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Joint Optimization of Distribution Center Location and Inventory for Railway Vehicle Components Using Location-Inventory Models

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Abstract: This paper addresses the joint optimization problem of distribution center location, key component procurement batch size, and safety stock design in the distribution network for high-speed trains and rolling stock maintenance. A location-inventory optimization model is developed and applied to a case study of a Networked Railway Vehicle Manufacturing Enterprise. Simulation results reveal that fixed construction costs significantly influence the distribution network design, emphasizing the need for proactive selection of distribution center locations. Transportation costs are found to be highly positively correlated with the total cost of the distribution network, indicating that reducing unit transportation costs is crucial for optimizing total costs. The findings provide valuable insights for efficient distribution network design in the railway vehicle manufacturing industry.

Keywords: collaborative supply; component inventory; location-inventory model; railway rolling stock manufacturers

1 INTRODUCTION

In the era of global manufacturing intelligence and digitization, network-oriented railway vehicle manufacturers urgently seek to boost production efficiency and streamline logistical operations. For large-scale enterprises with networked deployments, a common organizational structure is a multi-tiered supply chain. Managing diverse product components from numerous suppliers and processing facilities, these companies cover expansive markets and meet the maintenance needs of regional customers. The network-oriented railway vehicle manufacturing parts supply chain exhibits distinctive features: demand for the same component involves production demand from the main manufacturing plant and maintenance demand from regional customers. Main plant production demand is typically scheduled based on annual plans, resulting in stable demand within a single cycle. Conversely, regional customer demand is urgent and subject to significant fluctuations. Machine failures prompt immediate demand orders for spare parts from nearby central warehouses.

However, most current network railway rolling stock manufacturing enterprises (NRRSM) still adhere to traditional supply chain models, where production and maintenance supply chains operate independently. Refer to Fig. 1 for the traditional supply chain model.

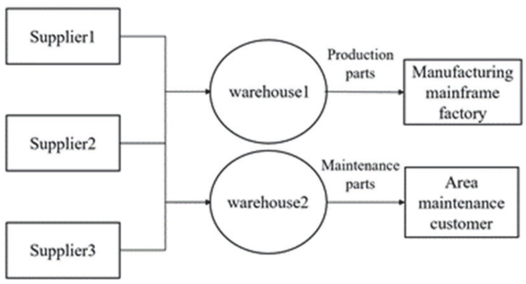

Figure 1 Traditional supply chain

Digitization and collaboration in manufacturing is critical [1]. However, due to differences in management organization causing information barriers, the two supply chains operate independently, leading to duplicated inventory, unnecessary warehouses, and stockout risks. In NRRSM, vehicle production and maintenance are core activities. The same component is universal for meeting both manufacturing and maintenance needs, and can be centrally managed by the corporate group. Building a shared information platform and integrating various effective resources has become an important means for enterprises to enhance their competitiveness [2]. Based on this, a proposal is put forth for a shared distribution mode. The shared distribution model achieves the unified storage and distribution scheduling of common components by establishing an information platform. Materials in the shared warehouse can be used to meet both manufacturing and maintenance needs, addressing the contradiction between long-term stable demand and short-term fluctuating demand in the supply chain for railway vehicle manufacturing components.

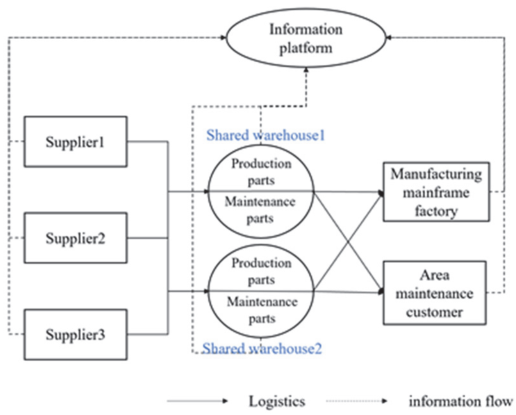

Figure 2 Shared supply chain

This paper aims to address facility coordination issues in NRRSM by exploring the establishment of a modern integrated regional logistics base-shared warehouses. By achieving information sharing and business collaboration among logistics facilities, this serves as a bridge and link between the fragmentation of demand from manufacturing main plants and the scale of material supply from suppliers for NRRSM. The main tasks of this paper include: (1) constructing a joint inventory model for shared warehouses based on the characteristics of network NRRSM, determining the location of shared warehouses, and optimizing the network structure of component supply chains; (2) Using enterprise-related data for simulation and calculation, conducting sensitivity analysis on key cost factors, and summarizing management recommendations based on the findings.

The research framework of this paper is outlined as follows: Section 2 provides a comprehensive review of relevant studies on railway vehicle manufacturing supply chains and supply chain network optimization. Subsequently, Section 3 establishes the main model of this paper, including independent supply and collaborative supply aspects. Section 4 conducted model simulation calculations based on data examples and performed sensitivity analysis. Finally, Section 5 summarizes the research conclusions and prospects of this paper.

2 RELATED WORKS

Currently, scholars have conducted very few supply chain-related studies on the railway vehicle manufacturing industry, and most of them are qualitative studies. Andrea Diaz [3] discussed how the service-oriented transformation of rail vehicle manufacturing is influenced by industry demands and regulatory changes, and analyzed the potential challenges that may be faced. Zhao [4] proposed an accurate prediction model of railroad freight volume under different freight types by fully mining the information of railroad cargo ticket data. Xu [5] discussed various potential research directions and open issues of deploying 5G network on high-speed rail. Aboolian [6] minimizes network costs in a planning model, discussing the design of a responsive supply chain for manufacturing-assembly facilities facing stochastic demand and service time.

Supply chain network optimization is a recent hot topic. Jang et al. [7] construct a cost-oriented optimization model; Bidhandi [8] researches supply chain network design under multiple constraints; Santoso et al. [9] propose a stochastic programming model for large-scale scenarios; Wang L [10] discusses joint distribution models for fast-moving consumer goods, presenting three optimization models with Chaopi as an example. Addressing stock-out risks in the traditional retail channel under stochastic demand in a dual-channel supply chain, Yang et al. [11] propose a cooperative inventory strategy where excess demand in the retail channel is complemented by the manufacturer's direct channel inventory through transhipment. Du [12] proposes a new cloud computing allocation algorithm based on improved ant colony algorithm. According to the limit conditions of cloud computing environment and computing resources, this paper finds the shortest response time of all resource nodes and gets a set of best available nodes.

The joint location-inventory problem, a classic in supply chain network design, has been studied since around 2000. In early studies, Daskin et al. [13] and Shen et al. [14] formulate a similar nonlinear integer programming model, using the Economic Order Quantity model for cycle inventory and considering safety stock with risk-pooling effects, resulting in a convex objective function. Snyder et al. [15] study a stochastic joint location-inventory model, considering scenario uncertainty and recognizing parameter differences across scenarios. They propose a nonlinear integer programming model and an exact algorithm based on Lagrangian relaxation. Çetinkaya et al. [16] relate transportation costs to truck/freight capacity constraints, investigating a joint location-inventory problem where transportation costs depend on capacity. Zhu [17] established the optimal updating mechanism of rail transit stations based on Tod model. Wang [18] uses a dynamic approach to scheduling the bus system based on genetic algorithms to optimize the demand of the bus network. Fathi et al.'s [19] research considers uncertainty in customer demand and replenishment lead time.

Numerous scholars have extensively explored facility collaboration and joint location-inventory models. However, tailored location-inventory simulation studies for network railway rolling stock manufacturing enterprises remain unaddressed, demanding efficient modelling methods for industrial practices. This paper adopts the concept of supply chain network optimization, utilizing mixed-integer programming to build a location-inventory model for the component distribution network of a network railway rolling stock manufacturing enterprises. Simulation-based solutions yield optimal designs and assess the impact of key cost factors.

3 JOINT LOCATION-INVENTORY MODEL

To achieve the collaborative operation of the component supply chain network, this paper selected a location-inventory model for modelling research. This model can simultaneously consider the joint optimization of warehouse location and inventory level, which aligns well with the research objectives of this paper.

3.1 Model Assumptions

This chapter makes the following basic assumptions about the model: (1) The central warehouse orders from suppliers, and all demand points order from the central warehouse, excluding other procurement sources; (2) The positions of central warehouse, suppliers, manufacturing OEMs and regional customers have been determined, and the demand of each demand point must be met, and the total supply of each supplier is known; (3) The demand of parts and components required by customers in each manufacturing OEM and region obeys normal distribution. The quantities of demands at each demand point are independent and do not influence each other. (4) The demand of a demand point is only met by a central warehouse, and the demand of a central warehouse is only met by a supply point.

3.2 Model Symbol Description

The decision variables in this paper include:
Q'_j, Q''_j, Q'''_j Optimal order quantity of central warehouse j (unit); Z'_j, Z''_j, Z'''_j : 0 - 1variable, when selecting central warehouse j, take 1; $V'_{ij}, V''_{ij}, V'''_{ij}$: 0 - 1 variable, when the supplier i satisfies the central warehouse j, take 1, otherwise it is 0;

The model symbols in this paper are explained as shown in Tab. 1.

Table 1 Explanation of model symbol

Model Symbols	Meaning	Model Symbols	Meaning
I	supplier sets	T_{j,k_1}	Distance from the central warehouse j to the main manufacturing factory k_1.
J	central warehouses set	T_{j,k_2}	Distance from the central warehouse j to the main manufacturing factory k_2.
K_1	manufacturing main engine plants sets	c_{1j}	Single order cost of central warehouse j.
K_2	regional customer collection set	c_{2j}	Unit storage cost of central warehouse j.
C	unit transportation cost from supplier to central warehouse	c_{3j}	Shortage loss of central warehouse j.
h_1	unit transportation cost from the central warehouse j to the manufacturing factory	kk_j	Safety stock factor of central warehouse j.
h_2	unit transportation cost from central warehouse j to regional customers	f_j	Fixed construction cost of central warehouse j.
S_{ij}	Distance from supplier i to central warehouse j	P_i	the total supply of supplier i.
μ_{k_1}	Average value of k_1 demand in manufacturing factory	μ_{k_2}	Average value of k_2 regional customer demand.
σ_{k_1}	Standard deviation of k_1 demand of the manufacturing factory.	σ_{k_2}	Standard deviation of k_2 regional customer demand.

In addition, the following variables should be included:

W_{j,k_1} : 0 - 1 variable, when the central warehouse j meets the requirements of the manufacturing main engine factory k_1, take 1, otherwise it is 0.

W_{j,k_2} : 0 - 1 variable, when the central warehouse j meets the regional customers k_2, take 1, otherwise it is 0.

3.3 Model Establishment

3.3.1 Joint Location-Inventory Model under Independent Supply

In the independent supply mode, considering the production supply chain and the maintenance supply chain, the joint location-inventory model with the minimum operating cost of the supply chain is constructed respectively, and the total cost of the supply chain system in this mode is obtained by adding the minimum costs.

(1) Production supply chain.

The first part is the transportation cost:

$$\sum_{i=1}^{n}\sum_{j=1}^{m} cS_{ij}V'_{ij} + \sum_{j=1}^{m}\sum_{k_1=1}^{l_1} h_1 T_{j,k1} W_{j,k1} \tag{1}$$

The second part is the inventory cost of the central warehouse, including the cost of ordering times, storage cost and shortage cost:

$$\sum_{j=1}^{m}\left[c_{1j}\frac{\mu_{j1}}{Q'_j} + c_{2j}\left(\frac{Q'_j}{2} + SS_{j1}\right) + c_{3j}\varepsilon'_j\frac{\mu_{j1}}{Q'_j}\right] \tag{2}$$

The third part is the fixed construction cost:

$$\sum_{j=1}^{m} f_j Z'_j \tag{3}$$

The joint location inventory model of production supply chain of NRRSM established in this paper can be expressed as:

$$\min C_1 = \sum_{i=1}^{n}\sum_{j=1}^{m} cS_{ij}V'_{ij} + \sum_{j=1}^{m}\sum_{k_1=1}^{l_1} h_1 T_{j,k1} W_{j,k1} + \\ + \sum_{j=1}^{m}\left[c_{1j}\frac{\mu_{j1}}{Q'_j} + c_{2j}\left(\frac{Q'_j}{2} + SS_{j1}\right) + c_{3j}\varepsilon'_j\frac{\mu_{j1}}{Q'_j}\right] + \sum_{j=1}^{m} f_j Z'_j \tag{4}$$

The objective function is to minimize the total logistics cost of the production supply chain network, and the total cost is mainly divided into three parts, namely transportation cost, inventory cost and fixed construction cost. Constraints as follow:

$$\sum_{j=1}^{m} W_{j,k1} = 1,\ k_1 = 1,\ 2,\ ...,\ l_1 \tag{5}$$

$$W_{j,k1} \le Z'_j,\ j = 1,\ 2,\ ...,\ m.k_1 = 1,\ 2,\ ...,\ l_1 \tag{6}$$

$$V'_{ij} \le Z'_j,\ j = 1,\ 2,\ ...,\ m.i = 1,\ 2,\ ...,\ n \tag{7}$$

$$\sum_{j=1}^{m} \mu_{j1} V'_{ij} \le P_i,\ i = 1,\ 2,\ ...,\ n \tag{8}$$

$$\mu_{j1} \le Q'_j + SS_{j1},\ j = 1,\ 2,\ ....,\ m \tag{9}$$

The first constraint indicates that each main manufacturing plant is delivered by only one central warehouse. The second indicates that it is the corresponding selected central warehouse that satisfies each manufacturing main engine plant. The third indicates that the supplier supplies the corresponding selected central warehouse. The forth indicates that the number of parts provided by supplier i to central warehouse j is less than or equal to the supplier's own supply capacity. The fifth indicates that the sum of the ordered quantity of the central warehouse j and the safety stock is greater than or equal to its demand.

(2) Maintenance of supply chain.

The difference between maintenance supply chain and production supply chain lies in the characteristics of demand distribution, and the corresponding maintenance supply chain joint-inventory model includes. Objective function as follows:

$$\min C_2 = \sum_{i=1}^{n}\sum_{j=1}^{m} cS_{ij}V'_{ij} + \sum_{j=1}^{m}\sum_{k_2=1}^{l_2} h_2 T_{j,k2} W_{j,k2} + \\ + \sum_{j=1}^{m}\left[c_{1j}\frac{\mu_{j2}}{Q''_j} + c_{2j}\left(\frac{Q''_j}{2} + SS_{j2}\right) + c_{3j}\varepsilon''_j\frac{\mu_{j2}}{Q'_j}\right] + \sum_{j=1}^{m} f_j Z''_j \tag{10}$$

Constraints are analogous to the model of the production supply chain. The final total cost of the supply chain system is $C = \min C_1 + \min C_2$.

3.3.2 Joint Location-Inventory Model under Collaborative Supply

The total cost of the supply chain system can be divided into three parts in the inventory optimization model of central warehouse joint location under the collaborative supply model.

The first part is the transportation cost.

$$\sum_{i=1}^{n}\sum_{j=1}^{m} cS_{ij}V_{ij} + \sum_{j=1}^{m}\sum_{k_1=1}^{l_1} h_1 T_{j,k1} W_{j,k1} + \sum_{j=1}^{m}\sum_{k_2=1}^{l_2} h_2 T_{j,k2} W_{j,k2} \tag{11}$$

The second part is the inventory cost of the central warehouse, including ordering cost, ordering frequency cost, storage cost and shortage cost.

$$\sum_{j=1}^{m}\left[c_{1j}\frac{\mu_{j3}}{Q'''} + c_{2j}\left(\frac{Q'''}{2} + SS_{j3}\right) + c_{3j}\varepsilon'''_j\frac{\mu_{j3}}{Q'''}\right] \tag{12}$$

The expected shortage of central warehouse j in the ordering cycle is:

$$\varepsilon'''_j = \int_{R_j}^{+\infty}(x - R_j)\varphi_j(x)\mathrm{d}x = [kk_j\int_{-\infty}^{kk_j}\frac{1}{\sqrt{2\pi}}\mathrm{e}^{-\frac{x^2}{2}}\mathrm{d}x + \\ + \int_{-\infty}^{kk_j}\frac{1}{\sqrt{2\pi}}\mathrm{e}^{-\frac{x^2}{2}}\mathrm{d}x - kk_j]\sqrt{L_j}\sigma_{j3} \tag{13}$$

The third part is the fixed construction cost of distribution centre.

$$\sum_{j=1}^{m} f_j Z'''_j \tag{14}$$

To sum up, the joint location inventory model of supply chain system of NRRSM established areas follows:

$$\min C_3 = \sum_{i=1}^{n}\sum_{j=1}^{m} cS_{ij}V_{ij} + \sum_{j=1}^{m}\sum_{k_1=1}^{l_1} h_1 T_{j,k1} W_{j,k1} + \\ + \sum_{j=1}^{m}\sum_{k_2=1}^{l_2} h_2 T_{j,k2} W_{j,k2} + \sum_{j=1}^{m} f_j Z'''_j + \\ + \sum_{j=1}^{m}\left[c_{1j}\frac{\mu_{j3}}{Q'''} + c_{2j}\left(\frac{Q'''}{2} + SS_{j3}\right) + c_{3j}\varepsilon'''_j\frac{\mu_{j3}}{Q'''}\right] \tag{15}$$

The objective function is to minimize the total logistics cost of the production supply chain network, and the total cost is mainly divided into three parts, namely transportation cost, inventory cost and fixed construction cost. The constraints in this subsection are analogous to those in Section 3.3.1.

4 EXAMPLE SIMULATION AND RESULT ANALYSIS

This paper's case study focuses on Enterprise A, a networked railway rolling stock manufacturer, whose operational model is primarily composed of rail vehicle processing and customer warranty. Enterprise A owns four main manufacturing plants, which are relatively dispersed.

Figure 3 The distribution of facility locations related to enterprise A demand points

The example used in this paper is a bearing, a crucial component in the enterprise's operations, with corresponding demand in both vehicle processing and customer warranty. All data used in this paper were obtained after the relevant operational data of the enterprise were uniformly dimensioned and rounded. The positions of each node have undergone certain transformations based on real positions.

4.1 Data Introduction of an Example

It is known that there are three suppliers P1, P2 and P3 in Enterprise A, and it is planned to select five alternative warehouses W1, W2, W3, W4 and W5 as the central warehouses to meet the spare parts requirements of four main manufacturing plants M1, M2, M3 and M4 and eight maintenance customers M5, M6, M12. The number of nodes in the three-level distribution network involved in this paper is 20, and the number of supply points, alternative warehouses, manufacturing main engine plants and maintenance customers is represented by five-pointed stars, rectangles, triangles and circles, which are 3, 5, 4 and 8 respectively. The transformed position of each node in the network is shown in Fig. 4.

The transportation mode between different nodes only considers road transportation, so the unit transportation cost between these nodes is 50 yuan per unit distance. Relevant transportation distance parameters of each node are shown in Tab. 2, with distances between nodes calculated using the Euclidean distance.

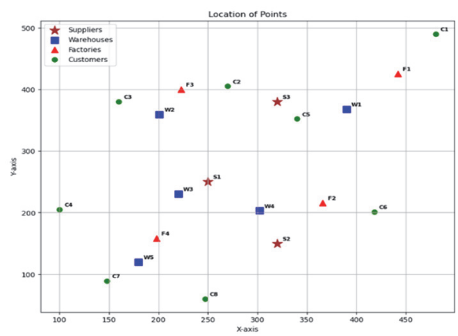

Figure 4 Distribution network of bearing parts

Table 2 Distance table from supplier to alternative warehouse

Distance	W1	W2	W3	W4	W5	Distance	W1	W2	W3	W4	W5
P1	183.10	119.51	36.06	70.09	147.65	M6	125.57	82.93	182	204.52	298.87
P2	228.96	240.50	128.06	55.97	143.18	M7	230.31	46.07	161.55	226.92	260.77
P3	71.02	120.84	180.28	177.91	295.30	M8	332.67	184.17	122.58	202.01	116.73
M1	77.16	249.87	295.48	262.46	402.08	M9	52.5	139.18	171.13	153.77	281.82
M2	153.88	218.34	146.67	65.31	209.31	M10	169.33	268.43	200.11	116.02	251.41
M3	170.04	46.53	170.03	212.25	283.28	M11	369.33	275.15	158.32	191.6	44.55
M4	284.54	201.02	75.29	113.32	42.05	M12	339.58	302.52	172.13	153.21	89.94
M5	151.6	308.22	367.7	337.72	476.34	------------------					

Among them, the supply capacities of suppliers P1, P2 and P3 are 1500, 2000 and 2500 respectively. M1 - M4 are the main manufacturing plants, and the demand features are large average and small variance. M5 - M12 are the demand points of maintenance customers, and the demand features are small average and large variance. The demand of each demand point satisfies normal distribution, which is represented by N1 - N12: N1(1000, 50), N2(900, 50), N3(1100, 50), N4(1000, 80), N5(150, 90) and N6(180, 100).

The relevant attributes of each alternative warehouse are presented in Tab. 3.

Table 3 Alternate shared warehouse attributes

Shared warehouse attribute	W1	W2	W3	W4	W5
Fixed construction cost	50000	45000	55000	55000	40000
Upper capacity limit	2400	2200	2600	2400	1800
Unit storage cost	5	2	2.5	1.5	2
Unit out-of-stock cost	8	8	8	8	8

4.2 Model Solution

The simulation experiments in this article utilize the Pulp library from a third-party Python library for solving mixed-integer programming models. The experiments were conducted in a Windows 10 environment with Python 3.7. Under the independent supply mode, the material demand management department of the main manufacturing plant and the material demand management department of the maintenance customer are independent, and the best supply chain network design scheme is obtained by modelling and calculating according to their own needs. For the OEM, solving the mixed integer programming model in 3.3.1 of this paper can get the supply chain network design scheme as Fig. 5.

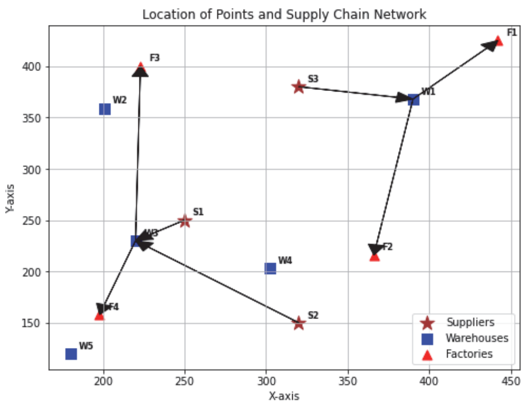

Figure 5 Distribution network of parts required by manufacturing OEM

The selected shared warehouses are alternate warehouses 1 and 3. The distribution network relationships for this scheme can be seen in Fig. 5. The total cost for the supply chain network of networked railway rolling stock manufacturer A is 152751, significantly outperforming enterprise A under independent supply mode.

For maintenance service customers, the design scheme of the supply chain network can be obtained by solving the mixed integer programming model in Section 3.3.1 of this paper, as shown in Fig. 6.

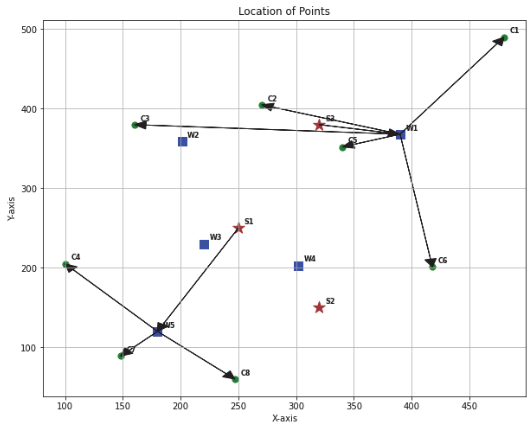

Figure 6 Parts Distribution network about maintenance customer's demand

The selected shared warehouses are alternate warehouses 1 and 5. The distribution network relationships for this scheme can be seen in Fig. 6. The total cost for the maintenance customer's supply chain network of networked railway rolling stock manufacturer A is 160838.5. In summary, under independent supply mode, the total cost for enterprise A is 263589.5.

Under the collaborative supply mode, the material demand management department of the main engine plant collaborates with the material demand management department of the maintenance customer to jointly manage and exchange information. They create a unified model and perform calculations based on their respective needs to obtain the optimal supply chain network design scheme with the minimum total cost. The solution is as follows.

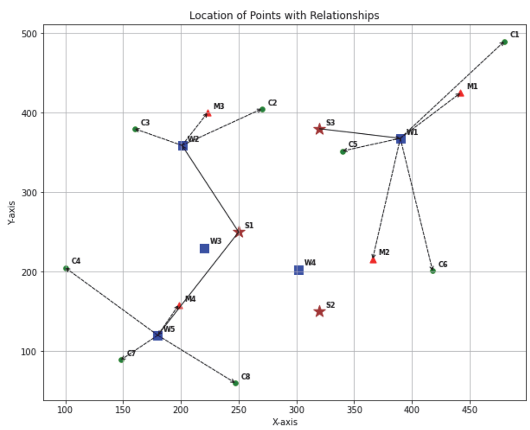

Figure 7 Parts Distribution network about joint demand

The selected shared warehouses are alternate warehouses 1, 2, and 5. The distribution network relationships for this scheme can be seen in Fig. 7. In terms of distribution network, the main manufacturing plant 1 and the main manufacturing plant 2 and the maintenance customers 1, 5 and 6 are supplied by the alternative warehouse 1, the main manufacturing plant 3 and the maintenance customers 2 and 3 are supplied by the alternative warehouse 2, and the main manufacturing plant 4 and the maintenance customers 4, 7 and 8 are supplied by the alternative warehouse 5.

Table 4 Cost situation under different modes

Cost	Fixed construction cost	Transportation cost	Inventory cost	Total cost
Independent supply (Manufacturing OEM)	105000	41039	6712	263589.5 (Removing redundant fixed construction cost)
Independent supply (Maintenance Customer)	90000	68214.5	2624	
Collaborative supply	135000	70572.5	7260	212832.5

While alternative warehouses 2 and 5 are supplied by supplier 1, and alternative warehouse 1 is supplied by supplier 3. Under the collaborative supply mode, the total cost for the supply chain network of networked railway rolling stock manufacturer A is 212832.5, with a fixed construction cost of 135000, transportation cost of 70572.5, and total inventory cost of 7260, significantly outperforming enterprise A under independent supply mode. The comparison of various costs can be found in Tab. 4.

4.3 Sensitivity Analysis

Based on simulation examples, it is found that in the entire logistics distribution network construction, fixed construction costs are the largest, accounting for approximately 64% of the total cost, followed by transportation costs, accounting for about 33%. Therefore, a sensitivity analysis of key parameters such as fixed construction costs and unit transportation distance costs is conducted.

Considering the authenticity of cost variations and the attainability of conclusions, we have determined the fluctuation range of each key cost factor to be −6% to 6%, with a fluctuation interval of 1%.

(1) When fixed construction costs fluctuate within the range of −6% to 6%, the variations in total distribution network costs are presented in the following Tab. 5.

Table 5 Distribution network total cost variations with fluctuations in fixed construction costs

Volatility (Fixed Construction Costs)	−6%	−5%	−4%	−3%	−2%	−1%
Total Cost	209066.5	206082.5	207432.5	208787.5	210132.5	211482.5
Volatility Volatility (Fixed Construction Costs)	1%	2%	3%	4%	5%	6%
Total Cost	214182.5	215532.5	204381.5	205431.5	206481.5	207531.5

The data from the above table, when plotted, result in a line graph as shown in Fig. 8.

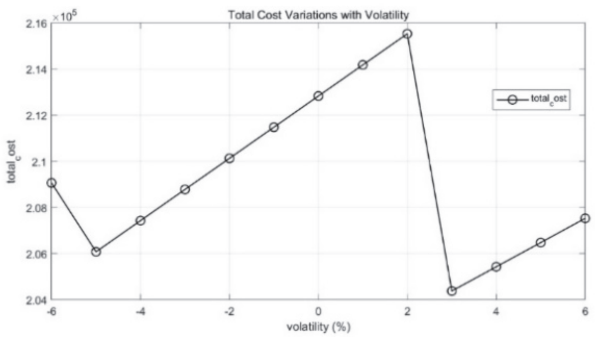

Figure 8 Curve of total cost variations with fluctuations in fixed construction costs

At a −6% fluctuation rate in fixed construction costs, the capacity reduction in shared warehouse 1 cannot meet the original distribution targets, necessitating adjustments in the distribution network structure. Maintenance customer 5's service warehouse shifts from shared warehouse 1 to shared warehouse 2, increasing distribution costs. In fluctuation rates between −5% and 2%, the network structure remains unchanged, with only fixed construction costs affecting the total cost. At 3 - 6% fluctuation rates, shared warehouses 1 and 3 meet regional distribution needs with reduced fixed construction costs. However, changes in the distribution network structure offset cost reductions, maintaining an overall cost level. As fluctuation rates increase, total cost proportionally rises.

(2) In terms of unit transportation costs, fluctuations impact the distribution network's total cost. Decreasing unit transportation costs per distance leads to selecting fewer shared warehouses and reduced total costs. Conversely, increasing unit transportation costs per distance prompts consideration of more warehouses to reduce overall transportation distance. Solution results are summarized in Tab. 6, showcasing variations in the distribution network's total cost.

Table 6 Distribution network total cost variations with fluctuations in transportation distance costs

Volatility (Transportation Distance Costs)	−60%	−50%	−40%	−30%	−20%	−10%
Total Cost	147848.6	156745.75	165642.9	191660.75	198718	205775.25
Volatility Volatility (Transportation Distance Costs)	10%	20%	30%	40%	50%	60%
Total Cost	219889.75	226947	234004.25	241061.5	248118.75	255176

The data from the above table, when plotted; results in a line graph are shown in Fig. 9.

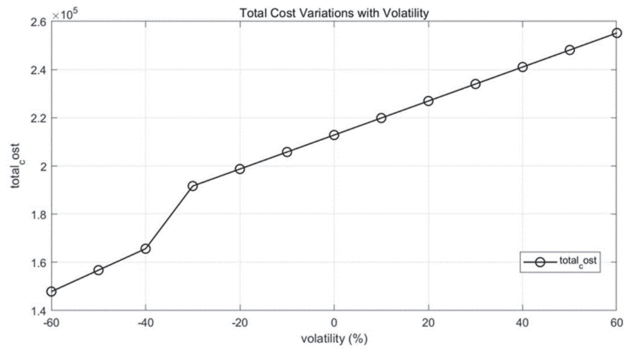

Figure 9 Curve of total cost variations with unit transportation distance cost fluctuations

Based on the analysis above, the following conclusions can be drawn: In the design of distribution networks, fixed construction costs have a significant impact, but pursuing the lowest fixed construction costs blindly is not optimal. It is also essential to consider the variations in inventory capacity brought about by the fixed construction scale. Achieving economies of scale while meeting the demand points is the optimal strategy; Changes in unit transportation distance costs are highly positively correlated with the total cost of the distribution network. As unit transportation distance costs increase, the total cost also increases. Therefore, enterprises need to reduce transportation costs to optimize the distribution network.

5 CONCLUSION

In today's digital era, network railway rolling stock manufacturing enterprises urgently need to establish collaborative logistics networks for efficient operations. This paper proposes a shared logistics distribution model based on a collaborative supply mode, utilizing a joint location-inventory model to determine the distribution scheme. Key conclusions include the superior cost-effectiveness of the collaborative supply mode over independent supply and the feasibility of facility coordination through a shared central warehouse. Simulation analysis highlights that reducing fixed construction costs alone may not minimize total costs, emphasizing the importance of considering construction scale effects on inventory capacity. Furthermore, a strong positive correlation exists between total costs and unit transportation distance costs, emphasizing the need to reduce transportation costs for cost-effective distribution network operations.

The management insights drawn from this study include: Firstly, it is recommended that enterprises focus on developing collaborative operation capabilities. By establishing collaborative supply modes, internal resources can be optimized and integrated to improve network operational efficiency. Secondly, managers need to focus on cost optimization. They should not only consider fixed construction costs but also comprehensively evaluate inventory capacity and unit transportation distance costs. However, this study also has certain limitations. For example, it only considers cost minimization as the objective. Future research could expand the model's objective function to include economies of scale and synergies.

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