WORKING PAPER SERIES

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May 17, 2023

No. 254

The Research Institute for Innovation Management, HOSEI UNIVERSITY

Simultaneous Optimization of Production and Transportation Networks Considering Railway Fare Fluctuations: Insights from International Rail Corridors

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Abstract:
This study examines the role of transportation in global supply chain management, focusing on the China Railway Express as an attractive alternative to sea, road, and air freight due to its cost and lead-time advantages. The research proposes a supply chain plan that simultaneously considers production areas and transportation routes and accounts for freight rate risk, aiming to optimize operations. The proposed model addresses uncertainties in fare structures across different routes and multiple carrier partnerships in international rail corridors. By adopting a strategic approach to route selection, businesses can balance production and transportation costs while managing market fluctuations and volatility.

Key words:
China Railway Express, Supply chain optimization, Simultaneous decision model

1. Introduction

Supply chains serve as a link between the upstream and downstream product flows. This is particularly true in the case of global supply chains, where raw materials, parts, and finished products are sourced from various parts of the world, produced in multinational factories, and sold on a global scale. Given the uncertain business environment, it is essential to diversify risks by collaborating with multiple supply chains. As product flows become increasingly complex and interconnected, the supply chain has transformed into a supply network. In the context of global supply networks, transportation plays a critical role in ensuring smooth and efficient supply chain operations. As a result of the greater distance between the origin and destination of supply activities in the case of global supply chains, the transportation process has become more complex than ever before. Therefore, it is crucial to focus on optimizing the transportation process of global supply networks to ensure the smooth flow of materials, parts, and finished products.

Over the past few years, ocean freight rates have experienced a significant surge owing to disruptions in European and intra-Asian routes, port congestion, and other factors, such as ship accidents in the Suez Canal, temporary port closures in response to the COVID-19 pandemic, and the suspension of transportation services owing to the Russia–Ukraine War. This has led to a significant increase in transportation costs, forcing Japanese companies to re-evaluate their international transportation routes (Figure 1).

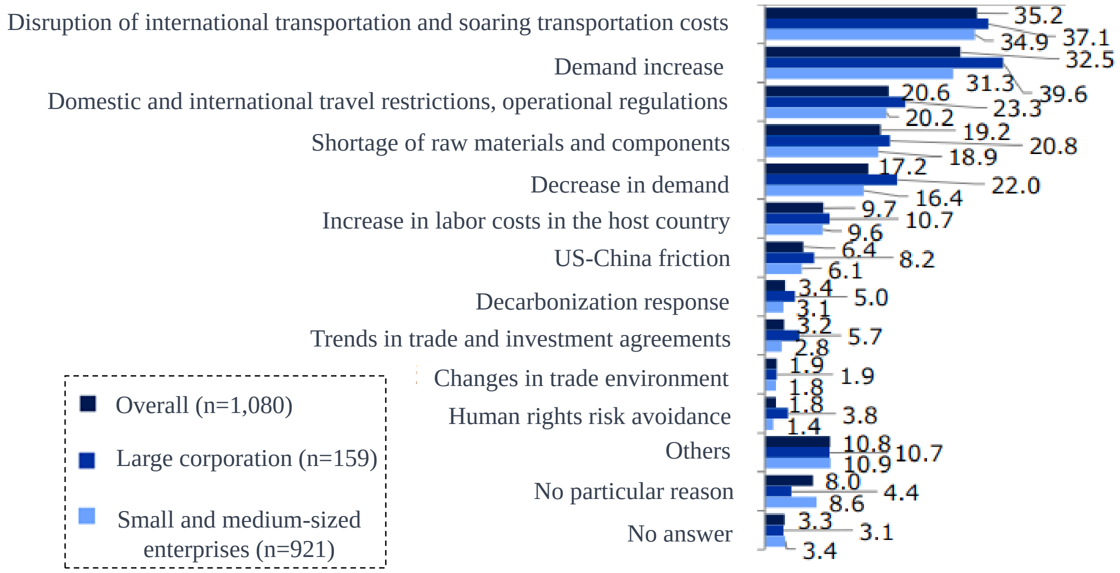


Figure 1. Reasons for redesigning supply networks (JETRO, 2022)

The China Railway Express (CRE) is gaining popularity as a freight railway transportation service because of its advantages in transportation lead time and costs. The lead time is often shorter than maritime transportation, as the CRE takes 20 to 30 days to transport goods from Japan to Europe, compared with the usual 40 to 50 days by sea. Moreover, CRE is often cheaper than air freight, which tends to be significantly more expensive than railway freight. The volume of goods transported by the CRE has increased significantly, with the official Chinese data indicating that the number of trains has risen from 17 in 2011 to over 12,400 in 2020, and that the amount of goods transported has grown from 40,000 tonnes to over 1.14 million tonnes over the same period. New routes have been added and existing ones optimized to better serve customers. For example, in 2018, the world's longest railway route was launched, extending over 13,000 km to link the Chinese city of Yiwu with the Spanish capital of Madrid. Furthermore, extending the CRE to South Asia has been discussed, with one proposed route connecting Kunming in China to Kolkata in India via Bangkok in Thailand, Malaysia, and Singapore. Railway transportation has the potential to become a primary mode of transportation, particularly for long-distance transport of goods. Although sea and air transportation have traditionally dominated international trade, the development of CRE and similar services have shown that railway transportation can be a feasible and cost-effective alternative. In addition, railway transportation is more environmentally friendly than sea and air transportation, as it generates fewer greenhouse gas emissions.

Choosing the right route for rail transportation can be challenging given the growing complexity of rail networks. To make an informed decision, many factors must be considered, including cost, distance, transit time, capacity, availability, safety, and security. Assumption factors other than cost and distance are similar for different routes, cost and distance then become the critical considerations. Surprisingly, a longer route can sometimes be more cost effective; carriers may offer lower rates on longer routes that have excess capacity to fill their trains and improve operations. To make the best decision, shippers should compare the costs of different routes and consider additional fees, such as customs clearance and fuel surcharges. Furthermore, carriers may offer volume discounts and other incentives for larger shipments or long-term contracts, making it beneficial to consider these options.

Rail transportation fares can vary considerably depending on the route, owing to the involvement of multiple partners in international carriers. When a shipment involves multiple carriers, each with their own pricing policies and fee structures, comparing fares across different routes can be challenging. Moreover, carriers may differ in their expertise or capabilities in different regions or modes of transportation, which can further impact the overall cost of the shipment. Such uncertainties regarding fares can make it difficult for shippers to select the most appropriate route for their shipment. To overcome this challenge, shippers may need to adopt a more strategic approach to route selection. The aim of this study is to propose a supply chain plan that can determine the production area and transportation route simultaneously while also considering the freight rate risk.

The proposed supply chain plan offers a valuable approach to support shippers in making informed decisions when selecting routes for their shipments. This approach involves considering both the production area and transportation route, enabling businesses to make strategic decisions that balance the cost of production and transportation, and also accounting for the risks associated with fluctuating freight rates of international rail corridors. By implementing this plan, businesses can optimize their supply chain operations, reduce lead times, improve delivery performance, and manage their exposure to market fluctuations and volatility in the transportation market of international rail corridors. This simultaneous consideration of production and transportation factors enables businesses to achieve sustainable growth and long-term success by optimizing their operations. Overall, the proposed supply chain plan represents a significant step toward developing a more efficient and effective global supply chain. By addressing the challenge of fare uncertainty, businesses can make informed decisions, reduce costs, and increase efficiency, while also managing risk and achieving their strategic objectives in a rapidly changing market.

2. Relevant Literature

Supply chain planning involves mathematical optimization methods to address the complexity of multi-layer, multi-site, and multi-product networks. The goal is to optimize the flow of goods and services while minimizing costs and maximizing efficiency. Mathematical optimization methods, such as linear programming, integer programming, and mixed-integer programming, are commonly used to develop models and find optimal solutions. Studying model construction and solution methods is crucial. Piplani et al. (2020) provide an overview of optimization techniques used in supply chain management. Mentzer et al. (2001) propose a framework for supply chain management, and Chopra and Meindl (2016) discuss the design and management of supply chain networks. Lee (2004) proposes the “Triple-A” framework for effective supply chain management, while Ivanov and Dolgui (2013) discuss the challenges and opportunities of managing supply networks. Christopher and Peck (2004) emphasize the critical role of logistics in effective supply chain management. These studies highlight the need for a holistic approach that considers multiple factors.

Research on the complexity of algorithms and techniques in supply network planning has been conducted. Sarker et al. (2019) propose a self-adaptive differential evolution algorithm for solving multi-objective supply chain optimization problems. Ghiani et al. (2014) discuss the use of genetic algorithms in supply chain management, and Zhang et al. (2018) propose a hybrid algorithm based on ant colony optimization and simulated annealing for solving a multi-objective supplier selection problem. Pishvaee et al. (2018) discuss the use of robust optimization techniques in supply chain management. These studies demonstrate the complexity of algorithms and techniques used in supply chain planning and the importance of developing new and innovative methods to address the challenges of uncertainty and complexity in the supply network.

Several studies examine the role of transportation infrastructure in shaping firms' location choices and the structure of global value chains. Krugman (1991) establishes the "new economic geography" and presents a core–periphery model, which suggests that firms may choose to locate in peripheral regions if they have access to transportation infrastructure that connects them to the core. Javorcik et al. (2018) provide evidence from Asia, showing that transportation infrastructure improvements have led to the relocation of manufacturing activities to lower cost countries and the formation of new global value chains. Similarly, Pham and Le (2019) investigate the impact of transport infrastructure on the location decisions of foreign manufacturing firms in Vietnam and find that better transport infrastructure in a country is associated with higher levels of foreign direct investment in that country. Hoskins et al. (2020) examine the influence of transport infrastructure on the location decisions of manufacturing firms in South Africa and find that firms are more likely to locate in areas with better transport infrastructure, such as those close to ports or major highways. Singh et al. (2021) conduct a similar analysis for India and reach the same conclusion, that manufacturing firms are more likely to locate in regions with better access to transportation infrastructure, such as those close to major highways or railroads. Finally, Mukherjee et al. (2020) focus on the impact of transportation infrastructure on industrial location choices in India, discussing recent policy initiatives that aim to improve transportation infrastructure and reviewing empirical studies of the relationship between transportation infrastructure and industrial location choices in the country. These studies suggest that transportation factors are a crucial consideration for manufacturing firms when deciding where to locate their operations, and that improvements in transportation infrastructure can attract more investment and promote economic growth in certain regions.

Eurasian rail transportation is a complex system. To optimize the system, it is necessary to analyze and understand factors such as cargo types, container technology, transportation routes, and hub cities from different perspectives. One strand of literature focuses on cargo types and container technology as a means of analyzing Eurasian rail transportation. Different types of cargo require different handling and transportation methods, and the choice of container technology can have a significant impact on the efficiency and safety of the transportation process. Olaniran and Adesope (2019) review the different types of cargo and container technology used in intermodal transportation, and highlight the challenges and opportunities for emerging economies. Buzueva et al. (2020) compare the transportation modes of containers by rail and sea, and evaluate their advantages and disadvantages in the context of the Kazakhstan–China corridor. Another strand of literature considers transportation networks and hub cities as approach to optimizing Eurasian rail transportation. Transportation networks refer to the system of rail routes and connections between different cities and countries, while hub cities are strategic locations where cargo is consolidated and distributed. By analyzing these factors, it is possible to determine the optimal transportation routes and hub cities that can minimize transportation time and costs. Karaklioumi and Vinokurov (2020) examine the development of the Eurasian rail network and its impact on transport and trade between Europe and Asia. Wan and Yang (2021) analyze the transportation routes and hub cities of China's Belt and Road Initiative, and propose an optimization model to improve intermodal transportation in Eurasia. Overall, this review of the literature provides insights into the various factors that affect Eurasian rail transportation, and demonstrates the importance of analyzing the system from multiple perspectives.

In this study, we propose a model that can simultaneously determine the decision-making of production and transportation networks, while simultaneously considering the risk of fluctuations in the fare market. In addition, because the fare market varies depending on the transportation route and the logistics company that provides the service, we devise a classification of transportation routes and examine the fluctuation of the fare market in multiple scenarios. This is necessary because transportation costs can have a significant impact on production and supply chain operations. By considering the risk of fare market fluctuations and analyzing the transportation routes of the international rail corridor, manufacturing companies can make more informed decisions about production and transportation.

3. Proposed model

This study involves a multi-stage, multi-facility, and multi-product network. The locations in this network are divided into production nodes, transportation nodes, and sales nodes, and the transportation routes consist of multiple transportation routes. We use binary variables to represent in which factory each product is produced in each market and which transportation route is used to transport each product. Our objective is to minimize production and transportation costs. The cost of rail container transportation is determined based on the transportation distance, extra fare, and discount fare. There are two formulas used to calculate the total transportation cost in this study. Whether the transported volume meet discount fare or not. The formular will work when the discount fare is applied(3), or nor(4).

To determine which production area should use which route under different rates. We formulate the mathematical formulations and verify the result from numerical experiments of multiple scenarios. we specify the following steps:

1. Define the objective function: The objective function should be defined to minimize the total cost of the production and transportation network. This can be expressed as the sum of the production cost and the transportation cost.
2. Set the decision variables: The decision variables should be defined to represent the production and transportation quantities. They should also be defined to represent the discount factor for each transportation route.
3. Formulate the constraints: The constraints should be formulated to ensure that the production and transportation quantities are balanced and that the transportation capacity is not exceeded. The constraints should also be formulated to ensure that the discount factors are within a certain range.
4. Implement the model: The simultaneous optimization model can be implemented using a linear programming solver. The solver will use the objective function and constraints to find the optimal production and transportation quantities and discount factors.
5. Verify the results: After running the optimization model, the results can be verified by checking that the total cost has been minimized. In addition, the results can be checked to ensure that the transportation capacity has not been exceeded and that the discount factors are within the specified range.
6. Sensitivity analysis: To verify which route and how much to discount the transportation capacity, sensitivity analysis should be performed. The sensitivity analysis involves changing the discount factor for each transportation route and observing the effect on the total cost. The discount factor for each transportation route can be adjusted until the optimal discount factor is found that minimizes the total cost.

The supply chain planning model handled in this study is formulated as follows.

Sets

$i, h, j \in \{I \cup H \cup J\}$: Nodes ($I$: factory nodes, H: transportation nodes, J: markets nodes)

$k \in K$: Products

$r \in R = \{(i, a), (a, b), \ldots, (t, j)\} \in A$: Routes

$p \in P = (i, a, b, \ldots, t, j) \in A$: corridors

$A = \{(i,h,j) | i \in I, h \in H, j \in J\}$: Arcs

Parameters

C_i^{ass}: Depreciation cost of production equipment at factory i

C_{ik}^{prod}: Production unit cost of product k at factory i

C_r^{tran}: Standard transportation unit price for route r

C_h^{lport}: Handling unit price of cargo at land port h

$PCap_i$: Production capacity at factory i

$RCap_r$: Booking limit on route r

$Path_{ijp}$: $(i, a, b \dots t, j)$ Combination of route r from factory i to market j through transportation

s_r: Administrative instability coefficient on route $r, s_r \leq 1$

r_r: Discount rate on route r

ε_r: Loading ratio of required transportation volume for the discount rate s_r

d_{jk}: Demand quantity of product k in market j

Objective function

$$Min\left(\sum_{i \in I} C_i^{ass} + \sum_{j \in J}\sum_{k \in K}\sum_{i \in I} C_{ik}^{prod} d_{jk} y_{jki} + \sum_{p}\sum_{r} RC_{pr}\right) \tag{1}$$

$$if \qquad RQ_r = \sum_{j}\sum_{k}\sum_{i}\sum_{p} d_{jk} y_{jki}\, Path_{jip} x_{jkp} \geq RCap_r \varepsilon_r \tag{2}$$

$$then \qquad RC_r = C_r^{tran}\left(1 - \frac{r_r}{s_r}\right) RQ_r \tag{3}$$

$$else \qquad RC_r = C_r^{tran} RQ_r \qquad (4)$$

Decision variables

y_{jki}: Binary variable 0/1 for producing product k in market j at factory i

x_{jkp}: Binary variable 0/1 for transporting product k in market j via route p

RQ_{pr}: Total transportation volume for route r when using route p

RC_{pr}:Total transportation cost for route r when using route p

Constraints

Restrictions on the number of production areas:

$$\sum_{i \in I} y_{jki} = 1, \ \forall j \in J, \forall k \in K \qquad (5)$$

Restrictions on the number of transportation routes:

$$\sum_{p \in P} x_{jkp} = 1, \ \forall j \in J, \forall k \in K \qquad (6)$$

Production capacity constraint:

$$\sum_j \sum_k d_{jk} y_{jki} \leq PCap_i, \quad \forall i \in I \qquad (7)$$

Transportation capacity constraint:

$$\sum_j \sum_k \sum_i \sum_p d_{jk} y_{jki} \, Path_{jip} x_{jkp} \leq RCap_r, \quad \forall r \in R \qquad (8)$$

4. Numerical experiments

In this study, we conduct numerical experiments using data from a manufacturing company, which makes mechanical parts and has factories and markets globally. There are 7 factories and 13 markets around Eurasia continent (see Tables 1 and 2), and a railway express group that provides rail freight transportation services across the Eurasian continent. There are East, Central, West, South corridors start from China mainland to Europe, which constituted by different major cities in each corridor. (see Tables 3). Some main routes are also list in Table 4. As the name of "Zheng-Ou" meas the route start from "Zhengzhou(Zheng)" city to "Europe(Ou)", and Hamburg is the destination city in Europe. The route go though the Frontier station called Alashankou or Horgos or Erenhot, the about transportation time is 15 to 18days, and some major cities are list in the table.

Table 1. Location of factories of case study firm

node	**Location of factory**
1	Tianjin(China)
2	Lianyungang(China)
3	Kunshan(China)
4	Cambodia
5	Malaysia
6	Japan
7	Czech

Table 2. Location of sales markets of case study firm

node	**Location of market**	**node**	**Location of market**
1	Norway	8	France
2	Sweden	9	Spain
3	Finland	10	Turkey
4	Poland	11	Singapore
5	Netherlands	12	Shanghai(China)
6	Belgium	13	Japan
7	Germany		

Table 3. Four corridors of the railway express network

Corridor	Location of China area	Major Cities
East Corridor	Along China’s eastern coast	Beijing, Tianjin, Qingdao, Lianyungang
Central Corridor	In the middle of China	Lanzhou, Zhengzhou, Almaty, Tashkent
West Corridor	In western China	Chengdu, Chongqing, Urumqi, Horgos
South Corridor (Planning)	In southern China	Kunming, Hanoi, Bangkok, Yangon

Table 4. Example of main routes within corridors (Li, 2018)

Route	Origin	Destination	Frontier Station	Transportation Time (Days)	Major Cities
Zheng-Ou	Zhengzhou	Hamburg	Alashankou/ Horgos/ Erenhot	15-18	Zhengzhou, Erenhot, Warsaw, Hamburg
Yu-Xin-Ou	Chongqing	Duisburg	Alashankou/ Horgos/ Erenhot	15-18	Chongqing, Alashankou, Nur-Sultan, Moscow, Duisburg
Rong-Ou	Chengdu	Duisburg	Alashankou/ Horgos	12-18	Chengdu, Alashankou, Warsaw, Hamburg
Han-Ou	Wuhan	Duisburg	Horgos / Alashankou	12-18	Wuhan, Alashankou, Nur-Sultan, Moscow, Duisburg
Yi-Xin-Ou	Yiwu	Duisburg	Horgos / Alashankou	15-18	Yiwu, Alashankou, Nur-Sultan, Moscow, Duisburg
Su-Man-Ou	Suzhou	Warsaw	Manzhouli	14-20	Suzhou, Zhengzhou,

					Manzhouli, Moscow, Warsaw
Ying-Man-Ou	Yingkou	Warsaw	Manzhouli	14-20	Yingkou, Manzhouli, Moscow, Warsaw
He-Xin-Ou	Hefei	Hamburg	Alashankou	15	Hefei, Alashankou, Nur-Sultan, Berlin, Hamburg
Xiang-Ou	Changsha	Hamburg	Alashankou/Erenhot	15	Changsha, Alashankou, Minsk, Hamburg
Ha-Ou	Harbin	Warsaw	Manzhouli	10-15	Harbin, Manzhouli, Moscow, Warsaw
Sha-Xin-Ou	Xiamen	Hamburg	Alashankou	16	Xiamen, Alashankou, Minsk, Hamburg

The production–rail transportation network is contracted and visualized in Figure 2, Table 5. The main routes within the corridors of the CRE based on actual CRE data from Table 4.

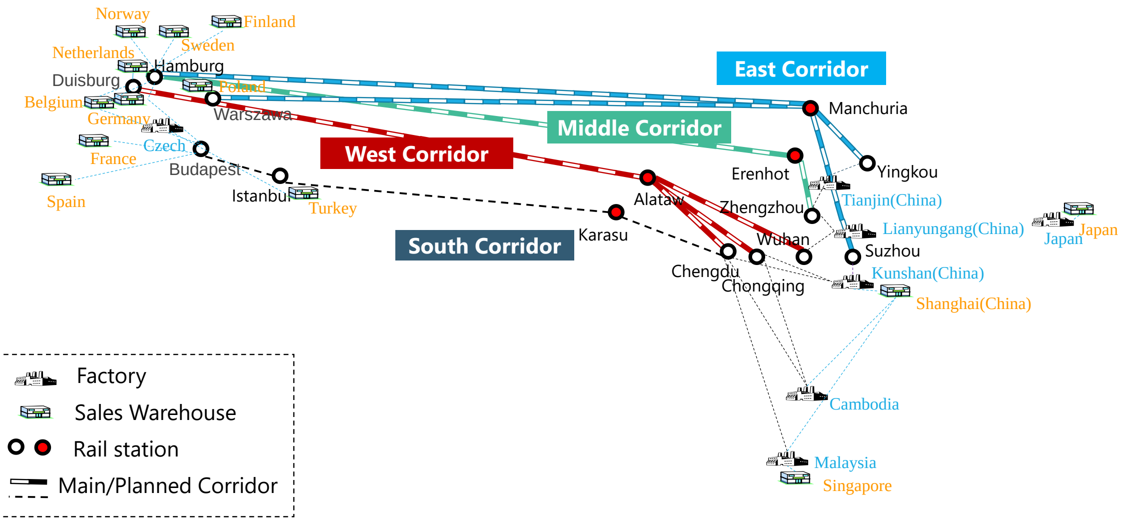


Figure 2. Possible cargo flows in the Eurasian area.

Table 5. Railway routes used in numerical experiments

route	**From**	**To**	**route**	**From**	**To**
1	Norway	hamburg	22	hamburg	erenhot
2	Sweden	hamburg	⋮	⋮	⋮
3	Finland	hamburg	39	chongqing	Kunshan
4	Poland	warszawa	40	chengdu	Cambodia
⋮	⋮	⋮	41	chengdu	kunshan
21	hamburg	manchuria	42	chengdu	Malaysia
22	manchuria	Yingkou			

To check the effectiveness of the proposed model in explaining the importance of transportation conditions on manufacturing decisions, we define four scenarios with varying manufacturing and transportation conditions and examine how they impact on each other (Table 6). We use the CPLEX optimization software package to conduct this numerical experiment.

Table 6. Scenarios of numerical experiment

Comparison	**Type**	**fare market fluctuations**	**Route capacity requirement**	**Fare discount**
Transportation optimization	Scenario 1	No	—	—
	Scenario 2	Yes (Duisburg-Alataw)	≧90%	20%
	Scenario 3	Yes (Duisburg-Alataw)	≧60%	20%
Production and Transportation optimization	Scenario 4	Yes (Duisburg-Alataw)	≧60%	20%

The four scenarios involve different optimization approaches for transportation and production, and different costs are associated with each scenario, as shown in Table 7. Transportation optimization occurs in Scenarios 1, 2, and 3, but transportation costs vary, whereas the production cost is held constant for all three scenarios, at 234,500. Scenarios 1 and 2 have the same transportation cost of 23,410, whereas Scenario 3 has a lower transportation cost of 21,310. Therefore, Scenario 3 has the lowest total cost at 255,810, whereas Scenarios 1 and 2 have the same total cost of 257,910. Scenario 4 uses both production and transportation optimization, with a production cost of 231,500 and a transportation cost of 21,910. This scenario has the lowest total cost at 253,410. Therefore, on the basis of the information provided, Scenario 4 has the lowest total cost in terms of production and transportation optimization.

Table 7. Results of the numerical experiment (One million yen)

Comparison	**Type**	**Production cost**	**Transportation cost**	**Total costs**
Transportation optimization	Scenario 1	234,500	23,410	257,910
	Scenario 2	234,500	23,410	257,910
	Scenario 3	234,500	21,310	255,810
Production and Transportation optimization	Scenario 4	231,500	21,910	253,410

In Scenario 4, a discount fare was implemented in the transportation network and its impact on the total cost of the proposed simultaneous determination model was investigated. The results indicate that transportation cost increased, but the total cost decreased from 255,810 to 253,410 owing to a decrease in production cost. This suggests that the simultaneous determination model had a positive impact on the overall cost, despite increasing the transportation cost in Scenario 4. By decreasing the production cost, the model was able to achieve a lower total cost, even with the increased transportation cost.

5. Discussion

Scenario 1 demonstrates the significance of transportation optimization for manufacturers with established factory locations, as long-distance transportation costs make up a substantial portion of their total operational expenses. This is particularly true for global manufacturers, where the distance between the origin and destination of products is considerable. Although the transportation network in this case is facilitated by railway stations, the calculation method for optimizing transportation is similar to those for other modes, such as road, sea, and air.

Scenario 2 reveals that fare market fluctuations are unique characteristics of the Eurasia railway express transportation compared with other modes of transportation. Identifying which route has fare market fluctuations is crucial for manufacturers when selecting a route. However, the level of the fare discount and the conditions under which a shipper (the manufacturer in our case study) can access preferential pricing are significant factors for shippers to consider. In Scenario 2, we observed that the fare discount between the Alataw and Duisburg section is favorable. However, the route capacity requirement is quite strict, and the product flow has not been redistributed to the new route, resulting in a similar outcome to Scenario 1, as shown in Figure 3.

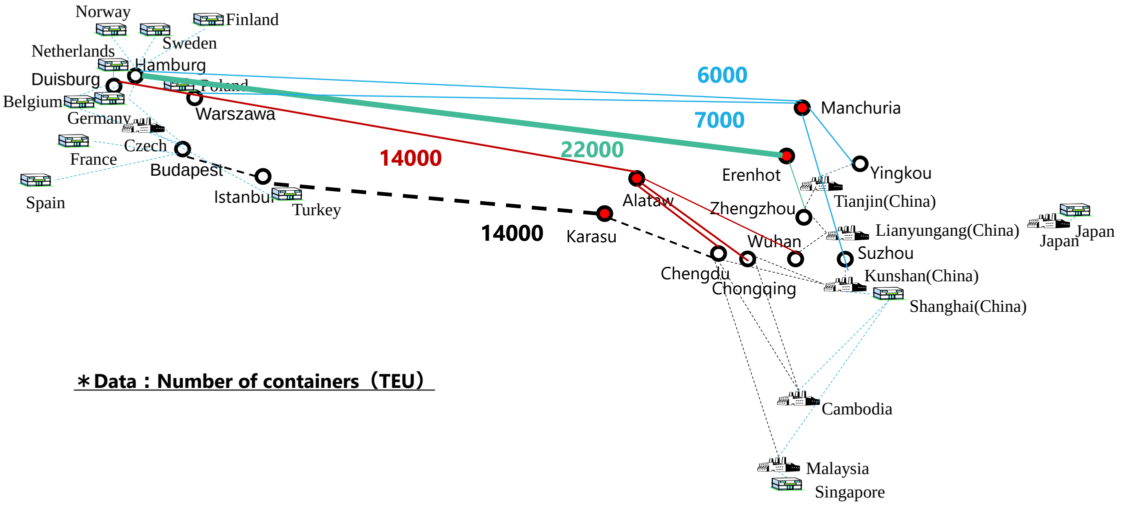
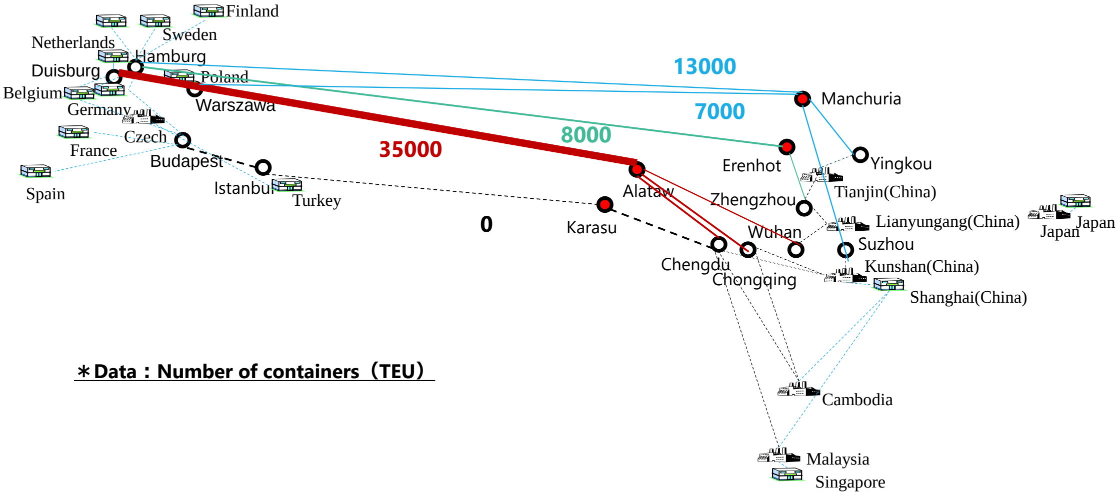


Figure 3. The flow of products between railway transportation stations

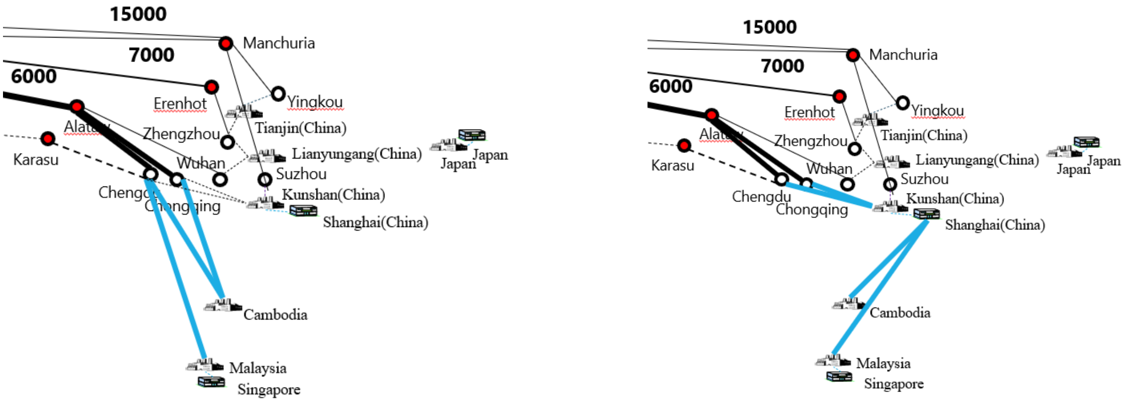
Scenario 3 demonstrates a positive result in terms of total cost reduction, primarily owing to adjustments made to the conditions for utilizing fare discounts. Consequently, more product flow shifts to the main Duisburg–Alataw route. In Figure 3, the product flow for the Duisburg–Alataw section is 14,000 containers, which are measured in twenty-foot equivalent units (TEUs); this increases to 35,000 TEUs, as shown in Figure 4. The increased product flow on this section is primarily caused by reductions in the product flows on the Turkey–Karasu and Hamburg–Erenhot sections. On the basis of these findings, we recommend that manufacturers seeking lower transportation costs should use cost simulators to compare complex transportation networks. In addition, local governments aiming to attract more cargo for transport should consider manufacturers' needs and offer mutually beneficial fare discounts.



＊Data：Number of containers（TEU）

Figure 4. The change in the flow of products between railway transportation stations

In Scenario 4, we observe minor changes in the flows of products among railway transportation stations, such as Hamburg–Erenhot, with the most significant changes occurring between the factory location and nearby transportation stations, as shown in Figure 5 (e.g., Kunshan–Chongqing). This suggests that the decrease in total cost is related to both production and shipping activities. Interestingly, the transportation cost does not decrease but slightly increases, indicating that local production for local markets is not always the best approach. Striking a balance between different production locations and prioritizing global optimization over local optimization leads to greater cost savings.



(a) Before production area changes (b) After production area changes

Figure 5. The change in the product flow between factories and transportation stations

6. Conclusion

In this study, we proposed a simultaneous optimization model for production and transportation networks that accounted for railway fare fluctuations. The effectiveness of this model was verified through numerical experiments, demonstrating that improved transportation conditions attracted cargo flows and that economies of scale in transportation influenced production location decisions. We drew four conclusions from this study, as follows.

1. Production decisions should be made concurrently with transportation activities, as long-distance global transportation processes significantly influence production decision-making.
2. International rail corridors exhibit unique characteristics, featuring a complex transportation network with multiple participants engaged in transportation activities as trains traverse multiple countries. Therefore, fare market fluctuations should be incorporated into the design of production–transportation networks.
3. Local production for local markets could be an efficient risk mitigation strategy in many cases. However, considering the future, we found that global optimization was generally more advantageous than local optimization.
4. International rail corridor transportation activities are not solely a cost calculation for manufacturers; they also serve as crucial factors in strategic decision-making regarding factory locations and production volumes.

Acknowledgment

This work was supported by JSPS KAKENHI (Grant Number 20K14987 and 23K01655) and the Research Institute for Innovation Management at Hosei University.
We thank Amanda Fitzgibbons, PhD, from Edanz (https://jp.edanz.com/ac) for editing a draft of this manuscript.

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