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China-Europe Container Multimodal Transport Path Selection Based on Multi-objective Optimization

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Abstract: With the advancement of the "Belt and Road" initiative, trade between China and Europe has been steadily growing, and China-Europe container transportation has received increasing attention. This study analyzes the influencing factors of China-Europe container transport path selection and, based on the physical network of China-Europe container transport, constructs virtual nodes according to the transport modes that can be transited at different nodes and their own transshipment operations. By reflecting cost, time, and carbon emission factors in the virtual network, we construct a service network for China-Europe container multimodal transport, which in turn forms a multi-objective transport scheme selection model considering transportation cost, time, and carbon emissions. Subsequently, the economic and practical aspects of this transport path selection model are verified through five case studies of container transport from Dalian to Hamburg, Germany. Lastly, the sensitivity of factors, such as cost and time, to the China-Europe container multimodal transport path selection is assessed based on scenario analysis. This analysis offers valuable references for various decision-makers involved in the selection of the China-Europe container transport path.

Keywords: China-Europe container transport; Path optimization; Multi-objective optimization; Carbon emissions; China-Europe train services

1 Introduction

Under the political and economic context of the Belt and Road Initiative, three main railway trade routes have emerged, connecting China with other Eurasian countries through Manzhouli, Erenhot, Alashankou, and Horgos, with a total of 61 China-Europe block trains linking 56 Chinese cities and 49 cities in 15 European countries, accumulating over 30,000 trips [1, 2]. In the early stage of China-Europe block train operation, shippers had to choose between sea container transport and air transport, the former having longer transit time but lower freight, and the latter having extremely short transit time but extremely high freight [3]. The outbreak of COVID-19 in 2020 has had a significant impact on air and sea transport, with airport closures and port closures among other factors [4]. Consequently, China-Europe block trains have become essential for maintaining international supply chain stability, as the number of operating cities and trips has increased significantly [5]. However, due to the need for China-Europe block trains to pass through different railway systems with different track gauges, transshipment operations are required at border stations, leading to extensive delays that significantly affect the timeliness of the China-Europe block trains. As one of the most critical entry points for westbound container trains, Malaszewicze station has reported delays of up to 4-6 days, as the current infrastructure is unable to cope with the surge in China-Europe rail freight trade [6]. On the other hand, as the container handling capacity of each seaport is limited, serious delays may occur once this capacity is close to or already exhausted. For example, during the COVID-19 pandemic, the concentration of arriving containers at seaports and the shortage of equipment and labor led to average waiting times of over 50 hours and 92 hours at China's Qingdao port and the UK's Felixstowe port, respectively [7]. In addition to port congestion, the Suez Canal is another well-known bottleneck on the China-Europe shipping route due to the limited throughput of the large number of ships passing through. Even after its expansion in 2015, 41.4% of the Suez Canal's length still only allows for one-way traffic [8].

In light of the above background, the present study aims to investigate the selection of multimodal transport routes between China and Europe under the practical constraints of the Belt and Road Initiative, green transportation, and multi-objective optimization. On the one hand, considering the higher requirements for the green development of the Belt and Road Initiative due to the ”dual carbon” goal, carbon emissions are taken as the research object in this study, and the cost, time, and carbon emissions of different segments of the multimodal transport process are analyzed in detail. The study investigates the selection of China-Europe multimodal transport routes based on multi-objective optimization and explores the impact of different transport modes and different value goods on the transport mode and route selection between China and Europe. On the other hand, as a unique passage between China and Europe, the China-Europe block trains have experienced steady demand growth under the Belt and Road Initiative background, particularly playing a stabilizing role in the international supply chain during the 2020 outbreak. However, due to the need for China-Europe block trains to pass through different railway systems with different track gauges, transshipment operations are required at border stations, leading to extensive delays that significantly affect the timeliness of the China-Europe block trains. Therefore, this study considers the particularity of China-Europe block train operations and explores the changes in carrier choices of transport mode and route selection for goods between China and Europe under realistic scenarios such as different station types, operation efficiency, and transshipment operations. This study conducts a detailed analysis of container transport between China and Europe, identifies the perspective and approach to addressing the problem, and uses the existing Dalian-to-Hamburg multimodal transport network as a case study for verification and analysis.

The choice of multimodal transport routes is influenced by various factors, such as transportation costs, transportation time, service quality, technical level, carbon emissions, and trip utilization rate. Most researchers have focused on cost minimization as the starting point for optimizing multimodal transport route selection models. For example, Reddy and Kasilingam [9] proposed a study on multimodal transport costs, which was the first to detail the total cost components of the multimodal transport process, optimizing multimodal transport routes with cost minimization as the objective function. Zhang et al. [10] established a comprehensive multi-stage Mixed Integer Programming (MIP) model to select transportation routes and methods, aiming to minimize total transportation cost. Recognizing that a single factor does not provide a comprehensive influence on multimodal transport route selection, researchers both domestic and abroad have focused on the impact of two factors: transport time and transport cost. For instance, Wang and Meng [11] incorporated transportation time as a constraint condition into the objective function based on transportation cost. They built a model for minimizing transportation costs under fuzzy demand and time constraint conditions. Cho et al. [12] aimed to minimize transportation cost and time. Due to the increasing prominence of environmental issues, scholars in recent years have introduced carbon emissions as a factor into multimodal transport route selection. Some have incorporated carbon emissions as a constraint condition into multimodal transport evaluation systems. For example, Zhang et al. [13] considered transport cost, transport time, carbon emissions, and logistics service time window constraints, optimizing multimodal logistics network design using a genetic algorithm.

Sun and Lang [14]used a time window as a constraint and converted carbon emissions into transportation costs, constructing a Mixed Integer Nonlinear Programming model to solve the optimal route problem in cargo transportation. Considering mixed time window constraints and changes in the transportation network, a Mixed Integer Programming model was established from a dynamic perspective [15]. Additionally, Zhang et al. [16] studied freight rate optimization models using container transport in the Dutch hinterland as an example. Ricci et al. [17] used the Munich-Riem case in Germany to assess the impact of innovative measures on multimodal freight stations.

On the other hand, research on the China-Europe train (CR Express) is a very new research topic. Qualitative research on it was mainstream a few years ago when it did not even have a universally recognized name. Keywords used in academic research before ”CR Express” became the official name included TransAsia railway [18], China-Europe Express [19], China-Europe block train [20], Sino-Europe Regular Cargo Train [21] among others. Some scholars have carried out qualitative analysis of its sustainable development from the perspective of its own development. For instance, Qin et al. [22] used cargo value characteristic analysis theory to analyze selected capital-intensive goods with higher added value, identifying potential sources of cargo for the China-Europe train, providing reference for the operation of trains in international intermodal transportation.

Li [23] analyzed the current operation of the China-Europe train and existing problems from a macro perspective, proposing optimization strategies for its development from aspects such as logistics center layout, infrastructure construction and optimization of railway stations, and rationalization of transport type structure. Besharati et al. [24] analyzed the reasons for the rapid development of the China-Europe train and detailed the subsidy policies provided by the provincial government in China for the China-Europe train. Li [25] used product lifecycle theory to divide the lifecycle of China-Europe trains in our country, analyzing their stage characteristics and planning objectives. Wang et al. [26] proposed regions with comparative advantages for China-Europe train transport. Choi [27] comprehensively reviewed the specific operation of the China-Europe train system according to routes and regions. Another group of scholars have carried out quantitative analysis from the perspective of node construction, route comparison, network optimization, and empty container optimization for the China-Europe train. For example, Fu et al. [20] constructed a value model from aspects such as location conditions, transport cost, transport time, service level, and calculated value costs for seven China-Europe trains as examples, filtering out the optimal route arrangement. Kostrzewski and Wrona [28] introduced cases of trade and manufacturing transport systems spanning the Eurasian continent, assessing the transport system from the perspective of efficiency and sustainable development priorities. Wu et al. [29–32] optimized the China-Europe train transport network from a network theory perspective. Xing et al. [33, 34] researched the optimization problem of empty container adjustment.

The route selection problem of China-Europe container intermodal transport is a subject that scholars have always been exploring, mainly focusing on research on the impact of single or multiple factors such as minimizing transport cost and transport time, time window constraints, transport capacity constraints, and different customer demands on intermodal transport. With the vigorous development of the Belt and Road initiative, more scholars are focusing on research in the field of China-Europe container transport. However, most scholars focus on reducing transport cost as the objective for analysis. There is less focus on the environmental friendliness and green transport research during the process of China-Europe container intermodal transport in the realistic context of COVID-19 and dual carbon policies. In addition, most current research is modeling from a single-objective optimization perspective. Although some scholars have considered the impact of multiple factors such as transport cost and transport time on China-Europe container intermodal transport, they basically transform other factors into the same dimension as transport cost and simply add them together. The method of eliminating dimensional differences lacks certain rationality.

Therefore, this study takes China-Europe container intermodal transport as the entry point and makes the following contributions: It deeply analyzes transport costs and transport time in different segments and carbon emissions of different transport methods. It constructs a multi-objective function China-Europe container intermodal transport route selection model with transport cost, transport time, and carbon emissions as objectives. It uses the DFS algorithm combined with the non-dominated sorting algorithm for solution. It can quickly obtain the choice of transport method and route selection for China-Europe intermodal transport.

The second part of the study provides a detailed problem description; the third part presents an optimization problem for China-Europe container intermodal transport route selection based on multi-objective optimization; the fourth part carries out a case study and discusses the research results, and the fifth part provides the conclusions of this study.

2 Problem Description

As the organizer of the entire journey of container goods, the intermodal carrier must consider its own cost factors when choosing a transport scheme, such as the transport costs that need to be borne directly by the carrier and the carbon emissions-related impact that the carrier needs to consider. At the same time, the carrier also needs to consider the demands of the consignor, such as the value characteristics of the goods transported by the consignor, taking into account the different demands of different types of goods for transport time.

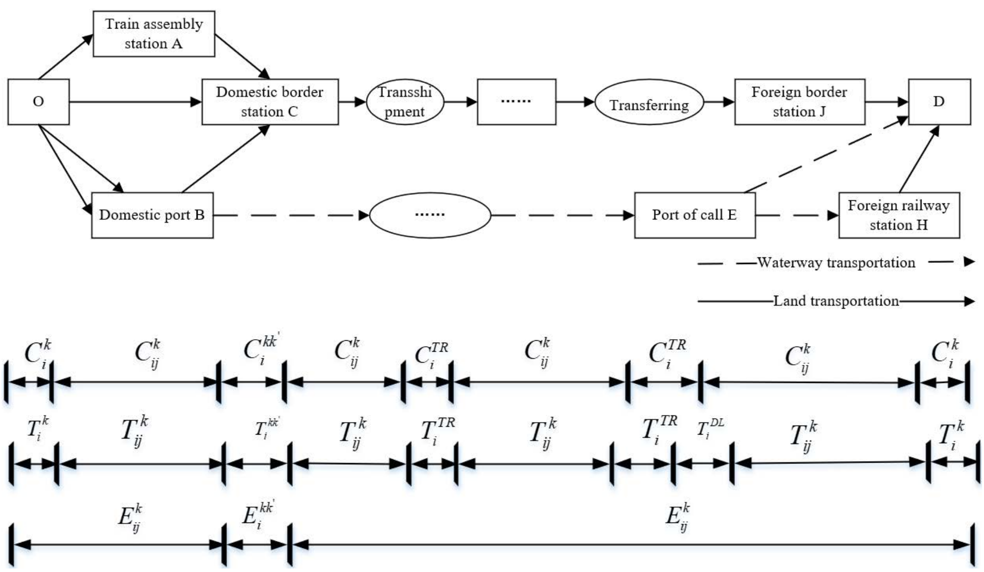

Figure 1. China-Europe container transport network diagram

Assuming that the carrier now accepts transport orders for several different value characteristic container goods, without considering the consolidation of different categories of goods, the goods need to be transported from a coastal port city node O in China to a city node D in Europe. Based on the currently available China-Europe train East, Central, and West routes, and China-Europe maritime transport, and road transport at both ends, a China-Europe container transport network is constructed. Let $G = (I, A)$ be the China-Europe container transport network, and let $K = (1, 2, 3)$ represent the mode of transport, where $K = 1$ represents railway transport, $K = 2$ represents road transport, $K = 3$ represents waterway transport. I is the set of all transport nodes in the network, with $i, j \in I$ representing a specific node, such as a container station, dock, etc.; A is the set of arcs between nodes, with a_{ij}^k representing an arc in the network from node i to node j using transport method k. Each arc in the network includes cost, time, and carbon emission attributes; as shown in Figure 1.

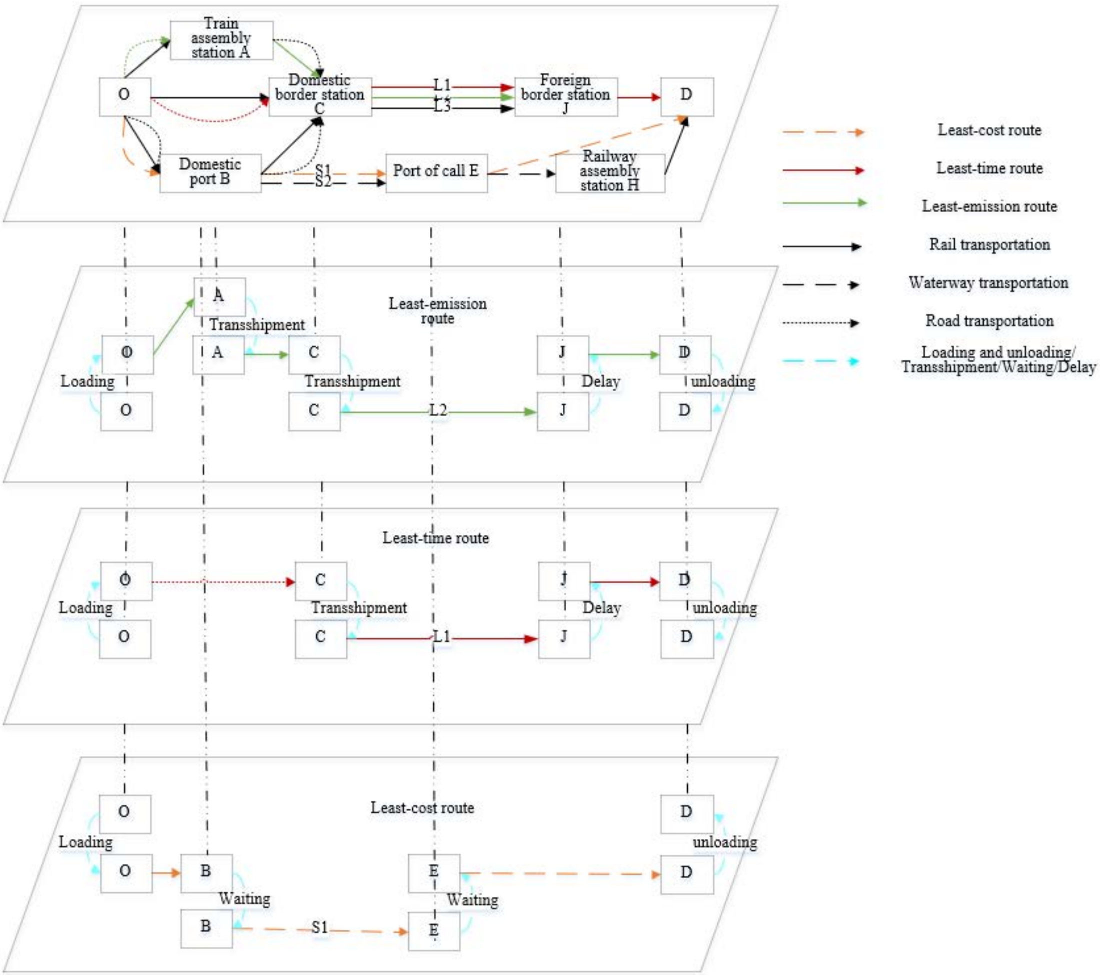

Figure 2. Container transport service network under different goals

As shown in Figure 2, intermodal carriers have the following transport schemes to choose from:

(1) If there is a direct China-Europe train running between the starting point O and D, the container can choose to take the China-Europe train directly from the coastal port city node O, passing through domestic border stations, transshipment stations, and foreign border stations to reach the destination D; If there is no direct train between the starting point O and D, the container will first be transported to the train assembly station A (such as Chongqing, Zhengzhou, etc.) for transfer (there is at most one transport mode change at the same transfer station), and then take the China-Europe train through domestic border stations, transshipment stations, etc. to reach the destination D.

(2) Containers can be transported from a coastal port city node O via maritime or inland waterway transport to the assembly station B (such as Shanghai, Wuhan) for a China-Europe train for transshipment (transshipment does not divide cargo volume), and then take the China-Europe train from the assembly station through domestic border stations, transshipment stations, etc. to transport the containers to the destination D.

(3) Containers can be transported directly from the coastal port city node O via container ship transport through domestic port B, calling port E, etc. to transport the container goods to node D, or via container ship transport to a certain Mediterranean port city H in Europe and then via European railway transport or road transport to the destination D.

3 Mathematical Models and Solution Methods

3.1 Mathematical Model

Based on the organization of container multimodal transport and the characteristics of the entire process, we analyze the China-Europe container multimodal transport from the perspectives of ”point” to ”line”, ”station” to ”route”, and ”transshipment” to ”transportation”. The model’s solution objectives consider establishing a model for transportation costs, transportation time, and emissions at three levels.

Transportation costs: In this paper, the transportation costs of China-Europe container multimodal transport are divided into three categories from the perspective of ”station” to ”route”: (1) in-transit transportation costs C_{ij}^k; (2) node operation costs C^J; (3) other costs C_i^{ELSE}. The comprehensive transportation cost can be expressed as:

$$\begin{aligned}\min W_1 = &\sum_{i,j\in I}\sum_{k\in K} C_{ij}^k * x_{ij}^k \\ &+ \left[\sum_{i\in O,D}\sum_{k\in K} C_i^k + \sum_{i\in B} C_i^{TR} + \sum_{i,j\in I}\sum_{k,k'\in K} C_i^{kk'} * y_i^{kk'}\right] + \sum_{i\in I} C_i^{ELSE}\end{aligned} \tag{1}$$

Wherein, the in-transit transportation costs are related to the distance between nodes and the rates of different transportation modes, which can be expressed as:

$$C_{ij}^k = n_{ij}^k \times \left[B^k + f^k \times L_{ij}^k\right] \tag{2}$$

n_{ij}^k: Billing container quantity, TEU; f^k: Long-haul container transportation price, CNY/TEU·km; L_{ij}^k: Container transportation distance, km; B^k: Base price for container road transportation, CNY/TEU.

Node operation costs are mainly related to the specific charging standards for loading and unloading operations, transshipment operations, and equipment change operations at the node. Loading and unloading operation costs are represented by C_i^k, equipment change costs are represented by C_i^{TR}, and transshipment costs are represented by $C_i^{kk'}$.

Other costs are collected by the carrier from the consignor based on specific situations such as shunting fees, demurrage fees, vehicle tolls, and container usage fees.

Transportation time: The composition of transportation time for China-Europe container multimodal transport is similar to transportation costs. According to the organization of China-Europe container multimodal transport and the characteristics of the entire transportation process, the transportation time of China-Europe container multimodal transport is divided into three categories from the perspective of ”station” to ”route”: (1) in-transit transportation time T_{ij}^k; (2) node operation time T^J, divided into loading and unloading time at the starting node, equipment change time at the train station, and delay time at the border station. The node operation time is directly proportional to the number of containers that need to be operated and inversely proportional to the operation efficiency; (3) border station delay time T_i^{DL}, estimated using the prediction method proposed by Lv et al. [4].

$$\min W_2 = \sum_{i,j\in I}\sum_{k\in K} T_{ij}^k \times x_{ij}^k + \left[\sum_{i\in O,D}\sum_{k\in K} T_i^k + \sum_{i\in B} T_i^{TR} + \sum_{i\in I}\sum_{k,k'\in K} T_i^{kk'} \times y_i^{kk'}\right] + \sum_{i\in I} T_i^{DL} \tag{3}$$

The in-transit time is mainly determined by the distance between nodes and the operating speed, which can be expressed as:

$$T_{ij}^k = \frac{L_{ij}^k}{v_{ij}^k} \tag{4}$$

L_{ij}^k: Represents the transportation distance from node i to j; v_{ij}^k: Represents the transportation speed.

Assuming that the delay duration t follows a certain probability distribution $F(t)$, $E(T_i^k)$ is the mathematical expectation of the delay time at node i, its probability density function is $f_i(t)$, $t \geq 0$, $t = 0$ represents no delay, then the delay time at the border node is T_i^{DL}:

$$T_i^{DL} = E\left(T_i^k\right) = a_i^k \Gamma\left(1 + 1/b_i^k\right) \tag{5}$$

Carbon emissions: This paper analyzes and calculates the carbon emissions of China-Europe container multimodal transport based on the organization of China-Europe container multimodal transport, the characteristics of the entire transportation process, and the influencing factors of carbon emissions from different transportation modes. Carbon emissions are divided into two parts: carbon emissions generated during transportation E_{ij}^{k} and carbon emissions generated during transportation mode conversion $E_i^{kk'}$.

$$\min W_3 = \sum_{i,j\in I}\sum_{k\in K} E_{ij}^{k} * x_{ij}^{k} + \sum_{i,j\in I}\sum_{k,k'\in K} E_i^{kk'} * y_i^{kk'} \tag{6}$$

$$E_{ij}^{k} = U^{k} \times n_{ij}^{k} \times L_{ij}^{k} \tag{7}$$

When a container is transferred from one transportation mode to another, it needs to be transshipped at the transshipment node, and the container needs to be short-hauled from one container station to another container station by road transportation for transshipment assembly. The container will also undergo loading and unloading, inspection, handling, and storage operations. This process also generates carbon emissions. The carbon emissions generated during transportation mode conversion are mainly related to the conversion between different transportation modes and short-haul road transportation. Therefore, the calculation formula for carbon emissions generated by the conversion between different transportation modes is as follows:

$$E_i^{kk'} = n_i^{kk'} \times \partial_i^{kk'} \tag{8}$$

s.t.

$$\sum_{j\in I,k\in K} x_{Oj}^{k} = \sum_{i\in I,k\in K} x_{iD}^{k} = 1 \tag{9}$$

$$\sum_{i,j\in I,k\in K} x_{ij}^{k} = \sum_{i,j\in I,k\in K} x_{ji}^{k} \tag{10}$$

$$\sum_{i,j\in I,k\in K} x_{ij}^{k} = 1 \tag{11}$$

$$\sum_{i\in I}\sum_{k,k'\in K} y_i^{kk'} \leq 1 \tag{12}$$

$$x_{ij}^{k} x_{j(j+1)}^{k'} = y_i^{kk'} \tag{13}$$

$$t_{ik} + t_{ij}^{k} + t_i^{kk'} + t_i^{k} - t_{jk} \leq \left(1 - x_{ij}^{k}\right) M \tag{14}$$

Equation (9) is the starting point constraint, which ensures that the selected route on the ChinaEurope container multimodal transport service network must contain an arc connecting the starting point. Equation (10) is the flow conservation constraint, which ensures the conservation of inbound and outbound cargo volume at any node in the China-Europe container multimodal transport service network. Equation (11) is the constraint that ensures that only one transportation mode can be selected between adjacent nodes on the China-Europe container multimodal transport service network. Equation (12) is the constraint that ensures that there is at most one transportation mode conversion at point i on the China-Europe container multimodal transport service network. Equation (13) is the starting point constraint, which ensures that in the China-Europe container multimodal transport service network, the transportation mode from node i to node j through mode k, the transportation mode at node j changes to k', and the transportation mode to the next node $j+1$ is k. Equation (14) is the time connection constraint.

3.2 Solution Method

In multi-objective optimization problems, the improvement of one objective's performance often comes at the cost of sacrificing the performance of other objectives due to the mutual constraints between different objectives. Therefore, there is no solution that can optimize all objective performances at once. In multi-objective optimization problems, the solution generally refers to a set of non-dominated solutions—the Pareto solution set. When multiple Pareto optimal solutions appear simultaneously, it is difficult to determine which solution is preferable without more information about the problem. Thus, any Pareto optimal solution may be considered equally important. Accordingly, the goal for multi-objective optimization problems is to find as many Pareto optimal solutions as possible for the problem. In this paper, the first step in solving multi-objective optimization problems is to use the DFS algorithm to find all feasible solutions in the multimodal transportation network and then combine the non-dominated sorting algorithm to find a set of solutions that are as close as possible to the Pareto optimal feasible domain.

(1) DFS algorithm to find all feasible solutions

Figure 3 shows an undirected network composed of 8 vertices. The traversal steps of the DFS algorithm are introduced using Figure 3 as an example. The DFS algorithm traverses all vertices in the network and obtains a path containing all vertices, as shown in Figure 4.

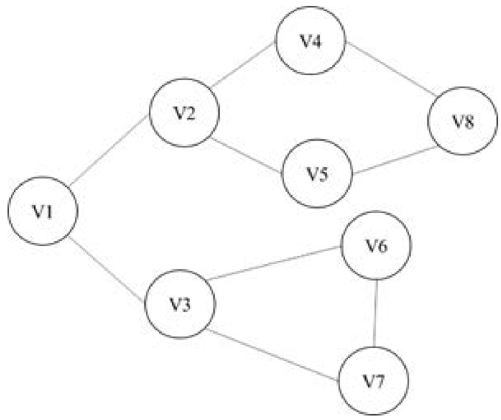

Figure 3. Traversal network schematic

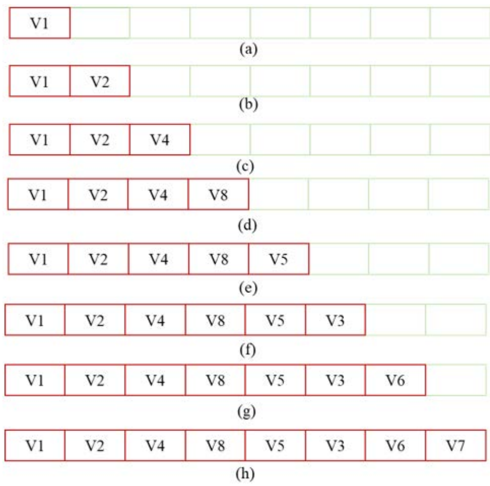

Figure 4. DFS algorithm traversal schematic

(2) Non-dominated sorting algorithm to find the Pareto frontier

Before introducing the solution algorithm for multi-objective optimization problems, the concepts of dominance and non-dominance relationships need to be explained: dominance and non-dominance relationships are a set of relative concepts. In multi-objective optimization problems, if there is a solution p that has at least one objective value better than solution q, and the other objective values of solution p are no worse than solution q, solution p is said to dominate solution q, solution q is dominated by solution p, and solution p is non-dominated. The bubble sort algorithm is used in combination with non-dominated sorting theory to perform non-dominated sorting on all feasible solutions obtained by the DFS algorithm. The specific steps are as follows:

1) Set $i = 0$, where the value of i represents one of the objectives of the solution, with 0 representing cost, 1 representing emissions, and 2 representing time;

2) Use bubble sorting to sort all X_i function values from smallest to largest;

3) Set Min_{X_i} the solution with the smallest as the initial solution;

4) Compare the dominance and non-dominance relationships between the initial solution and the next solution;

5) If none of the function values of the next solution are better than the function values of the initial solution, remove the next solution and return to step (4) to perform non-dominated sorting on the next solution; if at least one function value of the next solution is better than the function values of the initial solution, place the initial solution in the Pareto solution set, replace the initial solution with the next solution, and return to step (4) to continue sorting the remaining solutions until all solutions in the current bubble sort are completed;

6) Replace the solution set obtained by the DFS algorithm with the Pareto solution set obtained in step (5), set $\mathrm{i} = \mathrm{i} + 1$, and if $\mathrm{i} \neq 3$, perform step (2); if $\mathrm{i} = 3$, end the loop and output the Pareto solution set.

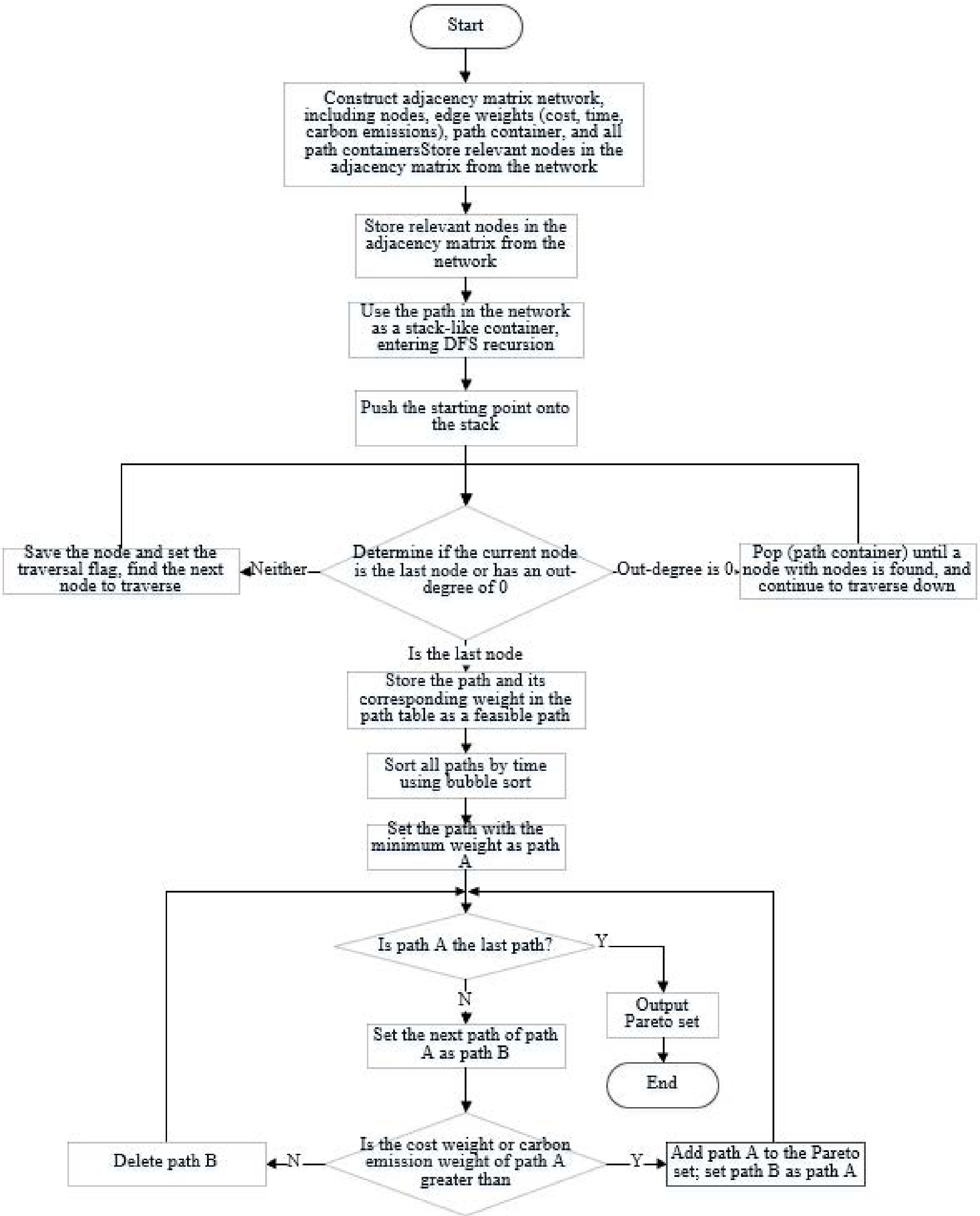

Figure 5. DFS hybrid algorithm flowchart

The non-dominated sorting algorithm in this section, combined with the DFS algorithm introduced in the previous section, can solve the Pareto set of multi-objective problems. The flowchart of the DFS hybrid algorithm used in this paper is shown in Figure 5.

(3) Fuzzy evaluation method to select a unique optimal solution

In the case of multiple Pareto optimal solutions, it is difficult to choose which solution is more preferable without more information about the problem. Therefore, all Pareto optimal solutions can be considered equally important. A further evaluation of the Pareto set can be performed by defining an evaluation function to obtain the best satisfactory solution in the Pareto set.

To obtain the optimal solution based on the decision-maker's needs, a fuzzy decision-making method is employed to obtain the optimal solution, as this method can generate the optimality of the selected solutions based on the decision-maker's preferences. The linear membership function of the Pareto objective function is first generated by the following formula:

$$\theta_i\left(f_i^S\right)=\begin{cases}1 & f_i^S \leq f_i^I \\ \frac{f_i^N-f_i^S}{f_i^N-f_i^I} & f_i^I \leq f_i^S \leq f_i^N i=1,2,3;1 \leq s \leq S \\ 0 & f_i^S \geq f_i^N\end{cases} \tag{15}$$

where, $\theta_i\left(f_i^S\right)$ represents the i-th objective function of the s-th solution, f_i^I and f_i^N are the lower and upper bounds of the i-th objective function, while f_i^s is the s-th Pareto solution in the i-th objective. The total membership degree θ^s is calculated using the following formula:

$$\theta^S=\sum_{i=1}^{3} \omega_i \theta_i\left(f_i^S\right) \tag{16}$$

where, ω_i is the weight of the i-th objective, and in this model $\sum_{i=1}^{3} \omega_i=1$. The decision-maker's preferences can determine the best solution with the maximum θ^s.

4 Case Analysis

4.1 Case Background

This study assumes that Dalian will export five different categories of goods to Hamburg, and selects Shenyang, Harbin, Wuhan, Chongqing, and Shanghai, which have 9 cities with direct access to Hamburg's China-Europe trains and basically achieve regular operations, as the alternative transfer cities for Dalian cargo to go through the China-Europe railway corridor; it selects "Tianjin Port, Shanghai Port, Ningbo Port, Shenzhen Yantian Port" as the alternative transfer ports for the sea-rail intermodal corridor, and selects "Dalian-Hamburg" existing sea routes with "timeliness" and good operations as the alternative routes to study the "Dalian-Hamburg" China-Europe container multimodal transport route selection optimization problem.

Figure 6. Dalian-Hamburg transportation network diagram

As shown in Figure 6, the Dalian-Hamburg transport network diagram, the goods start from Dalian and can be transported by land to the provincial capital Shenyang for distribution, then through the eastern corridor, through Manzhouli or Suifenhe border stations, connecting the Russian Siberian railway line and European countries. The central corridor of the China-Europe train connects China with Mongolia, Russia, Belarus, and Europe through the Erenhot pass, carrying part of the traffic to Russia and Eastern Europe, including Zhengzhou-Hamburg and Chongqing-Duisburg routes. The western corridor is one of the busiest corridors, transporting goods between Europe and China through Alashankou and Horgos, passing through Kazakhstan, Russia, Belarus, Poland, and entering other European countries. Assuming that the container operates normally at each node during the transportation process, the container cargo "door-to-door" pick-up and delivery operations and container lifting and empty return operations are not considered. The entire transportation process is timed from the container cargo transportation to Dalian cargo station or Dalian port, and the transportation end time is when the cargo arrives at Hamburg railway station or Hamburg port. The problem to be solved is: considering transportation costs, transportation time, and carbon emission factors, select the optimal multimodal transport route for five categories of container goods. The transportation flow chart is shown in Figure 7.

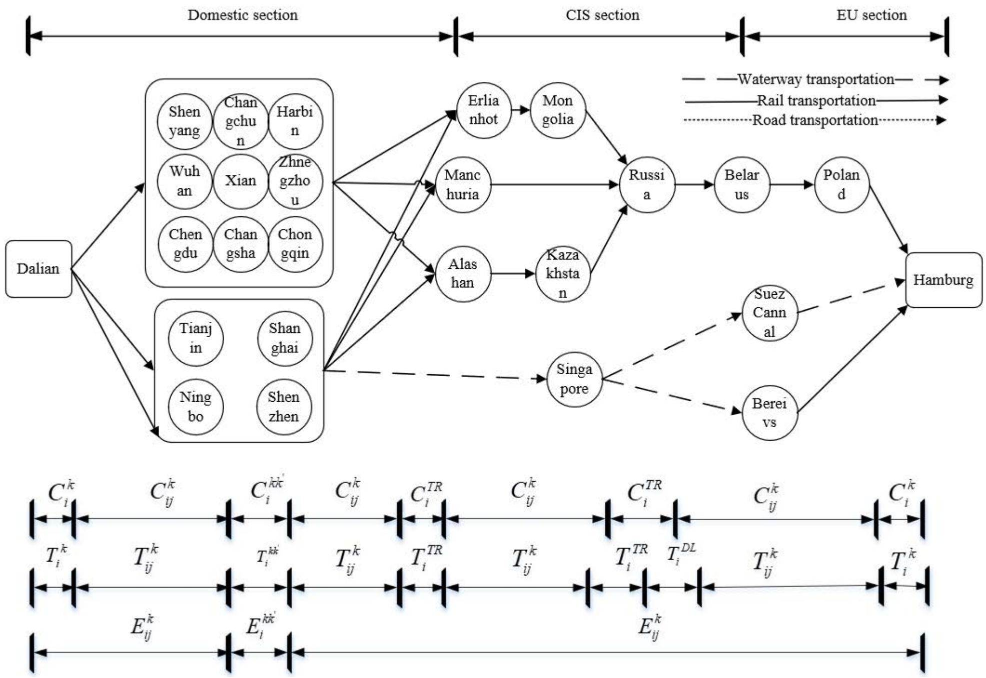

Figure 7. Dalian-Hamburg transport flow chart

4.2 Data Preparation

In the solution process, it is necessary to determine the importance of costs, time, and emissions to different decision-makers, that is, to determine the weight coefficients of costs, time, and emissions for different value types of goods for different decision-makers. For the China-Europe container multimodal transport route selection problem studied in this paper, it is necessary to determine the scoring of transportation costs, time, and carbon emissions sensitivity for high-tech electronic products, fast-moving clothing, auto parts, household goods, and steel products according to the scoring criteria table. The scoring tables for the five types of goods are shown in Table 1.

Table 1. Transportation cost, time, carbon emission sensitivity score table

Product category	Cost score	Time score	Emission score
Fast-fashion clothing	3.00	9.00	3.00
Electronics devices	1.00	7.00	9.00
Automobile parts	7.00	3.00	5.00
Home goods	5.00	5.00	7.00
Steel products	9.00	1.00	1.00

Based on the score table, calculate the weight coefficients for costs, time, and emissions for these five categories of goods. The matrix representation of the multi-modal transport carrier's scoring matrix for the five categories of goods for transportation costs, transportation time, and transportation emissions is shown in Table 2.

Table 2. Transportation cost, time, carbon emission weight coefficient table

Product category	Cost weight coefficient	Time weight coefficient	Emission weight coefficient
Fast-fashion clothing	0.20	0.60	0.20
Electronics devices	0.06	0.41	0.53
Automobile parts	0.47	0.20	0.33
Home goods	0.29	0.29	0.41
Steel products	0.82	0.09	0.09

The transportation costs, transportation time, carbon emissions, and other data required for different transportation modes are shown in Table 3.

Table 3. China-Europe train segment transportation costs

Transportation mode		Average speed	Transportation cost	Unit carbon emission
Railway	Domestic section	45km/h	2.75 Yuan/TEU/km	0.158 (kg/ TEU·km)
	Independent section	40,30,35km/h	0.3 USD/km	
	European union section	42km/h	0.44 USD/km	
Highway	Domestic section	90 km/h	7.5 Yuan/TEU/km	0.889 (kg/ TEU·km)
	Independent section	70 km/h	14 Yuan/TEU/km	
	European union section	120 km/h	32 Yuan/TEU/km	
Marine transport	/	20 (37 km/h)	0.23 Yuan/TEU/km	0.295(LFSO) and 0.211(MGO)

Data sources: "Railway Freight Tariff Rate Table", "International Container Trucking Charging Rules", http://www.yidaiyilu.gov.cn, http://www.cn-eship.com/steelPrice/gjgkryjg.jsp

Table 4. Border station operation costs and time table

Site type	Fixed operation cost (Yuan)	Container change operation cost (Yuan/TEU·km)	Customs clearance time (h)	Container change time (h)	Delay time (h)
Busy container change station	1436	718	24	6	63.8
Non-container change station	359	/	8	/	10.5
Non-busy container change station	1436	718	24	6	42.3

Data sources: "Railway Freight Tariff Rules" http://www.95306.cn/, http://www.ndrc.gov.cn/

Border station operation time, costs, delay time, etc., refer to the "Unified Transit Tariff Regulations for International Railway Freight Intermodal Transport" (2019) and take into account the research situation of Dalian train company. The details are shown in Table 4.

The conversion costs, conversion time, and carbon emission factors between transportation modes are calculated based on the formulas mentioned earlier and the charging standards of Dalian Port. The data can be seen in Table 5.

Table 5. Intermodal transfer costs for various transportation modes

Transfer method	Transfer cost (Yuan/TEU)	Transfer time (h)	Carbon emission factor (kg/TEU)
Rail-Road	150	5	2.17
Rail-Water	200	6	1.92
Water-Road	230	8	1.98
Water-Water	/	/	2.25

Data sources: "China-Europe Train Development Report 2021" http://www.liaoningport.com

4.3 Calculation Results

(1) The optimal route for a single objective

According to the selection results of the transportation paths in Table 6, there are no circuitous or repeated paths, and the transportation paths are basically consistent with China's geographical transportation environment. The most cost-effective path in the current transportation network is the all-water route, the most emission-efficient path is the rail-water combined transport route, and the most time-efficient path is the road-rail combined transport route. From the single-objective optimal path, it can be seen that the all-water route has transportation costs that are 20% and 9% lower than the other two routes, but the time consumed by this route is 1.9 times and 2.1 times longer than the other two routes. From the transportation emission data of the three routes, the all-water route has a higher carbon emission due to its longer transportation distance, which is about 30% higher than the road-rail combined transport route.

Table 6. Optimal route for a single objective

Objective	Transportation cost (RMB)	Transportation time (h)	Transportation emission (kg)	Transportation scheme
Cost-optimal	574985.88	601.58	460281.719	All-water route) Dalian-Ningbo-Singapore-Suez-Hamburg
Emission-optimal	2798310.75	311.36	139882.016	(Rail-Water combined) Dalian (water)-Tianjin-(transfer to rail)-Erenhot-Naushki-Krasnoyarsk-Malaszewicze-Poland-Hamburg
Time-optimal	6638670.50	281.10	335045.594	(Road-Rail combined) Dalian (road)-Shenyang-Manzhouli-(transfer to rail)-Naushki-Krasnoyarsk-Malaszewicze-(transfer to road) Poland-Hamburg

(2) Pareto Optimal Set (Figure 8)

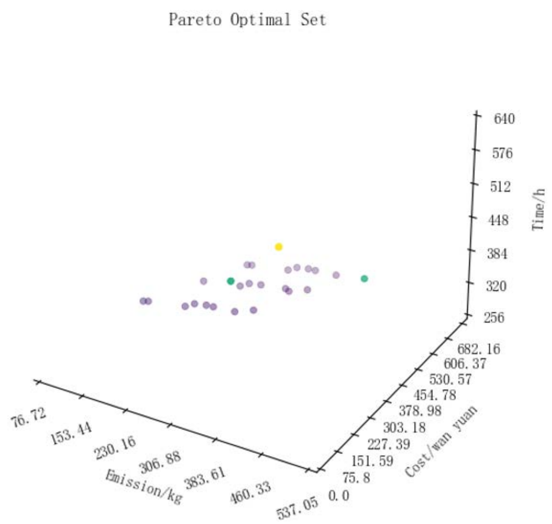

Figure 8. Pareto set for multi-objective problems

Table 7. Optimal transportation scheme for five types of goods

Goods type	Transportation cost (RMB)	Transportation time (h)	Transportation emission (kg)	Transportation scheme
Fast-fashion clothing	2945428.25	305.76	141081.38	(All-rail route) Dalian-Harbin-Manzhouli-Naushki-Krasnoyarsk-Malaszewicze-Poland-Hamburg
Electronic devices	2945428.25	305.76	141081.38	(All-rail route) Dalian-Harbin-Manzhouli-Naushki-Krasnoyarsk-Malaszewicze-Poland-Hamburg
Automobile parts	2798310.75	311.36	139882.016	(Rail-Water combined) Dalian (water)-Tianjin-(transfer to rail)-Erenhot-Naushki-Krasnoyarsk-Malaszewicze-Poland-Hamburg
Home goods	2798310.75	311.36	139882.016	(Rail-Water combined) Dalian (water)-Tianjin-(transfer to rail)-Erenhot-Naushki-Krasnoyarsk-Malaszewicze-Poland-Hamburg
Steel products	575760.50	600.72	459619.188	(All-water route) Dalian-Shanghai-Singapore-Suez-Hamburg

From the calculation results in Table 7, it can be seen that each scheme has its own strengths and weaknesses for goods with different value characteristics. For example, automobile parts, home goods, and steel products all adopt rail-water combined transport or all-water transport schemes. These schemes have the lowest total transportation costs due to the low freight rates of rail and water transport but also have longer transportation times due to the slower speeds of these two transportation modes. Fast-fashion clothing adopts an all-rail transport scheme that fully utilizes the speed advantage of rail transport to minimize the total transportation time; however, the higher rail transport costs also result in the highest total transportation costs for this scheme. The transportation scheme for electronic devices combines low-pollution, low-energy water transport with fast, flexible road transport, achieving both reduced total emissions and shorter total transportation times. Overall, the results show that time-sensitive goods are more inclined to choose faster road and rail transport in the constructed network, while cost-sensitive goods tend to prefer the more cost-effective water transport. For goods that are not particularly sensitive to costs, time, or emissions, rail-water combined transport schemes are more likely to be chosen to reduce emissions.

4.4 Sensitivity Analysis

Table 8. Optimal transportation schemes after the increase in EU rail transportation costs

Goods type	Transportation cost (RMB)	Transportation time (h)	Transportation emission (kg)	Transportation scheme
Fast-fashion clothing	5839425.50	291.97	215443.81	(Road-Rail Intermodal) Dalian-Harbin-Manzhouli-Navushki-Krasnogor-Malashevichi-(Switch to Road)-Poland-Hamburg
Electronic devices	7477475.50	305.76	141081.38	(Full Rail) Dalian-Harbin-Manzhouli-Navushki-Krasnogor-Malashevichi-Poland-Hamburg
Automobile parts	575760.50	600.72	459619.188	(Full Waterway) Dalian-Shanghai-Singapore-Suez-Hamburg
Home goods	5692308.00	297.57	214244.44	(Water-Rail Intermodal) Dalian (Waterway)-Tianjin-(Switch to Rail)-Erenhot-Navushki-Krasnogor-Malashevichi-(Switch to Road)-Poland-Hamburg
Steel products	575760.50	600.72	459619.188	(Full Waterway) Dalian-Shanghai-Singapore-Suez-Hamburg

In this section, the computational experiment demonstrates the optimal transportation schemes for five types of goods with different value characteristics under different transportation rates. Among the tested transportation rates, domestic road transportation and EU rail transportation rates are greatly affected by oil prices and electricity prices. Therefore, based on the actual possible transportation rates, three different transportation rate scenarios were designed: domestic road transportation rate increase, EU rail transportation rate increase, Table 8 shows the optimal transportation schemes for the five types of goods when European electricity prices rise, resulting in a significant increase in EU rail transportation costs, which are equal to road transportation costs. Under other conditions unchanged, when considering the rise in European electricity prices, the EU rail transportation costs significantly increase and are equal to road transportation costs, the optimal transportation schemes for the five types of goods can be obtained as shown in Table 8.

As shown in Table 8, when the EU rail transportation cost rises to ¥40/km, the change in EU rail transportation costs will not affect the transportation scheme choices for goods such as electronic equipment, home supplies, and steel products, the electronic equipment will still choose the full rail transportation scheme, and steel products will still choose the cheaper sea transportation. However, auto parts, which have a high value but are not sensitive to time and focus more on cost, will be affected by the increase in EU rail transportation costs. When the rail transportation cost rises to the same level as road transportation, it will choose the more cost-advantageous sea transportation.

In the next part of the computational experiment, the optimal transportation schemes for the five types of goods with different value characteristics under different transportation times are demonstrated. Among the tested transportation times, the time for changing equipment at stations, the delay time at border stations, and the time for sea transportation are greatly affected by factors such as station operation efficiency and port congestion. Therefore, based on the actual possible situations, several different transportation time scenarios were designed, including reduced waiting time for equipment change, shortened border station delay time, and extended sea transportation time; Table 9 shows the optimal transportation schemes for the five types of goods when the Suez Canal is congested for two weeks.

Table 9. Optimal transportation schemes during the Suez Canal congestion

Goods type	Transportation cost (RMB)	Transportation time (h)	Transportation emission (kg)	Transportation scheme
Fast-fashion clothing	2798310.75	311.36	139882.016	(Water-Rail Intermodal) Dalian-Tianjin-(Switch to Rail)-Erenhot-Navushki-Krasnogor-Malashevichi-Poland-Hamburg
Electronic devices	2945428.25	305.76	141081.38	(Full Rail) Dalian-Harbin-Manzhouli-Navushki-Krasnogor-Malashevichi-Poland-Hamburg
Automobile parts	2798310.75	311.36	139882.016	(Water-Rail Intermodal) Dalian (Waterway)-Tianjin-(Switch to Rail)-Erenhot-Navushki-Krasnogor-Malashevichi-Poland-Hamburg
Home goods	2798310.75	311.36	139882.016	(Water-Rail Intermodal) Dalian (Waterway)-Tianjin-(Switch to Rail)-Erenhot-Navushki-Krasnogor-Malashevichi-Poland-Hamburg
Steel products	575760.50	936.72	459619.188	(Full Waterway) Dalian-Shanghai-Singapore-Suez-Hamburg

As shown in Table 9, when the Suez Canal experiences congestion and the sea transportation time increases by two weeks, the transportation schemes of all five types of goods are affected. During the congestion, the sea transportation time increases significantly, and the water-rail intermodal transportation scheme becomes more advantageous for fast fashion, auto parts, home supplies, and steel products. Electronic equipment still chooses the full rail transportation scheme due to its higher value and time sensitivity.

The sensitivity analysis shows that different transportation rate and time scenarios have a significant impact on the optimal transportation schemes for goods with different value characteristics. For goods with high value and time sensitivity, such as electronic equipment, the full rail transportation scheme is preferred regardless of changes in transportation costs or times. For goods with lower value and higher sensitivity to transportation costs, such as auto parts and steel products, the transportation scheme selection may be affected by changes in transportation costs and times. Fast fashion and home supplies, which have medium value and time sensitivity, may also adjust their transportation scheme choices under different scenarios.

In conclusion, the choice of transportation scheme for goods with different value characteristics is mainly affected by factors such as transportation costs, time, and emissions. Through sensitivity analysis, it can be seen that the change in transportation costs and times can significantly affect the optimal transportation scheme. Therefore, it is essential for enterprises to fully consider the possible changes in transportation costs and times when making transportation decisions, and to choose the transportation scheme that best suits the characteristics of the goods, in order to improve the overall transportation efficiency and reduce the impact of transportation on the environment.

5 Conclusion

In this study, based on the characteristics of goods value, carrier costs, and shipper demands, we have clarified the research perspective and decision-makers, constructed a China-Europe multimodal container transportation network and service network, and correspondingly divided and described three typical transportation scenarios. We proposed a multi-objective China-Europe multimodal transportation route selection model that considers transportation costs, time, and carbon emissions. The main factors affecting the route selection of goods with different value types were analyzed. Through a case study, it was found that the China-Europe trains could significantly reduce transportation time by substituting roads, effectively reducing the depreciation of time-sensitive goods. However, the data sources in this study are limited, and the scenarios considered in the analysis are not comprehensive enough, which restricts the applicability of the model. The limitations of generalization and application also need further discussion. This research is only a preliminary attempt in studying the container cross-border multimodal transportation route selection under the "Belt and Road" initiative. In future research, we can continue to explore the impact of factors such as transportation capacity, transportation reliability, and service level of different transportation modes on route selection.

Data Availability

The data supporting our research results are included within the article or supplementary material.

Conflicts of Interest

The author declares no conflict of interest.

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Appendix

Category	Symbol	Meaning
Set	K	Represents transportation modes, k = (1, 2, 3), corresponding to rail transportation, road transportation, and water transportation
	I	The set of all transportation nodes in the network, where O is the origin and D is the destination
	A	The set of all transportation arcs in the network
	B	Set of train station sites; (($B \subseteq I$))
Parameter	C_{ij}^{k}	The transportation cost (in yuan) from node i to j using transportation mode k
	C_i^J	Various handling fees (in yuan) at node i
	C_i^{ELSE}	Other fees (in yuan) at node i
	C_i^k	Container loading and unloading fees (in yuan) at node i
	C_i^{TR}	Container transshipment fees (in yuan) for trains at node i
	$C_i^{kk'}$	Cost (in yuan) for changing transportation mode from k to k' at node i
	T_{ij}^{k}	Transportation time (in hours) from node i to j using transportation mode k
	T_i^J	Various handling times (in hours) at node i
	T_i^{DL}	Delay time (in hours) at node i
	T_i^k	Loading and unloading operation time (in hours) at node i
	T_i^{TR}	Total container transshipment time for trains (in hours)
	$T_i^{kk'}$	Transshipment operation time (in hours) for changing transportation mode from k to k' at node i
	E_{ij}^{k}	Carbon emissions for transportation mode k (in kg)
	U^k	Unit carbon emissions for transportation mode k (kg/TEU·km), (kg/kWh)
	L_{ij}^{k}	Transportation distance (in km) from node i to j using transportation mode k
	v_{ij}^{k}	Average transportation speed (in km/h) for transportation mode k
	n_{ij}^{k}	Number of containers charged (TEU)
	f^k	Basic freight rate (in yuan/TEU·km) for transportation mode k
	a_i^k	Shape parameter
	b_i^k	Scale parameter
	T_i^{DL}	Delay time (in hours) at node i
	T_i^k	Loading and unloading operation time (in hours) at node i
Decision variable	x_{ij}^{k}	0-1 variable, indicating whether arc ij is selected
	$y_i^{kk'}$	0-1 variable, indicating whether transshipment is performed at node i