	Unit transportation cost (yuan/t-km)	Unit carbon emission factor	Average speed (km/h)
Road transportation	1	0.283	90
Railway transportation	0.65	0.022	60
Water transportation	0.35	0.016	30
Air transportation	2	1.036	900

Table 4: Discount factor of freight volume.

Range of freight volume	More than 30t	Between 15 t and 30 t	Less than 15 t
Discount factor of freight volume	0.93	0.96	1

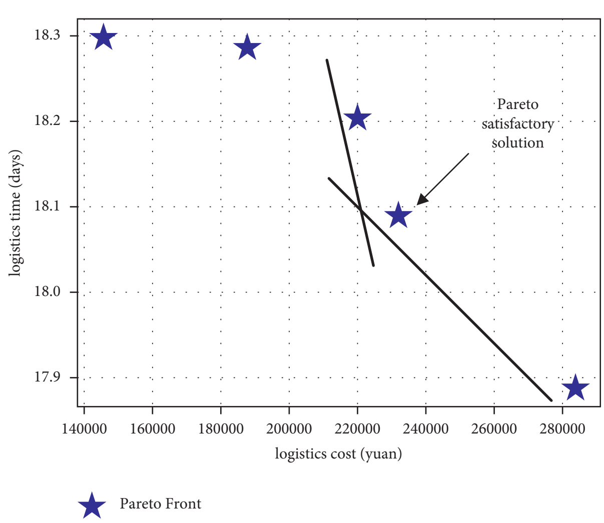

Figure 5: Baoji-New Delhi optimal path Pareto optimal solution sets.

paths corresponding to all Pareto satisfactory solutions from the source to the destination can be obtained, and there are 168 paths in total. Among them, the number of optimal cross-border logistics paths using road-air multimodal transportation, road-rail multimodal transportation, road-rail-sea multimodal transportation, and road-sea multimodal transportation are 47, 93, 26, and 2, respectively.

For simplicity of analysis, the road-sea multimodal transportation and the road-rail-sea multimodal transportation are collectively called cross-border water transportation; meanwhile the road-rail multimodal transportation and road-air multimodal transportation are called cross-border water transportation and cross-border air transportation, respectively. According to the geographical regions of the domestic sources of supply, the cross-border logistics paths are divided into five regions including the northeast region of China, the northwest region of China, the southeast region of China, the southwest region of China, and the central region of China.

4.2.1. Proportion Analysis of Optimal Cross-Border Logistics Paths. The proportion of transportation modes in the optimal cross-border logistics paths in the five regions is given in Figure 6.

As shown in Figure 6, the highest proportion of transportation modes is cross-border railway transportation. It indicates cross-border railway transportation should be more adopted by inland regions for organizing cross-border logistics. That is to say, China Railway Express is now a powerful way to enhance the capacity of cross-border logistics in the inland regions, while the lowest proportion of transportation modes is cross-border water transportation in inland regions. Though there are the greatest advantages of cross-border water transportation in southeast regions, cross-border water transportation accounts for only 9.1%. It indicates that inland regions should not use cross-border water transportation in large quantities to organize cross-border logistics. Cross-border air transportation accounts for an important proportion in all optimal cross-border logistics paths of inland regions. Among them, the region with the highest proportion of cross-border air transportation is the northwest region, reaching 45.5%. The regions with a middle proportion of cross-border air transportation are the southwest regions and central regions,

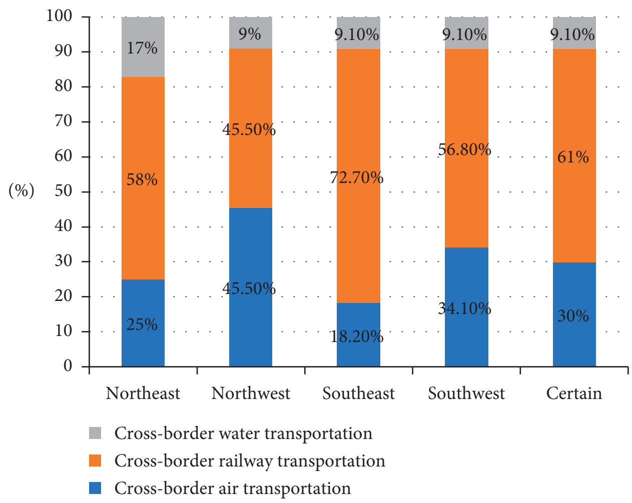

Figure 6: Proportion of transportation modes in optimal cross-border logistics paths.

reaching between 30% and 35%. The regions with the lowest proportion of cross-border air transportation are the northeast regions and southeast regions, reaching 25% and 18.2% respectively. Such a result indicates that there is a great potential for northwest regions, southwest regions, and central regions to organize cross-border logistics through cross-border air transportation.

However, only Beijing, Shenzhen, and Zhengzhou have been constructed as airport-type national logistics hubs among the existing national logistics hubs according to the recent government policies. Therefore, there is an urgent need for China to build national airport-based logistics hubs in the northwest and southwest regions, which can optimize and enhance the cross-border air logistics capacity of these two regions.

4.2.2. Result Analysis of Optimal Cross-Border Logistics Paths. The transportation modes of cross-border logistics from inland regions to foreign destinations are different. From the results of optimal cross-border logistics paths, the cross-border railway transportation accounts for 81% of cross-border logistics paths to Central and West Asia. That is to say, when cargoes are transported from inland regions to Central and West Asia, cross-border railway transportation should be given priority, while destinations of inland regions using cross-border water transportation to organize cross-border logistics are South Asia. It indicates cross-border water transportation should be given priority, when cargoes are transported from inland regions to South Asia. Cross-border air transportation accounts for 47% of the cross-border logistics paths to Central and Eastern Europe. Therefore, cargoes are transported from inland regions to Central and Eastern Europe, and cross-border air transportation should be given priority. Among them, there are 89% paths are passing through Lodz in Central Europe and Minsk in Eastern Europe. Therefore, Lodz and Minsk are significant foreign airports for inland regions to organize cross-border logistics.

In order to analyze the optimal cross-border logistics paths for different regions, the results of the optimal cross-border logistics paths in five regions are given in Figures 7–10.

As shown in Figures 7–10, cargoes are transported from northwest region mainly to Central and Eastern Europe, and partly to Central and Western Asia by cross-border air transport. Cargoes are transported from southwest region mainly to Eastern Europe, and partly to Central Europe and Central Asia. Cargoes are transported from central region mainly to Eastern European, and partly to Central European. Although cargoes are transported from southeast region and northeast region rarely to foreign destinations by cross-border air transportation, there are still stable cross-border logistics paths by this transportation mode. Among them, cargoes are transported from northeast region to Kiev via the path of "Chengdu–Lodz," and cargoes are transported from southeast region to Tashkent via the path of "Xi'an-Almaty." Therefore, there are differences in foreign destinations to which the cargoes are transported from each region. Therefore, the selection of cross-border air transportation should be based on the above results. Similarly, when inland regions choose other cross-border transportation modes for cross-border logistics, the optimal cross-border logistics paths should be selected based on the above results.

Since there is an urgent need for the construction of airport-type national logistics hubs in the northwest and southwest regions, the percentage of optimal cross-border logistics paths through each airport hub within these two regions is calculated. The results are listed in Table 5.

As listed in Table 5, the percentage of optimal cross-border paths through Xi'an in northwest region and inland regions are 50% and 30%, respectively. The percentage of optimal cross-border paths through Chengdu in southwest region and inland regions are 80% and 53%, respectively. For other airports hubs, Chongqing is only passed by a few optimal cross-border logistics paths. At present, according to the list of national logistics hubs, Xi'an and Chengdu are only constructed as dry port-type national logistics hubs. Therefore, China should build Xi'an and Chengdu as airport-type national logistics hubs when planning the construction of national logistics hubs in the future.

4.2.3. Necessity Analysis of Introducing Cross-Border Air Transportation. The main theoretical contribution of this study is to integrate air transportation with the theoretical research framework of cross-border logistics multimodal transportation. Therefore, this study compares the optimization results of the abovementioned cross-border logistics paths with those excluding cross-border air transportation, and focuses on analyzing the logistics cost and logistics time in the optimization objectives. The results of the comparison are given in Figures 11 and 12.

As shown in Figures 11 and 12, the logistics cost and logistics time of each logistics path are summarized in this study. The total logistics cost of all optimal cross-border logistics paths is $C_1 = 236554507$ yuan and the total logistics time is $T_1 = 636.33$ days, while the total logistics cost of all

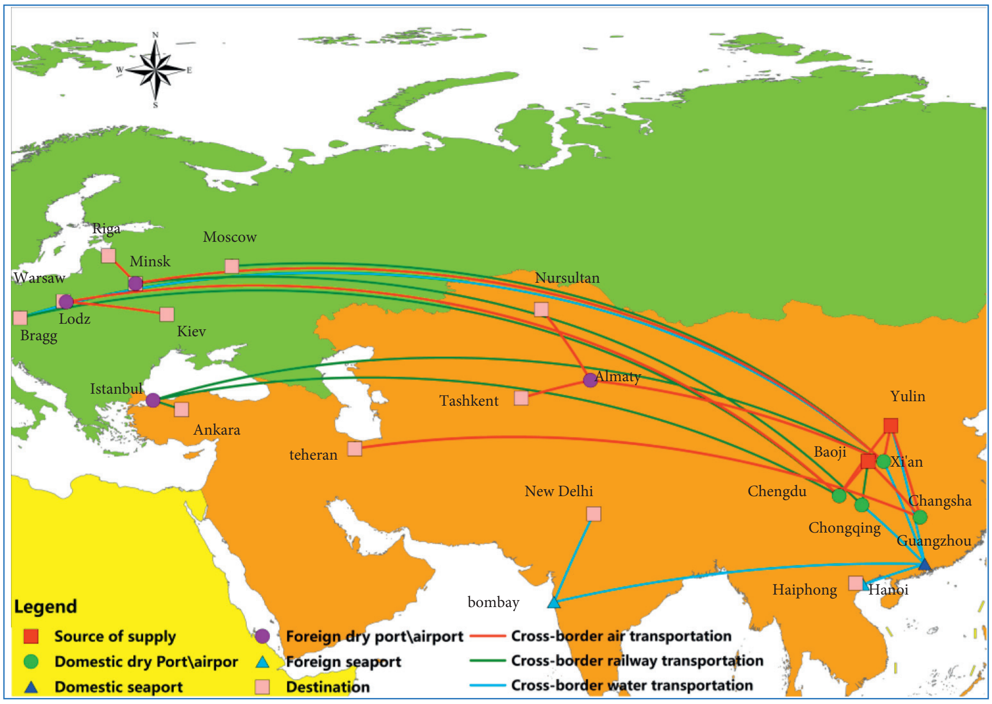

Figure 7: The optimal cross-border logistics paths in northwest region.

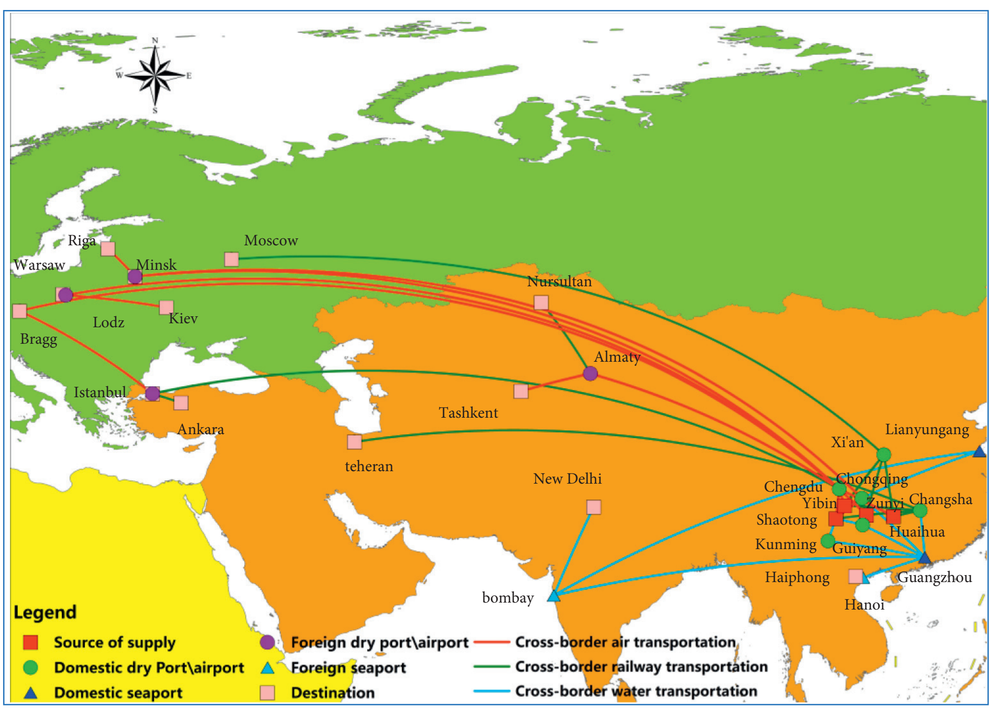

Figure 8: The optimal cross-border logistics paths in southwest region.

optimal cross-border logistics paths excluding cross-border air transportation is $C_2 = 71196217.86$ yuan and the total logistics time is $T_2 = 2654.67$ days. Therefore, if there is a 1-fold increase in logistics cost, the logistics time can reduce by 1.37 folds after joining the cross-border air transportation. The reduction of logistics time is far greater than that of the increase in logistics cost.

To explore the impact on cross-border logistics after joining cross-border air transportation, this study compares the transportation proportion of the above two optimal

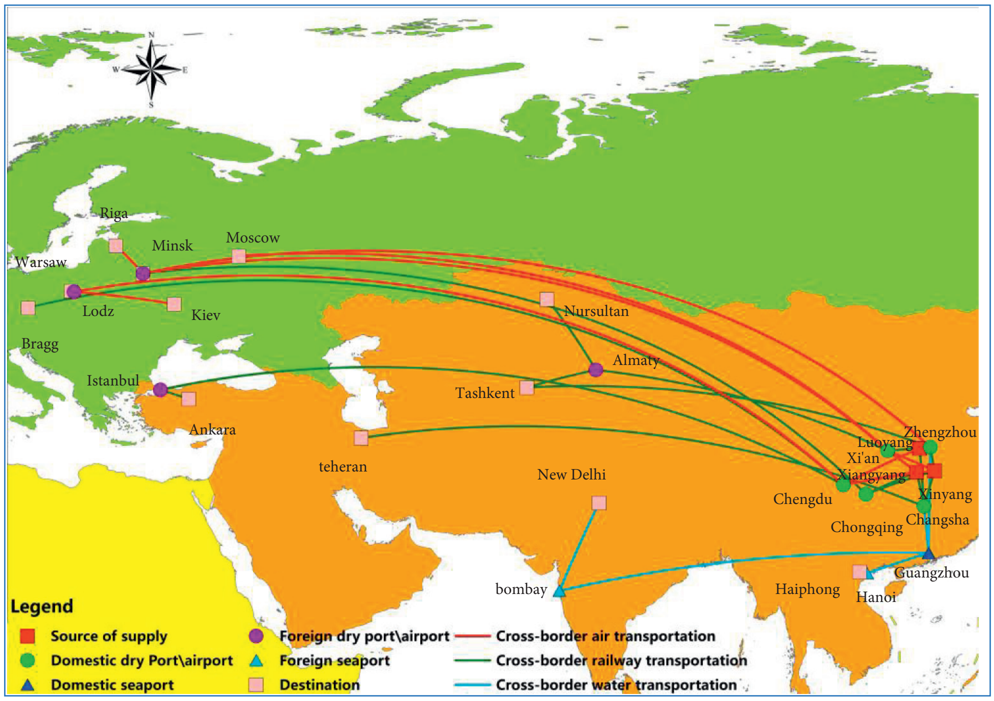

Figure 9: The optimal cross-border logistics paths in central region.

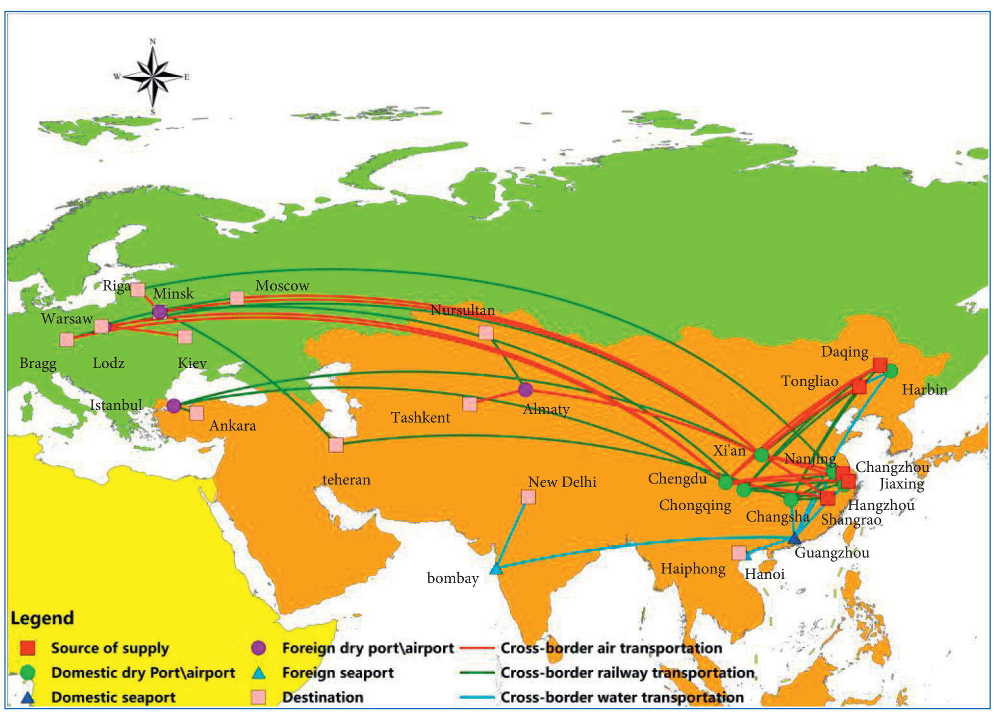

Figure 10: The optimal cross-border logistics paths in northeast and southeast regions.

Table 5: The percentage of the optimal cross-border paths through the airport.

City	Xi'an (%)	Chengdu (%)	Chongqing (%)	Kunming (%)	Guiyang (%)
Percentage of region	50	80	20	0	0
Percentage of all regions	30	53	7	0	0

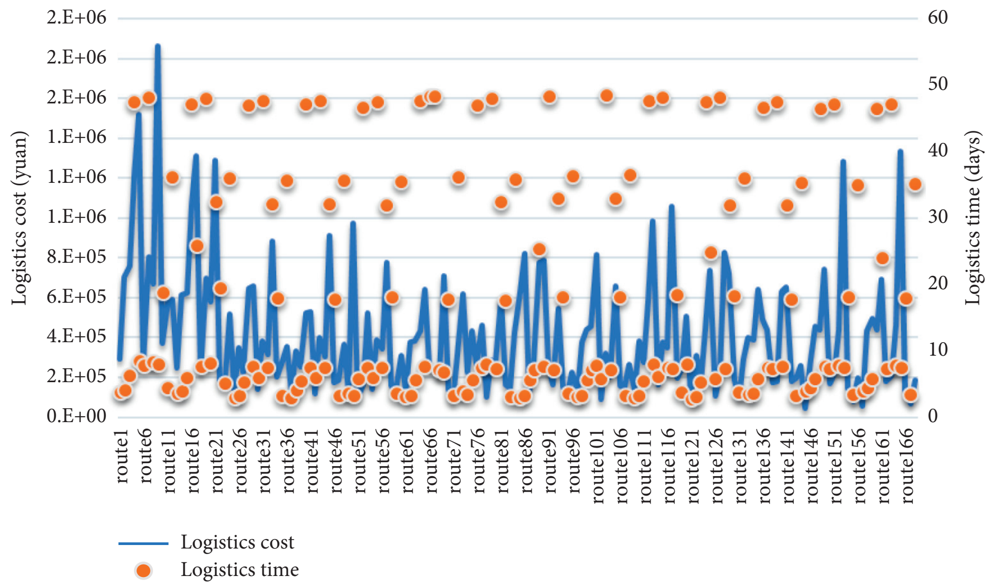

Figure 11: The result of optimal cross-border logistics paths excluding cross-border air transportation.

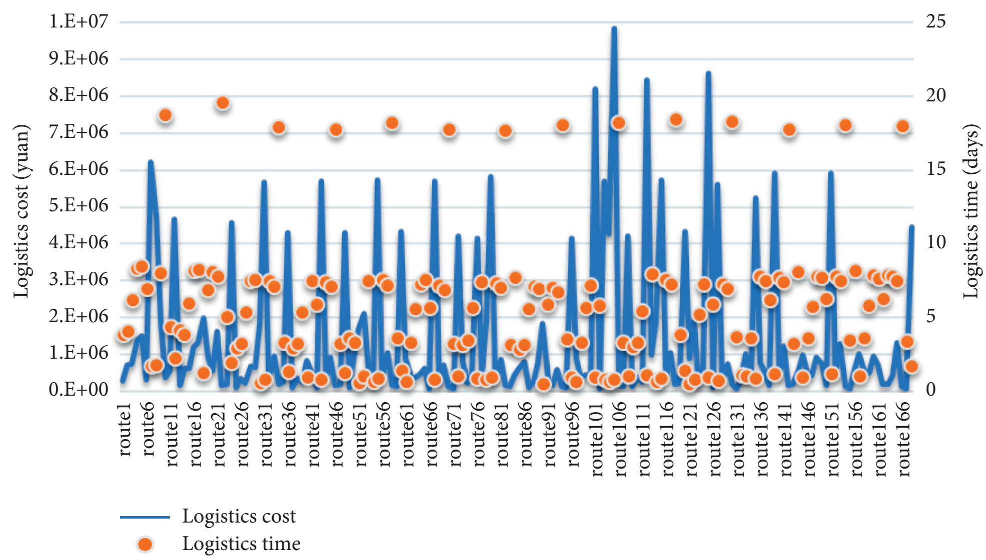

Figure 12: The result of optimal cross-border logistics paths.

Table 6: The comparison of transportation proportions for optimal cross-border logistics paths based on bi-objective optimization.

	The result of optimal cross-border logistics paths (%)	The result of optimal cross-border logistics paths excluding cross-border air transportation (%)
Cross-border air transportation	28	0
Cross-border water transportation	17	47.70
Cross-border railway transportation	55	52.30

results based on bi-objective optimization. Table 6 lists the results of the comparison.

As listed in Table 6, in the result of optimal cross-border logistics paths excluding cross-border air transportation, the transportation proportions of cross-border railway transportation and cross-border water transportation are 52.3% and 47.7%, respectively. After joining cross-border air transportation, the proportion of cross-border air transportation increases to 28%, cross-border water transportation decreases to 17%, while cross-border railway transportation slightly increases to 55%. Therefore, the joining of cross-border air transportation will not affect the development of the "China Railway Express" but will only reduce the pressure on the coastal ports of cross-border water transportation. Such a result will promote the efficiency of cross-border logistics and the development of trade along the "Belt and Road."

5. Conclusions

It is important for inland regions to choose cross-border logistics paths reasonably to participate in the "Belt and Road" initiative. In this study, the logistics cost, logistics time, and carbon emissions are taken as optimization objectives, and a mixed-integer programming model for the multiobjective optimization of the cross-border logistics paths is constructed. We integrate innovatively air transportation with the theoretical research framework, and then explore the influence of air transportation on cross-border logistics and the importance of building airport-type logistics hubs in the national logistics hub system. The NSGA-II algorithm is used to obtain the optimal cross-border logistics paths.

Based on the proportion of transportation modes in optimal cross-border logistics paths, cross-border railway transportation should be more adopted by inland regions, but the importance of cross-border air transportation cannot be ignored. Although Northwest China and Southwest China are the regions with the highest proportion of cross-border air transportation, there are no airport-type national logistics hubs in these two regions to organize cross-border logistics. Therefore, according to the percentage of the optimal cross-border paths through the airport, Chengdu and Xi'an should be constructed as airport-type national logistics hubs. Moreover, the foreign destinations of cross-border air transportation are distributed in different regions, mainly in Eastern Europe and Eastern Central Europe. To explore the impact of joining cross-border air transportation on cross-border logistics, we compared the cross-border logistics path optimization with that excluding air transportation. The results show that if there is a 1-fold increase in logistics cost, the logistics time can reduce by 1.37 folds, and the reduction of logistics time is far greater than the increase of logistics cost. Such a result has effectively guided the transition from cross-border water transportation to cross-border air transportation. Therefore, cross-border air transportation can play a more important role in the cross-border logistics of the "Belt and Road." China should speed up the construction of national airport-type logistics hubs in the Northwest and Southwest. The results of the optimal cross-border transportation paths will provide a direct basis for inland regions to organize cross-border logistics by considering cost, time, and carbon emissions. Our study provides important insight for inland regions to better participate in the "Belt and Road" initiative and enhance the level of opening up to the outside world. [36].

Data Availability

Previously reported data were used to support this study and these prior studies (and datasets) are cited at relevant places within the text as references.

Additional Points

Significance. The theoretical significance of current work lies in incorporating air transportation into the multimodal transportation theory research framework of cross-border logistics transportation. In this article, the inland regions are optimized to participate in the "One Belt and One Road" cross-border logistics route, and it is found that Chengdu and Xi'an should carry a large amount of cross-border air transportation and be constructed as a national-level airport-type logistics hub city. In addition, compared with the optimization results without air transportation, the optimization results after adding cross-border air transportation can reduce logistics time by 1.37 times for every doubling of the logistics cost. This shows that in the "Belt and Road" cross-border logistics transportation, cross-border air transportation can play a more important role.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] A. Gani, "The logistics performance effect in international trade," *The Asian Journal of Shipping and Logistics*, vol. 33, no. 4, pp. 279–288, 2017.

[2] A. G. Herrero and J. Xu, "China's Belt and road initiative: can Europe expect trade gains?" *China and World Economy*, vol. 25, no. 6, pp. 84–99, 2017.

[3] M.-C. Niculescu and M. Minea, "Developing a single window integrated platform for multimodal transport management and logistics," *Transportation Research Procedia*, vol. 14, no. 5, pp. 1453–1462, 2016.

[4] J. Liu, "Development of transportation logistics in China," *Current Chinese Economic Report Series*, pp. 47–70, 2019.

[5] H. Wei, "Optimal design of an integrated cross-border logistics network for China's inland regions," *Journal of Coastal Research*, vol. 37, no. 3, pp. 644–655, 2021.

[6] Y. H. Zhang, B. L. Lin, D. Liang, and H. Y. Gao, "Research on a generalized shortest path method of optimizing intermodal transportation problems[J]," *Journal of the China Railway Society*, vol. 28, no. 4, pp. 22–26, 2006.

[7] W. Bing and X. Wang, "Genetic algorithm application for multimodal transportation networks[J]," *Information Technology Journal*, vol. 12, no. 6, pp. 1263–1267, 2013.

[8] D. Liu, L. Wang, and C. Tian, "Optimization of transportation capacity combinatorial procurement in container sea-rail intermodal transportation[C]//," in *Proceedings of the Fifth*

International Conference on Transportation Engineering, Dalian, China, 26 September 2015.
[9] Q. Wang and Z. Han, "The optimal routes and modes selection in container multimodal transportation networks[C]//," in *Proceedings of the International Conference on Optoelectronics & Image Processing*, IEEE Hong Kong, China, 11 November 2010.
[10] J. Liu, S. W. He, R. Song, and H. D. Li, "Study on optimization of dynamic paths of intermodal transportation network based on alternative set of transportation modes[J]," *Journal of the China Railway Society*, vol. 33, no. 10, pp. 1–6, 2011.
[11] T. G. Crainic, P. Dell'Olmo, N. Ricciardi, and A. Sgalambro, "Modeling dry-port-based freight distribution planning," *Transportation Research Part C: Emerging Technologies*, vol. 55, no. 6, pp. 518–534, 2015.
[12] N. N. Jia, H. R. Wei, and Z. H. Hu, "Optimization of cross-border logistics network based on dry ports under the Belt and Road Initiative[J]," *Journal of Shanghai Maritime University*, vol. 40, no. 1, pp. 1–7, 2019.
[13] C. Hao and Y. Yue, "Optimization on combination of transport routes and modes on dynamic programming for a container multimodal transport system," *Procedia Engineering*, vol. 137, pp. 382–390, 2016.
[14] H. L. Yang, F. Dong, and D. Liu, "Segmented procurement optimization of container multimodal transportation service based on convergence combination[J]," *Transportation System Engineering and Information*, vol. 14, no. 4, pp. 17–22, 2014.
[15] G. Hu, W. Sun, and J. Jiang, "Optimization of train operation scheme for container sea- rail multimodal transport," *Journal of Physics: Conference Series*, vol. 1802, no. 3, p. 032068, Article ID 032068, 2021.
[16] E. Demir, W. Burgholzer, M. Hrušovský, E. Arıkan, W. Jammernegg, and T. V. Woensel, "A green intermodal service network design problem with travel time uncertainty," *Transportation Research Part B: Methodological*, vol. 93, no. 7, pp. 789–807, 2016.
[17] M. L. Chen, X. J. Zhao, X. G. Deng et al., "Multimodal transportation path optimization under uncertain conditions [J]," *Journal of Highway and Transportation Research and Development*, vol. 38, no. 1, pp. 143–150, 2021.
[18] M. Hrusovsky, E. Demir, W. Jammernegg, and W. Van, "Hybrid simulation and optimization approach for green intermodal transportation problem with travel time uncertainty[J]," *International Journal of Flexible Manufacturing Systems*, vol. 30, no. 3, pp. 486–215, 2016.
[19] Y. Sun and M. Lang, "Bi-objective optimization for multimodal transportation routing planning problem based on Pareto optimality[J]," *Journal of Industrial Engineering and Management*, vol. 8, no. 3, pp. 1195–1217, 2015.
[20] H. Zhang, Y. Li, Q. Zhang, and D. Chen, "Route selection of multimodal transport based on China railway transportation," *Journal of Advanced Transportation*, vol. 2021, pp. 1–12, Article ID 9984659, 2021.
[21] H. F. Li and L. Su, "Multimodal transportation path optimization model and algorithm considering carbon emission multitask[J]," *The Journal of Supercomputing*, vol. 76, no. 1, 2020.
[22] H. Wei and M. Dong, "Import-export freight organization and optimization in the dry-port-based cross-border logistics network under the Belt and Road Initiative," *Computers & Industrial Engineering*, vol. 130, pp. 472–484, 2019.
[23] X. Q. Cheng, C. Jin, Q. G. Yao, and C. Wang, "Research on robust optimization of multimodal transportation route selection under carbon trading policy[J/OL]," *Chinese Journal of Management Science*, vol. 29, pp. 1–10, 2021.
[24] H. Wei, A. Li, and N. Jia, "Research on optimization and design of sustainable urban underground logistics network framework," *Sustainability*, vol. 12, no. 21, p. 9147, 2020.
[25] Y. R. Cheng and W. Tan, "Synthetically optimization model and algorithm of multi-modal transporation with multiple transporation tasks considering carbon emissions[J]," *Journal of Industrial Technological Economics*, vol. 38, no. 06, pp. 5–11, 2019.
[26] B. Yu, Z. Peng, Z. Tian, and B. Yao, "Sailing speed optimization for tramp ships with fuzzy time window[J]," *Flexible Services and Manufacturing Journal*, vol. 31, 2017.
[27] J. Zheng, L. I. Kang, and D. Wu, "Models for location inventory routing problem of cold chain logistics with NSGA-IIAlgorithm[J]," *Journal of Donghua University*, vol. 34, no. 004, pp. 533–539, 2017.
[28] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, "A fast and elitist multi-objective genetic algorithm: nsga-II[j]," *Evolutionary Computation*, vol. 6, no. 02, pp. 182–197, 2002.
[29] P. Shina and K. Vijay, "Distributed query plan generation using multi-objective genetic algorithm[J]," *The Scientific World Journal*, vol. 2014, p. 628471, 2014.
[30] K. Deb and R. B. Agrawal, "Simulated binary crossover for continuous search space[J]," *Complex Systems*, vol. 9, no. 04, pp. 115–148, 1995.
[31] Q. Meng and X. Wang, "Intermodal hub-and-spoke network design: i," *Transportation Research Part B: Methodological*, vol. 45, no. 4, pp. 724–742, 2011.
[32] K. Deb and M. Goyal, "A combined genetic adaptive search (gene AS) for engineering design[J]," *Computer Science and Informatics*, vol. 26, no. 04, pp. 30–45, 1996.
[33] X. X. Wang, "Overview of the offshore RMB market in August 2021[J]," *China Currency Market*, no. 09, pp. 97-98, 2021.
[34] L. Li, H. Wu, X. Hu, and G. Sheng, "Evolutionary algorithm for multiobjective optimization based on density estimation ranking," *Wireless Communications and Mobile Computing*, vol. 2021, pp. 1–18, Article ID 4296642, 2021.
[35] Z. Gao and C. Ye, "Reverse logistics vehicle routing optimization problem based on multivehicle recycling," *Mathematical Problems in Engineering*, vol. 2021, pp. 1–9, Article ID 5559684, 2021.
[36] D. Liu and S. Z. Zhao, "Multi-objective optimization model and algorithm of sustainable intermodal network[J]," *Systems Engineering*, vol. 33, no. 08, pp. 133–139, 2015.