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Robust Optimization of Transport Organization for China Railway Express

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Abstract: This paper presents an in-depth analysis of the robust optimization of the China–Europe freight train transportation organization under uncertain cargo transportation demand. The study commences by constructing a robust optimization model tailored for specific environments, which is further extended to address the complexities of uncertain freight demand. A notable aspect of this research is the adoption of an innovative approach to manage the uncertainties in freight transportation demand at each node, employing a box-type uncertainty set distribution. This methodology allows for an effective and balanced optimization strategy that accommodates the dynamic nature of demand fluctuations. The research findings underscore that increased robustness in the optimization model is associated with higher transportation costs within the China–Europe freight train network, especially under conditions of variable demand. The model demonstrates a preference for adjusting transportation costs to maintain the stability of the transportation scheme, particularly in response to wider variations in cargo demand. This strategy, prioritizing cost-effectiveness and adaptability, highlights the importance of a comprehensive approach to managing demand uncertainties. The significant contributions of this paper include the development of a robust, economically viable, and efficient transportation organization plan for China–Europe freight trains, equipped to navigate the challenges posed by uncertain cargo demand at the originating nodes. The study's emphasis on the practical application of advanced optimization techniques and uncertainty management methods marks a notable advancement in the field of freight train transportation. Additionally, the paper suggests avenues for further research in the intricate and evolving landscape of freight transportation, providing valuable insights for future studies.

Keywords: China railway express; transportation organization optimization; uncertainty; robust optimization

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1. Introduction

The China–Europe Express, a cornerstone of the 'Belt and Road' Initiative, is pivotal in enhancing cross-border cargo transportation and strengthening trade ties between China and Europe. This transportation network faces numerous operational challenges, including extended routes, prolonged transit times, and elevated shipping costs, further compounded by a complex cargo distribution network and high rates of empty container returns. A significant aspect of these challenges is managing the inherent uncertainties in the transportation process, such as fluctuating road transportation costs, unpredictable transit durations, and variable freight capacities. Addressing these challenges involves a comprehensive approach to managing the uncertainties surrounding freight transportation demand at each node, while other parameters are considered deterministic. In this context, the transportation demand for goods at each node is modeled within a range of variability, allowing for a responsive and adaptable optimization strategy. This approach recognizes the fluctuating nature of demand, adapting the transportation organization to accommodate varying levels of cargo flow. This paper focuses on the robust optimization of the transportation organization for China–Europe freight trains. The aim is to address the complexities of cargo transportation demand and enhance the economic viability, efficiency, and stability of the China–Europe freight transportation system. This research holds substantial practical significance and offers valuable insights into the optimization of large-scale transportation networks. By exploring advanced optimization techniques and strategies for managing transportation uncertainties, this study contributes to the ongoing development and improvement of the China–Europe freight train operations.

Optimizing railway container transportation organization is pivotal for enhancing China–Europe freight train operations. Several studies have contributed insights in this domain. Tong et al. [1] developed a two-tier programming model aimed at maximizing revenue and minimizing CO_2 emissions and transportation costs in railways, employing a non-dominated sorting genetic algorithm with an elite strategy. Liu [2] focused on railway coal transport, formulating a multi-objective optimization model to balance carrier income and transportation costs, solved using genetic algorithms. Jin et al. [3] presented a high-speed railway freight service network model that balances costs and demand, resolved through a column generation algorithm, thereby optimizing operational costs. Hu et al. [4] addressed the minimization of necessary train containers in marshalling stations, considering both carrier and shipper benefits. Yang [5] examined Baoshen Railway's transportation organization optimization using qualitative measures and an evaluation system developed through the Delphi method, AHP, and the entropy weight method. Lastly, Zhao et al. [6–8] proposed an integrated model for container trains, focusing on maximizing revenue through stop schedule planning and space pre-allocation, and applied a linear transformation for solution effectiveness. These studies collectively enhance the understanding of efficient railway transportation organization, directly informing optimization strategies for China–Europe freight train transportation.

Research into multi-modal railway transport organization is also crucial for optimizing the China–Europe train system. Liu [9] developed a model for a container transport system that optimizes the operation of direct, aggregation, and transfer trains, aiming to reduce transport costs and container transit times for the China–Europe train. Yang [10] proposed a three-level railway container system, offering an analytical evaluation of various container transport organization modes. Fang [11] explored freight organization and container transfers within a railway container transport network, focusing on improving efficiency and the integration of railway and water transport. Lastly, Yan et al. [12–14] introduced a mixed integer programming model to optimize transshipments at seaport rail terminals. This model aimed to minimize operational costs while considering a range of factors, demonstrating its application in effectively managing multi-modal transport logistics. These studies collectively provide valuable insights into the complexities of multi-modal transport, directly informing strategies to enhance the efficiency and effectiveness of the China–Europe freight train system.

Moreover, the development of robust scheduling models for railway container transportation organizations, considering external factors, is a critical area of study. Parkhomenko et al. [15,16] introduced a rapid railway container transport organization model utilizing robust optimization techniques. Their model adopts a multi-objective approach, integrating considerations for the environment, traffic, municipal administration, and the economy. It establishes a near-optimal scheduling framework, effectively leveraging innovative solutions like the Metro Cargo terminal and Cargo Sprinter modular train. This model is designed to enhance the scheduling flexibility and resilience of railway container transport against external uncertainties, potentially offering significant improvements in operational efficiency and adaptability for such systems.

In the realm of transportation organization optimization under uncertain parameters, fuzzy and stochastic programming emerge as two predominant methods. Zhang [17] applied fuzzy optimization to tackle uncertainties in transportation demand, transit time, and costs, formulating a fuzzy chance-constrained programming model that underscores the interplay between transportation cost, demand, and capacity. Wang [18] addressed time uncertainties in container-rail routes using fuzzy variables, developing a dual-objective model optimized with fuzzy chance constraint programming for cost and emissions considerations. Li [19] proposed a multimodal transport model accounting for uncertain freight volume and arrival times, employing fuzzy programming and the NSGA-II algorithm for a solution. Radhika et al. [20,21] crafted a multi-objective transportation problem that leverages fuzzy numbers to manage uncertainty in cost and time and solved it using LINGO-WINDOWS-64x86-18.0. Yan et al. [22] utilized fuzzy theory and group decision making for assessing safety levels in road transport of hazardous goods. In contrast, Liu et al. [23–25] employed stochastic programming and genetic algorithms to optimize reliable paths for emergency material transportation under dual uncertainties. Wang et al. [26] optimized cold chain distribution vehicle routes under uncertain demand scenarios using stochastic algorithms, highlighting the benefits of multiple distribution centers. Chen [27] tackled multimodal transport network optimization considering node capacity and demand uncertainties through genetic algorithms. Finally, Wang [28] introduced an ELECTRE evaluation method based on stochastic simulation for minimizing total transportation costs in coal and mining resource transit. These diverse studies collectively exemplify the efficacy of fuzzy and stochastic programming in navigating the complexities of transportation systems amid varied uncertainties.

In the domain of robust optimization for transportation organization, addressing uncertain transportation demand is a critical focus. Wang et al. [29,30] developed a multi-objective model tailored for freight flow allocation within container port aggregation and distribution networks. This model particularly accounts for the uncertainty in transportation demand and enables decision-making under different robust risk scenarios. Liu et al. [31] introduced a two-stage multimodal transport model designed for dynamic pricing decisions under uncertain demand conditions. Their approach integrates opportunity-constrained programming and robust optimization techniques to effectively manage the complexities arising from fluctuating demand and pricing dynamics. These studies provide valuable insights into handling uncertainty in transportation demand, offering methodologies that are particularly relevant to enhancing the efficiency and reliability of large-scale transportation systems like the China–Europe freight trains.

2. Problem Description

The ‘Plan for the Construction and Development of China–Europe Railway Services (2016–2020)’ strategizes the adoption of a ‘trunk and branch integration and hub distribution’ model for enhancing China–Europe railway services. A key feature of this strategy is the establishment of ‘point-to-point’ direct trains operating regularly between major inland cargo origins and significant coastal ports. This approach consolidates goods destined for the same location at a single terminal, streamlining train operations and boosting efficiency. In 2020, the National Development and Reform Commission dedicated CNY 200 million to support the China–Europe Railway Line Assembly Center demonstration project. This project is operational in five critical hub cities: Zhengzhou, Chongqing, Chengdu, Xi’an, and Urumqi. The Central Europe Freight Train Assembly Center, serving as a hub for freight train assembly and transfer, plays a crucial role in this network. It coordinates dispersed cargo sources, consolidates containers, and enhances train operations, thereby reducing operational costs. In light of these developments, this section proposes a transportation organization optimization model for the China–Europe freight trains, accommodating both direct and aggregate transfer modes and addressing the robust optimization challenge posed by uncertain cargo transportation demand.

3. Optimizing China–Europe Freight Train Logistics Amidst Uncertain Transportation Demand

3.1. Assumptions

The main assumptions of this article are as follows:

- Freight trains are differentiated into two categories: domestic section transport trains, which operate exclusively within the domestic leg from the origin freight node to the cargo assembly transit center, and transnational section transport trains, which operate either from the origin freight node to the foreign freight terminal or from the cargo assembly transit center to the foreign freight terminal.
- Each freight train is allowed only a single assembly for transit. This entails adopting either a "point-to-point" direct transportation mode or a transfer scenario, where cargo moves from the freight node to the assembly transit center and then to the freight terminal.
- The model assumes a single transport section between any two nodes, with only one mode of transport being used for each section. This simplification aims to focus on the key logistical elements without the complexity of multiple transport modes or sections.
- The model does not differentiate specific sources of demand fluctuations and their impact on each node. This simplification is to streamline the focus on the overall functionality and efficiency of the freight transportation network, avoiding the complexities associated with analyzing individual demand influences at each node.
- The model does not account for the border process, including changes in railway gauge. This exclusion is to maintain focus on the broader aspects of transportation logistics and to simplify the model's scope.

3.2. Model Parameter

In the context of the China–Europe freight train transport network, the following notations are employed:

$G = (N, A, V)$ symbolizes the China–Europe freight train transport network.

N signifies the set of nodes within the China–Europe freight train network.

A represents the set of paths within the China–Europe freight train network.

V denotes the set of China–Europe freight trains.

O and D respectively denote the collection of origin points and destination points within the transportation network.

The definitions of sets, parameters, and decision variables pertinent to the model are provided in Table 1.

3.3. Determine the Transportation Organization Optimization Model in the Environment

The objective function, as depicted in Formula (1), aims to minimize both the train operating cost and container operating cost within the China–Europe freight train transportation organization.

$$\min F = \sum_{(i,j)\in A} \sum_{v\in V} \left[f_{ij}^{v} \cdot \left(C_v + C_{ijv} \cdot d_{ij} \right) \right] + \sum_{i\in N_3} \left[z_i \cdot Q_i \cdot C_i^{3} \right] \tag{1}$$

The schema constraints are as follows:

s.t.

$$x_{ij}^{v} \le Q_v \cdot f_{ij}^{v} \cdot y_{ij} \quad \forall (i,j) \in A, v \in V \tag{2}$$

$$\sum_{j\in N_2 \cup N_3} \sum_{v\in V} f_{ij}^{v} \ge 1 \quad \forall i \in N_1 \tag{3}$$

$$f_{ij}^{v} = 0 \quad \forall i \in N_2, j \in N \; \textit{or} \; \forall i \in N, j \in N_2, v \in V_1 \tag{4}$$

$$f_{ij}^{v} = 0 \quad \forall i \in N_1 \cup N_3 \; \textit{and} \; \forall j \in N_1 \cup N_3, v \in V_2 \tag{5}$$

$$f_{ij}^{v} \in Z^{+} \cup \{0\} \quad \forall (i,j) \in A, v \in V \tag{6}$$

$$x_{ij}^{v} \geq 0 \quad \forall (i,j) \in A, v \in V \tag{7}$$

$$y_{ij} \in \{0,1\} \quad \forall (i,j) \in A \tag{8}$$

$$z_i \in \{0,1\} \quad \forall i \in N_3 \tag{9}$$

Formula (2) represents the constraint related to train transportation capacity;
Formula (3) pertains to network site constraints;
Formulas (4) and (5) serve as constraints for the train's operational route;
Formulas (6) to (9) establish constraints for the decision variables.

Table 1. Model parameter definition.

	Assemble
Symbol	**Definition**
N	The node set of China–Europe railway network, the element is represented by i, $N = N_1 \cup N_2 \cup N_3$
N_1	Collection of domestic nodes of China–Europe railway network
N_2	Collection of foreign nodes of China–Europe railway network
N_3	China–Europe railway network transit assembly node collection
A	Set of China–Europe railway network paths, index is represented by (i,j)
V	Collection of China–Europe freight trains, indexed by v, $V = V_1 \cup V_2$
V_1	Domestic section transport train collection
V_2	Transnational section transport train collection
	Argument
Symbol	Definition
Q_i	Container freight demand at transport Node i, unit (TEU)
$\overline{Q_i}$	Average container freight demand at transport node i, units (TEU)
Q_v	Capacity, unit (TEU·train^{-1}) of Class v Central European freight train
C_v	Fixed cost per train operation of Class v CEIL, in units (CNY·train^{-1})
C_{ijv}	Class v China–Europe freight train, unit operating cost between China–Europe network routes, unit (CNY·km^{-1})
C_i^3	Container unit transfer cost at staging node i, unit (CNY·TEU^{-1})
Γ	Robust horizontal adjustment parameters
ε_i	Disturbance level of container freight demand at transport node i
	Decision variable
Symbol	Definition
f_{ij}^{v}	Frequency of Class v China–Europe freight train on Route (i,j) of China–Europe Railway network, unit (column·week^{-1})
x_{ij}^{v}	Weekly container freight demand of Class v China–Europe Freight trains on Route (i,j), units (TEU·week^{-1})
y_{ij}	The 0–1 decision variable is 1 if the goods are transported on the China–Europe railway network route (i,j), otherwise 0
z_i	0–1 decision variable: 1 is selected if the goods are collected at the transit assembly node i of the China–Europe railway network; 0 is selected otherwise

3.4. A Robust Transformation Model for Uncertain Cargo Transportation Needs

3.4.1. Uncertain Description of Goods Transportation Demand

This section focuses solely on the uncertainty surrounding the freight transportation demand at each node, while treating other parameters as deterministic. It is assumed that the transportation demand for goods at each node conforms to a box-type uncertainty set distribution. Specifically, the transport demand at each node is bounded within a symmetric interval.

$$Q_i = \overline{Q_i} \pm \overline{Q_i} \cdot \varepsilon_i \tag{10}$$

where $\overline{Q_i}$ represents the average freight demand at node i and ε_i represents the disturbance level of freight demand at node i. The formulation is given as:

$$U_i = \left[\overline{Q_i} - \overline{Q_i} \cdot \varepsilon_i, \overline{Q_i} + \overline{Q_i} \cdot \varepsilon_i\right] \tag{11}$$

In the context of robust optimization of transportation paths, U_i denotes the set encompassing demand uncertainties at various nodes.

3.4.2. Robust Optimization Model for China–Europe Freight Train Logistics Amid Uncertain Cargo Demand

Bertsimas robust optimization, based on robust optimization theory, converts uncertain optimization problems into linear programming problems for simplified resolution. Unlike traditional methods, it adeptly manages uncertainties, yielding high-quality and reliable solutions. Consequently, the Bertsimas robust optimization model is employed in this study to address the optimization challenges within China–Europe freight train logistics amidst uncertain cargo transportation demand.

The robust regulation parameter Γ is introduced to adjust the conservative degree of the robust model, $\Gamma \in [0, n]$, where n is the number of nodes with uncertainty of freight demand, $n \in [0, N_1 \cup N_3]$, and $\lfloor \Gamma \rfloor$ is the largest integer not greater than Γ. When the freight demand with a model maximum of $\lfloor \Gamma \rfloor$ nodes in the model changes in the uncertainty set of the box, the transformed robust model must be able to obtain a feasible solution. When the number of nodes changing the freight demand exceeds $\lfloor \Gamma \rfloor$, if the disturbance range is $(\Gamma - \lfloor \Gamma \rfloor) \cdot \overline{Q_i} \cdot \varepsilon_i$, the transformed robust model still has a high probability of obtaining a feasible solution.

In the established model of transport organization optimization in a definite environment, only the uncertainty parameters exist in the objective function, so the uncertainty parameters in the objective function are changed to the uncertainty parameters in the constraint.

Original objective function:

$$\min F = \sum_{i \in N} \sum_{j \in N} \sum_{v \in V} \left[f_{ij}^v \cdot y_{ij} \cdot \left(C_v + C_{ijv} \cdot d_{ij} \right) \right] + \sum_{i \in N_3} \left[z_i \cdot Q_i \cdot C_i^3 \right] \tag{12}$$

Minimizing the objective function to maximizing it:

$$\max - F = -\sum_{i \in N} \sum_{j \in N} \sum_{v \in V} \left[f_{ij}^v \cdot y_{ij} \cdot \left(C_v + C_{ijv} \cdot d_{ij} \right) \right] - \sum_{i \in N_3} \left[z_i \cdot Q_i \cdot C_i^3 \right] \tag{13}$$

Let $F_{tr} = -F$, then Formula (13) can be converted to the following form:

$$\max F_{tr} \tag{14}$$

$$F_{tr} + \sum_{i \in N} \sum_{j \in N} \sum_{v \in V} \left[f_{ij}^v \cdot y_{ij} \cdot \left(C_v + C_{ijv} \cdot d_{ij} \right) \right] + \sum_{i \in N_3} \left[z_i \cdot Q_i \cdot C_i^3 \right] \le 0 \tag{15}$$

The Bertsimas robust model of Formula (15) is as follows:

$$\begin{aligned} & F_{tr} + \sum_{i \in N} \sum_{j \in N} \sum_{v \in V} \left[f_{ij}^v \cdot y_{ij} \cdot \left(C_v + C_{ijv} \cdot d_{ij} \right) \right] + \sum_{i \in N_3} \left[z_i \cdot \overline{Q_i} \cdot C_i^3 \right] \\ & + \max_{\{S \cup \{t\} | S \subseteq N, |S| = \lfloor \Gamma \rfloor, t = N \backslash S\}} \left\{ \sum_{i \in S} \left[\overline{Q_i} \cdot \varepsilon_i \cdot W_i \cdot C_i^3 \right] + \left[(\Gamma - \lfloor \Gamma \rfloor) \cdot \overline{Q_t} \cdot \varepsilon_t \cdot W_t \cdot C_t^3 \right] \right\} \le 0 \end{aligned} \tag{16}$$

$$-W_i \le z_i \le W_i \quad \forall i \in S \tag{17}$$

When Γ takes an integer, Formula (16) can be reduced to the following form:

$$\begin{aligned} & F_{tr} + \sum_{i \in N} \sum_{j \in N} \sum_{v \in V} \left[f_{ij}^{v} \cdot y_{ij} \cdot \left(C_v + C_{ijv} \cdot d_{ij} \right) \right] + \sum_{i \in N_3} \left[z_i \cdot \overline{Q_i} \cdot C_i^3 \right] \\ & + \max_{\{S \cup \{t\} | S \subseteq N, |S| = \lfloor \Gamma \rfloor, t = N \setminus S\}} \left\{ \sum_{i \in S} \left[\overline{Q_i} \cdot \varepsilon_i \cdot W_i \cdot C_i^3 \right] \right\} \leq 0 \end{aligned} \tag{18}$$

Formula (18) is robustly transformed by Bertsimas as follows:

$$F_{tr} + \sum_{i \in N} \sum_{j \in N} \sum_{v \in V} \left[f_{ij}^{v} \cdot y_{ij} \cdot \left(C_v + C_{ijv} \cdot d_{ij} \right) \right] + \sum_{i \in N_3} \left[z_i \cdot \overline{Q_i} \cdot C_i^3 \right] + \lambda * \Gamma + \sum_{i \in S} \sigma_i \leq 0 \tag{19}$$

$$\lambda + \sigma_i \geq \overline{Q_i} \cdot \varepsilon_i \cdot W_i \cdot C_i^3 \quad \forall i \in S \tag{20}$$

$$\lambda \geq 0 \tag{21}$$

$$\sigma_i \geq 0 \quad \forall i \in S \tag{22}$$

To sum up, the optimization model of China–Europe freight train transportation organization with robust and controllable cargo transportation demand is as follows:

$$\max F_{tr} \tag{23}$$

s.t.

$$F_{tr} + \sum_{i \in N} \sum_{j \in N} \sum_{v \in V} \left[f_{ij}^{v} \cdot y_{ij} \cdot \left(C_v + C_{ijv} \cdot d_{ij} \right) \right] + \sum_{i \in N_3} \left[z_i \cdot \overline{Q_i} \cdot C_i^3 \right] + \lambda * \Gamma + \sum_{i \in S} \sigma_i \leq 0 \tag{24}$$

$$\lambda + \sigma_i \geq \overline{Q_i} \cdot \varepsilon_i \cdot W_i \cdot C_i^3 \quad \forall i \in S \tag{25}$$

$$-W_i \leq z_i \leq W_i \quad \forall i \in S \tag{26}$$

$$x_{ij}^{v} \leq Q_v \cdot f_{ij}^{v} \cdot y_{ij} \quad \forall (i,j) \in A, v \in V \tag{27}$$

$$\sum_{j \in N_2 \cup N_3} \sum_{v \in V} f_{ij}^{v} \geq 1 \quad \forall i \in N_1 \tag{28}$$

$$f_{ij}^{v} = 0 \quad \forall i \in N_2, j \in N \; or \; \forall i \in N, j \in N_2, v \in V_1 \tag{29}$$

$$f_{ij}^{v} = 0 \quad \forall i \in N_1 \cup N_3 \; and \; \forall j \in N_1 \cup N_3, v \in V_2 \tag{30}$$

$$f_{ij}^{v} \in \mathrm{Z}^{+} \cup \{0\} \quad \forall (i,j) \in A, v \in V \tag{31}$$

$$x_{ij}^{v} \geq 0 \quad \forall (i,j) \in A, v \in V \tag{32}$$

$$y_{ij} \in \{0,1\} \quad \forall (i,j) \in A \tag{33}$$

$$z_i \in \{0,1\} \quad \forall i \in N_3 \tag{34}$$

$$\lambda \geq 0 \tag{35}$$

$$\sigma_i \geq 0 \quad \forall i \in S \tag{36}$$

$$W_i \geq 0 \quad \forall i \in S \tag{37}$$

4. Example Analysis

Based on the 'Plan for the Construction and Development of China–Europe Railway Express (2016–2020)' and available research data, 16 key nodes including Nanjing, Xuzhou, Suzhou, Lianyungang, Nantong, Chongqing, Chengdu, Xi'an, Zhengzhou, Wuhan, Changsha, Yiwu, Hefei, Shenyang, Dongguan, and Lanzhou are designated as primary inland cargo sources. Additionally, five major China–Europe railway hub nodes—Zhengzhou, Chongqing, Chengdu, Xi'an, and Urumqi—are chosen as central cargo aggregation centers.

To simplify the calculation example, the railway network diagram for the China–Europe railway is structured with Moscow, Russia, serving as the ultimate destination of the railway transportation, depicted in Figure 1.

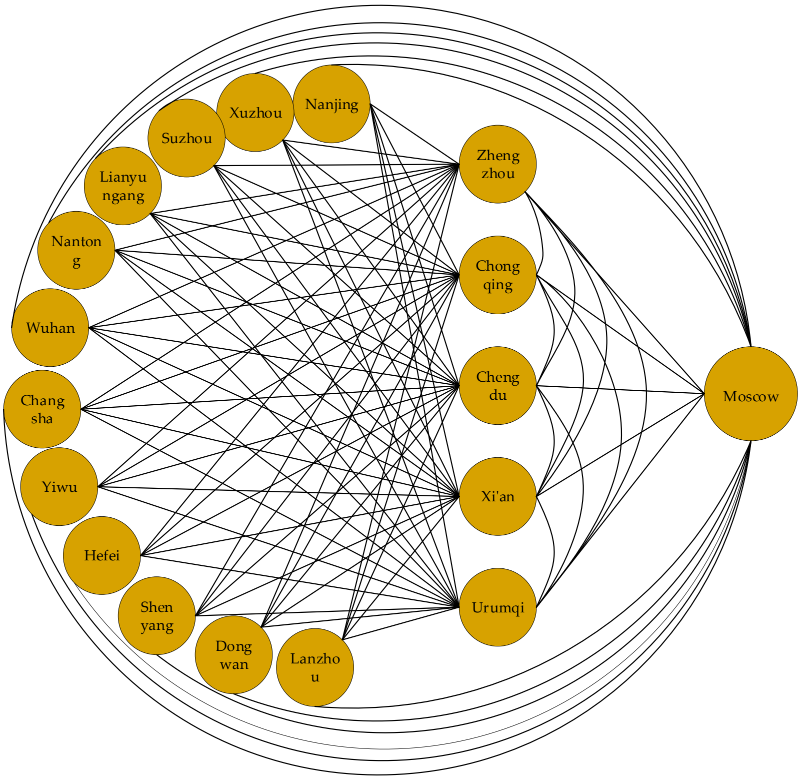


Figure 1. Diagram of the transport network of China–Europe freight trains.

4.1. Example Data

Relevant parameters of freight train transportation, as presented in Table 2, are obtained through the freight information network platform of the China Railway Corporation, along with data from railway departments and surveys conducted on China–Europe freight trains.

Table 2. Train transport parameters.

Argument	**Symbol**	**Type of Train**	
		Domestic Road Transport Train	**Transnational Road Transport Train**
Average travel speed (km·day^{-1})	S_v	500	1000
Packing capacity (TEU)	Q_v	100	75
Fixed cost of opening a column (CNY·column^{-1})	C_v	22,450	53,300
Variable cost of opening a column (CNY·km^{-1})	C_{ijv}	250	200

Based on the relevant research data, the cost data of loading, unloading, and shipping operations in the railway station are shown in Table 3.

Table 3. Cost parameters of in-station loading and unloading operations.

Argument	**Symbol**	**Data**
Cost of staging center transfer waiting operation (CNY·TEU^{-1})	C_i^3	580

By referring to the relevant information regarding the Belt and Road network platform and combining it with the electronic map ranging, the distance parameters of each node are obtained, as shown in Table 4.

Table 4. Transport distance between network nodes.

Node Spacing (km)	Zhengzhou	Chongqing	Chengdu	Xi'an	Urumqi	Moscow
Zhengzhou	0	1086	1157	495	2998	6724
Chongqing	1086	0	333	745	2749	6475
Chengdu	1157	333	0	676	2660	6386
Xi'an	495	745	676	0	2505	6231
Urumqi	2998	2749	2660	2505	0	3726
Nanjing	721	1343	1649	1167	3678	7404
Xuzhou	381	1444	1503	829	3338	7064
Suzhou	940	1565	1873	1382	3892	7618
Lianyungang	548	1618	1692	1030	3537	7263
Nantong	870	1597	1906	1336	3827	7553
Wuhan	504	836	1145	963	3665	7391
Changsha	859	832	1356	1253	3517	7243
Yiwu	1131	1560	2081	1591	4106	7832
Hefei	568	1185	1493	1003	3460	7186
Shenyang	1383	2930	2577	1914	4078	7804
Dongguan	1531	1289	1635	1987	4525	8251
Lanzhou	1032	873	813	577	1867	5593

Refer to the relevant information about the network platform of each train company to obtain the 2021 freight volume data of each node, as shown in Table 5. Among them, Urumqi only serves as a gathering center node and does not generate freight demand.

Table 5. Nodal freight demand.

ID	Nodes	Weekly Freight Volume (TEU)	ID	Nodes	Weekly Freight Volume (TEU)
1	Zhengzhou	414	9	Nantong	50
2	Chongqing	479	10	Wuhan	210
3	Chengdu	506	11	Changsha	172
4	Xi'an	232	12	Yiwu	157
5	Nanjing	252	13	Hefei	126
6	Xuzhou	106	14	Shenyang	108
7	Suzhou	249	15	Dongguan	59
8	Lianyungang	547	16	Lanzhou	117

In the determined environment, the optimal transportation organization scheme obtained by the solution is shown in Table 6, in which the total number of domestic section transport trains is 0, the total number of transnational section transport trains is 58, and the total transportation cost is CNY 86,478,780.

4.2. Parametric Sensitivity Analysis

4.2.1. Sensitivity Analysis of Different Robustness Level Parameters

The Γ parameter is used to control the robustness level of the model in the established China–Europe freight transport organization optimization model so as to obtain optimal results under different risk preferences.

The nodes with uncertain freight demand are composed of 16 cities: Zhengzhou, Chongqing, Chengdu, Xi'an, Nanjing, Xuzhou, Suzhou, Lianyungang, Nantong, Wuhan, Changsha, Yiwu, Hefei, Shenyang, Dongguan, and Lanzhou. The freight demand of each freight node i is disturbed $\varepsilon_i = 0.2$, and the freight demand of the node is shown in Table 5. The robustness level parameters are changed to solve the model, and the corresponding transport organization scheme is shown in Table 6. The specific values of uncertain cost and total transport cost under different robustness levels are shown in Table 7, depicted in Figure 2.

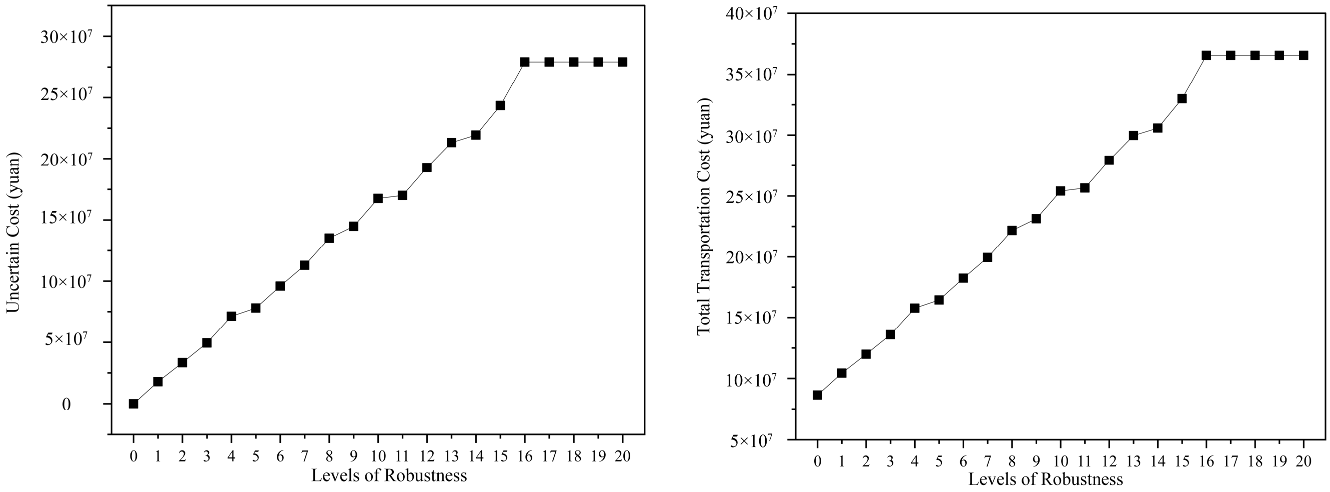
Table 6. Train operation plan.

Bank Opening Mode	**Opening Line**	**Opening Frequency (Column·Week^{-1})**	
		Domestic Road Transport Train	**Transnational Road Transport Train**
Through transport organization model	Zhengzhou–Moscow	0	6
	Chongqing–Moscow	0	7
	Chengdu–Moscow	0	7
	Xi'an–Moscow	0	4
	Nanjing–Moscow	0	4
	Xuzhou–Moscow	0	2
	Suzhou-Moscow	0	3
	Lianyungang–Moscow	0	8
	Nantong–Moscow	0	1
	Wuhan–Moscow	0	3
	Changsha–Moscow	0	3
	Yiwu–Moscow	0	3
	Hefei–Moscow	0	2
	Shenyang–Moscow	0	2
	Dongguan–Moscow	0	1
	Lanzhou–Moscow	0	2

Table 7. Uncertain cost and total transportation cost under different robustness level parameters.

Robust Horizontal Parameters Γ	**Uncertain Cost**	**Total Transportation Cost**
0	0	84,321,350
1	17,883,920	104,362,700
2	33,311,369	119,790,149
3	49,394,063	135,872,843
4	71,235,373	157,714,153
5	78,047,530	164,526,310
6	95,953,005	182,431,785
7	112,931,222	199,410,002
8	135,218,022	221,696,802
9	144,875,717	231,354,497
10	167,538,097	254,016,877
11	170,032,750	256,511,530
12	192,666,579	279,145,359
13	213,161,068	299,639,848
14	219,369,512	305,848,292
15	243,532,012	330,010,792
16	279,175,721	365,654,501
17	279,175,721	365,654,501
18	279,175,721	365,654,501
19	279,175,721	365,654,501

From the above research results, it can be seen that when the robustness level is $\Gamma = 0$, it means that the freight demand of all freight nodes in the model is determined, and the model is equivalent to the China–Europe freight train transportation organization optimization model in a certain environment. At this time, the model does not generate perturbations of uncertain costs, the total cost of transportation.



(**a**) Uncertain costs (**b**) Total transportation costs

Figure 2. Costs at different levels of robustness.

When the robustness level Γ gradually increases from 0, it means that the degree of conservatism of the model continues to increase, and the number of freight nodes with cargo demand disturbance in the China–Europe railway network increases successively. At this time, in order to maintain the original transportation scheme as a feasible scheme, the system will increase the relevant uncertain cost, and the corresponding total transportation cost of the model will also increase. Since there are only 16 freight supply nodes in the transport network, when the robust level parameter Γ exceeds 16, no additional freight nodes will be disturbed, so the uncertain cost will no longer change.

4.2.2. Sensitivity Analysis of Different Freight Demand Disturbance Ranges

In the established optimized model for the controllable robustness level of cargo transportation demands in the China–Europe freight train transportation organization, it is assumed that the cargo transportation demands at each node follow a box-type uncertainty distribution. The disturbance level of freight transportation demands at node *i* is denoted as ε_i. Specifically, $U_i = \left[\overline{Q_i} - \overline{Q_i} \cdot \varepsilon_i, \overline{Q_i} + \overline{Q_i} \cdot \varepsilon_i\right]$. The nodes affected by uncertain freight demands comprise sixteen cities: Zhengzhou, Chongqing, Chengdu, Xi'an, Nanjing, Xuzhou, Suzhou, Lianyungang, Nantong, Wuhan, Changsha, Yiwu, Hefei, Shenyang, Dongguan, and Lanzhou.

The robustness parameter Γ is set to 5. The freight transportation demand at the nodes is detailed in Table 5. By varying the disturbance level of freight demands ε_i, the total transportation costs under different disturbance levels are computed. Additionally, optimal transportation organization schemes under varying disturbance levels are presented in the following tables.

When the disturbance level of freight transportation demand $\varepsilon_i = 0$, the model represents a deterministic environment for transportation organization optimization. In this scenario, the total transportation costs, transportation organization schemes, and the results obtained align with those of a deterministic environment.

When the disturbance level of freight transportation demand lies between 0.1 and 1 ($0.1 \leq \varepsilon_i \leq 1$), the corresponding train operation schedule is presented in Table 8.

Table 8. Train Operation Schedule when $0.1 \leq \varepsilon_i \leq 1.0$.

Operating Mode	**Operating Routes**		$0.1 \leq \varepsilon_i \leq 0.6$		$0.7 \leq \varepsilon_i \leq 1.0$	
			Frequency of Operation (Trains/Week)		**Frequency of Operation (Trains/Week)**	
			Domestic Section Transport Trains	**International Section Transport Trains**	**Domestic Section Transport Trains**	**International Section Transport Trains**
The operating mode of China–Europe freight train assembly	Nanjing–Urumqi	Urumqi–Moscow	1	5	0	0
	Xuzhou–Urumqi		1		0	
	Hefei–Urumqi		1		0	
	Shenyang–Urumqi		1		0	
	Lanzhou–Urumqi		1		0	
Direct transportation organization mode	Zhengzhou–Moscow		0	3	0	6
	Chongqing–Moscow		0	2	0	7
	Chengdu–Moscow		0	3	0	7
	Xi’an–Moscow		0	2	0	4
	Nanjing–Moscow		0	4	0	4
	Xuzhou–Moscow		0	1	0	2
	Suzhou–Moscow		0	4	0	3
	Lianyungang–Moscow		0	1	0	8
	Nantong–Moscow		0	1	0	1
	Wuhan–Moscow		0	3	0	3
	Changsha–Moscow		0	1	0	3
	Yiwu–Moscow		0	3	0	3
	Hefei-Moscow		0	0	0	2
	Shenyang–Moscow		0	0	0	2
	Dongguan–Moscow		0	1	0	1
	Lanzhou–Moscow		0	1	0	2

When the disturbance levels of freight transportation demands within the uncertain set of nodes undergo changes within a certain range, the resulting total transportation costs are depicted in Figure 3.

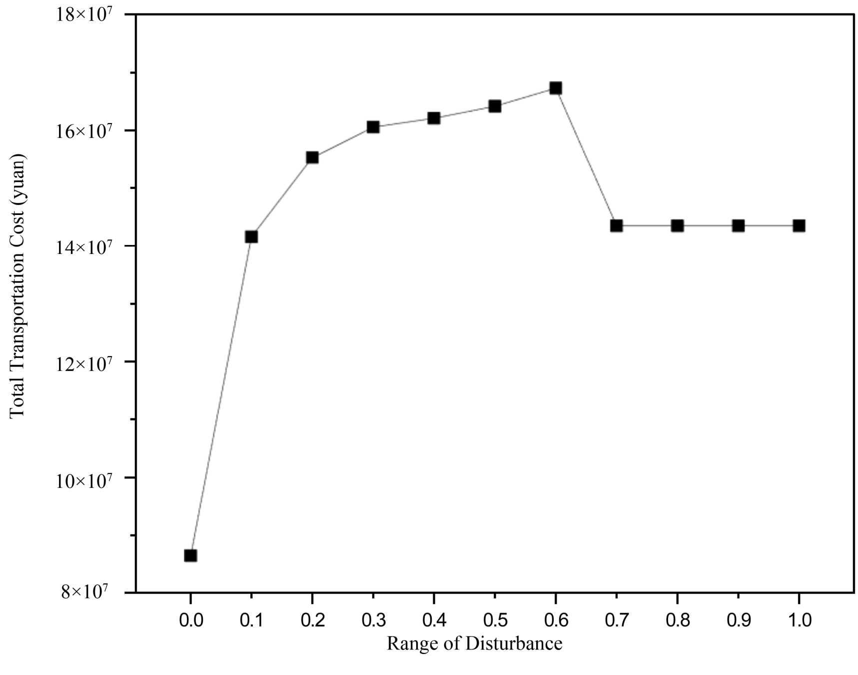


Figure 3. Total Transportation Costs under Different Disturbance Ranges.

With an incremental increase in disturbance levels from $\varepsilon_i = 0.1$ to $\varepsilon_i = 0.6$, the total transportation cost for cargo transportation also escalates, rising from CNY 86,478,780 in a deterministic environment to CNY 167,253,300. This increase occurs due to a consistent robustness level ($\Gamma = 5$). As the disturbance levels (ε_i) at various cargo transportation nodes rise, the China–Europe freight train network can only counteract this expanding disturbance by augmenting the uncertainty transportation costs within the transportation organization, aiming to maintain the optimal solution across the entire transportation network.

When the disturbance level in cargo transportation further increases to a point where $\varepsilon_i \geq 0.7$, the uncertainty transportation costs will escalate. To minimize the total transportation cost, adjustments will be made to the optimization plan of the freight train transportation organization. This adjustment leads to a change in the model's optimal solution. At this stage, some freight trains will be consolidated and rerouted through Urumqi, resulting in a significant reduction in overall transportation costs.

Based on the analysis of the uncertain cargo demand disturbance, it is evident that there is a strong correlation between the total transportation cost of goods and the disturbance level (ε_i) in cargo demand. To counter the increase in disturbance level (ε_i), the model will maintain the optimal solution by augmenting the uncertainty cost. As the disturbance level (ε_i) further increases, the model will re-search new optimization strategies for freight train organization to attain the optimum solution. At this point, the transportation network will reach a renewed stable state.

4.3. Summary of This Section

In this section, the Bertsimas robust optimization theory is used to transform the China–Europe freight transport organization optimization model, in which the freight transport demand is subject to the box-type uncertainty set distribution, into a mixed integer linear programming model with the minimum train operating cost and container operating cost as the objective function and with robust horizontal control parameters. And the above section of the establishment of the China–Europe freight train transport organization network case is analyzed and solved.

Through the model solution and parameter sensitivity analysis, it can be seen that when the robustness level Γ gradually increases from 0, that is, the number of nodes in the transport network where transport demand fluctuations occur also increases, the conservatism of the model will increase, and the model will maintain the stability of the original transport scheme by increasing the uncertain demand cost. When the robustness level is $\Gamma = 16$, all freight demand nodes in the transport network will produce uncertain fluctuations, and the uncertainty cost in the network reaches the highest point. When the robustness level is $\Gamma > 16$, since there are only 16 freight demand nodes at most in the example, the uncertainty cost will no longer be increased.

In the case of a robustness level $\Gamma = 5$, the freight disturbance range ε_i of each node is analyzed. When the disturbance range $0.0 \leq \varepsilon_i \leq 0.6$, the model will increase the uncertainty cost to maintain the stability of the original transport scheme. When the disturbance range is $0.7 \leq \varepsilon_i \leq 1.0$, the increase in the uncertainty cost will destroy the optimality of the original transportation scheme. At this time, the model will re-search for another optimal transportation organization scheme under the condition of the current freight disturbance range.

5. Conclusions

This paper has presented a comprehensive study of the robust optimization of the China–Europe freight train transport organization, particularly under the varying conditions of uncertain cargo transportation demand. The research commenced with the development of a robust optimization model suitable for specific environmental conditions and was further extended to incorporate models addressing the broader spectrum of uncertain freight demand. This included a flexible approach to adapt to varying demand levels, culminating in an extended fuzzy evaluation of the optimization structure.

The key findings of this study indicate that with increased robustness requirements in the optimization model, there is a corresponding rise in transportation costs, impacting the overall efficiency of the China–Europe freight train network. The sensitivity analysis underscores the model's approach to managing cost fluctuations in response to variable cargo demand, aiming to preserve the stability and reliability of the transportation scheme.

The research has successfully developed a robust and effective transportation organization plan for China–Europe freight trains, demonstrating resilience against uncertain cargo demand scenarios. This achievement enhances the economic feasibility, operational efficiency, and stability of the freight transportation system. The insights gained from considering a range of demand uncertainties contribute to a more adaptable and efficient transport organization strategy. These contributions mark significant advancements in the methodologies and practical applications related to China–Europe freight train logistics.

This study unveils the complexities arising from fluctuating cargo demand in China–Europe freight train logistics, underscoring the need for ongoing research. However, it also recognizes a limitation: the lack of a thorough analysis on how infrastructure capacity constraints might influence the proposed transport strategy. Our model, addressing demand uncertainties, requires further in-depth exploration into the effects of limited route capacities on operational strategies, a vital aspect for enhancing the real-world applicability and efficiency of transportation models. Future research should delve into optimizing freight aggregation points, routes, modal combinations, return train organization, and empty container management, thereby improving the robustness and efficiency of freight systems.

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