

Empirical Study on Low-Carbon-Oriented Supply Chain Network Optimization Considering Service Level Constraints

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Abstract: Taking the supply chain network of Company M as the research object, this paper collects relevant data of its existing supply chain network and applies statistical analysis methods to analyze from the dimensions of product flow, transportation distance, dispatch information, customer satisfaction rate regarding “two-day delivery”, and various types of costs. The findings indicate that the enterprise suffers from low overall operational efficiency and unbalanced product flow distribution. In addition, the absence of Central Distribution Center (CDC) in the supply chain network and the adoption of the factory-direct supply to Regional Distribution Center (RDC) model result in overly long transportation routes, which hinder the realization of production-sales synergy. To address these issues, this paper establishes distribution network system supplemented by CDCs, formulates differentiated transportation routes for different product categories, and sets “two-day delivery” time constraint for Class A products. It is verified that the optimized supply chain network can effectively control the total supply chain cost while ensuring the delivery timeliness of Class A products.

Keywords: Carbon Emissions; Service Level; Supply Chain Network; Empirical Research

1. Introduction

Against the dual backdrop of the deepening implementation of the “Dual Carbon” goals and the continuous upgrading of consumer demand, the low-carbon transformation of supply chain networks and the enhancement of service levels have emerged as pivotal issues for enterprises pursuing high-quality development [1]. With the increasingly stringent global climate

governance, countries are introducing carbon emission reduction policies, and as the main carrier of carbon emissions, the low-carbon operation of the supply chain has changed from an optional action to a rigid requirement [2]. Concurrently, in an increasingly competitive market landscape, customer expectations regarding delivery timeliness and service quality have risen markedly, rendering service capability a critical determinant in capturing market share and establishing core competitiveness [3]. However, existing supply chain network optimization efforts frequently encounter a trade-off between low-carbon objectives and service level improvements. Moreover, current research remains predominantly focused on theoretical modeling, with a notable lack of empirical validation based on real-world enterprise scenarios [1,4].

Supply chain networks, as the core carrier connecting suppliers, manufacturing enterprises, warehousing and distribution centers, and terminal customers, their rational layout and operational efficiency directly determine the balance effect of carbon emissions and service levels. Existing research on supply chain network optimization mainly focuses on cost minimization [5-9], as well as research combined with carbon emissions [10-12], however, there are few studies that consider the synergy of service levels, making it difficult to meet the dual demands of current green development and consumption upgrading. With the rapid development of operations research and digital technology, technical support is provided for the optimization of supply chain networks that take into account service levels from a low-carbon perspective, and also lays a foundation for empirical research. Based on this, this paper focuses on the optimization of supply chain networks considering service levels from a low-carbon perspective, combining empirical

research methods, and based on the analysis of the current status of supply chain networks, constructs optimization model for supply chain networks that takes into account both low-carbon goals and service levels. Through empirical analysis of actual enterprise cases, the effectiveness and feasibility of the model are verified, and targeted optimization paths are proposed.

2. Supply Chain Network Current Status Analysis

2.1 Overview of Company M's Supply Chain Network

This study focuses on a technology firm specializing in smart fitness equipment in China. For brevity, the company is referred to as Company M. Adhering to the principle of “empowering sports through data technology.” Company M is dedicated to developing high-tech smart fitness products based on a “hardware and software” integration model. The company currently offers comprehensive portfolio of nine products across four major series, including smart bracelets, sports watches, self-balancing scooters, and virtual reality (VR)

glasses, specifically comprising the Balance Car Pro, Balance Car S, Balance Car T, Bracelet Common, Bracelet NFC, Sport Watch, VR Glass H, VR Glass M, and VR Glass Pro.

Currently, the finished product supply chain network of Company M comprises factories, regional warehouses and distributors. Its factories are located in Shenzhen, while regional warehouses cover Beijing, Shanghai, Chengdu, Xi'an and Changsha, providing services for 144 distributors across 100 cities in 29 provinces nationwide. The layout of this supply chain distribution network is presented in Figure 1. At present, Company M's logistics network is divided into two phases.

·In the first phases, the factory distributes manufactured products to five regional warehouses via full-truckload transportation. The transportation and distribution in this stage are the responsibility of the factory.

·In the second phases, in accordance with the proximity principle, the five regional warehouses deliver products to distributors within their respective coverage areas. The distribution in this stage is undertaken by the regional warehouses, using express parcel delivery.

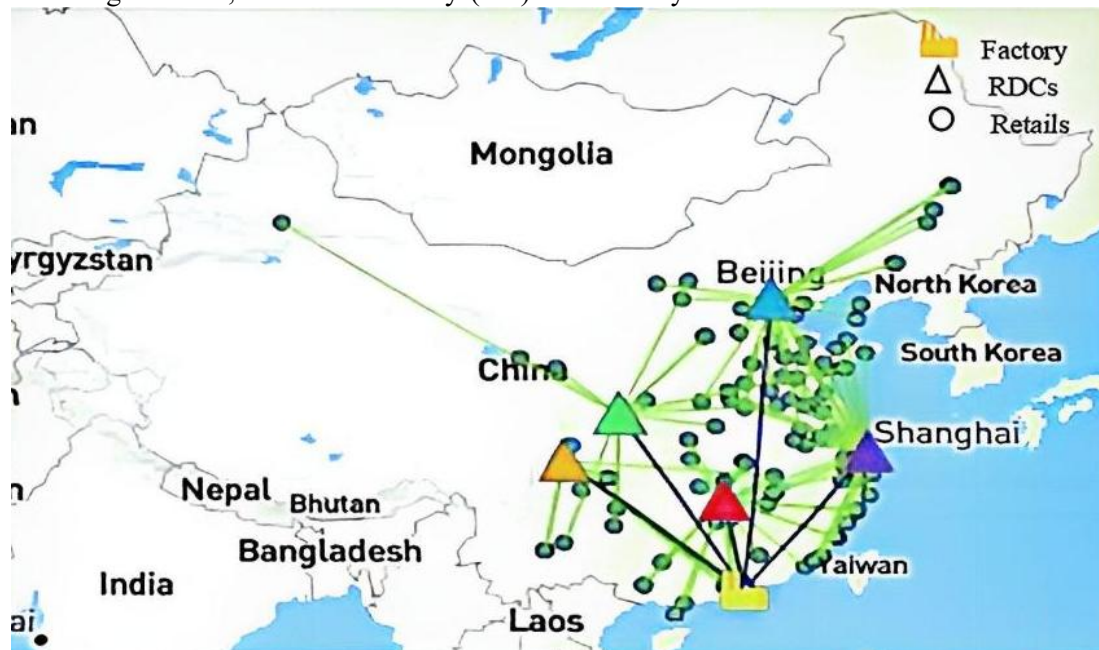


Figure 1. Distribution of Company M's Supply Chain Network

2.2 Company M Supply Chain Network Analysis

2.2.1 Factory to Regional Distribution Centre (RDC) Network Analysis

Based on statistical calculations, the transportation distribution from the factory to

the RDC is summarized in Table 1, while the product flow structure across RDC is illustrated in Figure 2. As indicated in Table 1, the total flow volume across the five RDC follows the order: RDC_Shanghai > RDC_Beijing > RDC_Changsha > RDC_Chengdu. Among these, RDC_Beijing is the farthest from the Shenzhen

factory, with distance of 2,273.78 km and corresponding transportation lead time of 3.8 days. Conversely, RDC _ Changsha is the

nearest, at 750.86 km with a transit time of 1.25 days.

Table 1. Overview of Distribution of Factory to RDC Transportation

Serial number	Source location name	Destination name	Total flow	Service distance/km	Transport time/day
1	Shenzhen Factory	RDC_ Shanghai	619876	1419.62	2.4
2	Shenzhen Factory	RDC_ Beijing	363868	2273.78	3.8
3	Shenzhen Factory	RDC_ Chengdu	195115	1561.76	2.6
4	Shenzhen Factory	RDC_ Xi'an	79421	1607.29	2.7
5	Shenzhen Factory	RDC_ Changsha	302437	750.86	1.3

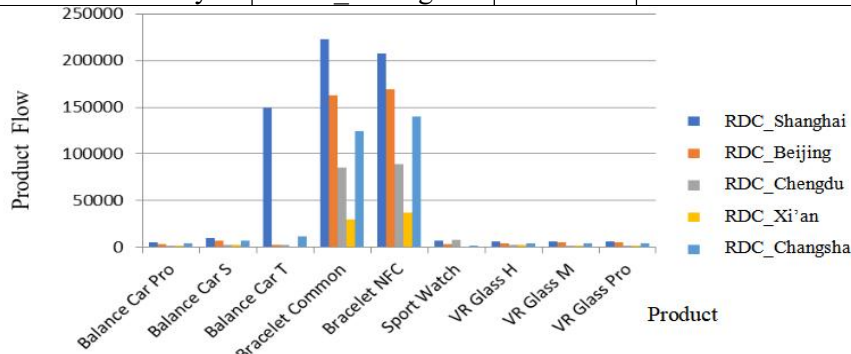


Figure 2. Product Flow from Factory to RDC

Figure 2 reveals that among the nine products manufactured by the Shenzhen factory, smart bracelets account for the highest sales volume, representing 81.3% of the total product flow, with distributions primarily concentrated in the RDC_ Shanghai and RDC_ Beijing. Within the self-balancing scooter category, the Balance Car T model exhibits the highest flow, 89.4% of which is allocated to RDC_ Shanghai. In contrast, the remaining five products demonstrate relatively low shipment volumes, with flows from the Shenzhen factory to the RDC generally falling below 5,000 units.

2.2.2 Network Analysis from RDC to Retailer

After statistical calculation, the distribution table of the retailer’s transportation time is obtained as Table 2 It can be seen that only 1/3 of the RDC to retailers deliveries can be completed within 6 hours, but half of the retailers need more than 10 hours to complete, with an average

transportation time of 10.8 hours. Therefore, there are many unreasonable places in the current supply chain network of Company M, such as long transportation distances in the distribution network, which further increases the retailer’s waiting time. In this regard, it is possible to re-plan the product flow distribution of RDC, or consider adding new CDC to improve the level of customer service.

2.2.3 Shipment Information Analysis

Based on a systematic analysis of Company M’s shipping records, it was determined that the total outbound volume from the Shenzhen factory to the Regional Distribution Centers (RDCs) matches the aggregate inbound volume from the RDCs to the 144 downstream retailers, maintaining demand satisfaction rate of 100%. The specific quantities of goods shipped and received are summarized in Table 3.

Table 2. Distribution of RDC to Retailers Transportation Time

Transport time/hour	0-3	3-6	6-9	10 >=10	Average
Number	21	30	19	73	10.8
Percentage	14.7%	20.9%	13.3%	51.1%	

Table 3. Annual Throughput of Each RDC

RDC name	Inflow	Outflow	Total throughput
RDC_ Beijing	363868	363868	727736
RDC_ Chengdu	195115	195115	39023
RDC_ Shanghai	619876	61986	123975
RDC_ Xi'an	79421	79421	158842
RDC_ Changsha	302437	302437	604874

2.2.4 Analysis of “Two-Day Delivery” Customer Demand Satisfaction

In order to better plan Company M’s supply chain network, according to the characteristics of the products. This paper divides the company’s four products into three categories, namely A, B, and C products, where A products are smart bracelets, and B, C products are sports watches, body balance cars, and VR glasses. The “two-day delivery” customer demand situation

Table 4. Customer Demand Satisfaction Rate for “Two-Day Deliver” of Different Categories of Goods

Product category	Total flow	≤960 km total flow	“Two-day delivery” customer demand satisfaction rate
Class A products	1268149	1056280	83.3%
Class B/C products	292568	262942	89.9%
Class A/B/C products	1560717	1,319,548	84.5%

2.2.5 Analysis of Various Costs in Supply Chain Networks

Supply chain network cost refers to the cost of the supply chain throughout the entire operational process and cycle. Supply chain cost is one of the elements reflecting the performance of the supply chain. This paper mainly considers two-stage transportation cost, fixed operating costs of factories and regional warehouses, inventory holding cost of RDCs, and carbon emission cost of the supply chain network. Statistical analysis shows that the total cost of Company M’s supply chain network is 70767044.09 yuan, including: fixed operating cost of 1500000 yuan, transportation cost of 62079368.56 yuan, inventory holding cost of 6844505.03 yuan, and carbon emission cost of 343170.5 yuan. The specific analysis is as follows:

(1) Transportation Cost Analysis

Transportation cost constitute dominant portion of Company M’s total supply chain expenditure, accounting for 87.7% of the overall cost. The cost structure across various logistics stages reveals significant imbalance. Specifically, shipments from the Regional Distribution Center (RDC) to retailers represent the largest share, consuming approximately two-thirds of the total transportation budget.

(2) Inventory Cost Analysis

Company M’s supply chain network inventory holding cost accounts for 9.6% of the total cost. The inventory holding cost ratios of various parts of the supply chain network. The inventory holding cost from the factory to the RDC is relatively high, accounting for 97%.

(3) Carbon Emission Cost Analysis

of the products is shown in Table 4 It can be seen that the total “two-day delivery” satisfaction rate of the products is 84.5%, the satisfaction rate of A products is relatively low at 83.3%, and “two-day delivery” customer demand satisfaction rate of B and C products is close to 90%. Therefore, the current supply chain network service level of Company M is not high, especially for A products.

Carbon emission cost comprise three primary components: ① Emissions from the factory and the RDC themselves. ② Transportation-related emissions from the factory to the RDC. ③ Transportation-related emissions from the RDC to retailers. Overall, this cost category represents merely 0.48% of the total supply chain cost, indicating relatively minor financial impact.

(4) Fixed Operating Cost Analysis

The operation cost of Company M’s supply chain network refers to the sum of the fixed operation cost of the Shenzhen factory and five RDCs, each distribution center has a different annual operation cost, and once put into use, operation costs must be paid regardless of whether there is inflow or outflow. Here, the sum of the fixed operation costs is 15,000,000 million yuan, accounting for 2.1% of the total cost, and the proportion is relatively small.

3. Company M Supply Chain Network Optimization Modeling

Through the analysis in section, we found that there are many unreasonable aspects in the supply chain network structure of Company M, such as Customer satisfaction rate for the “two-day delivery” is not high enough, transportation cost account for a large proportion in the entire supply chain network, and the proportion of customers whose RDC-distributor transportation distance exceeds 960km is 14.5% and so on. In response to this, this paper adjusts the existing supply chain network of company M by establishing a mathematical model, hoping to reduce cost while improving the ‘two-day delivery’ customer satisfaction rate for A-class

products. The specific settings are as follows:
 ·To add two CDC in Guangzhou and Zhengzhou.
 ·The Shenzhen factory ships the products to the CDC for storage, followed by differentiated processing
 ·Class A products are transported to RDC, where they are provided to retailers through express parcels, aiming to improve the service level of Class A products. The target service level for Class A products is reflected in covering 95% of retailers need within a radius of 960 kilometers, while Class B and C products are provided directly to retailers through express parcels by the CDC.

3.1 Model Establishment

3.1.1 Symbol Description

The specific symbolic meanings of the parameters and decision variables used in the model are shown in Table 5.

Table 5. Symbol Meanings of Parameters and Decision Variables

Symbol name	Symbol meaning
I	set of factories
J	Set of RDCs
U	Set of CDCs
K	Set of retailers
gd_i	Factory's fixed operating cost
G_u	CDC's fixed operating cost
F_j	Fixed operating costs of the RDC
d_{ij}	Distance from factory i to RDC j
d_{jk}	Distance from RDC j to retailer k
w	The value of goods
h	Inventory holding ratio
c_{ij}	Transportation cost per unit distance from factory i to RDC j (yuan/km)
c_{jk}	Transportation cost per unit from RDC j to retailer k (yuan/piece)
X_{jk}	Number of products transported from RDC j to retailer k
V_i	inventory level

X_{ij}	Factory i provides the quantity of products to the RDC j
x	Full vehicle load transport capacity
\bar{A}	Ceiling up
P	Carbon emission price (Yuan/Kg)
e_{ij}	Factory i to RDC j unit distance carbon emissions (kg/(kg· km))
e_{jk}	RDC j to retailer k unit distance carbon emissions (kg/(kg· km))
E_i	Carbon emissions from factories or RDC (kg/(kg· km))
c_{iu}	Transportation cost per unit distance from factory i to CDC u (yuan/km)
c_{uj}	Transportation cost per unit distance from CDC u to RDC j (yuan/km)
c_{uk}	Transportation cost per unit from CDC u to retailer k (yuan/piece)
X_{jk}^{BC}	Quantity of Class B and Class C products transported from RDC j to retailer k
X_{uk}^A	Quantity of Class A products transported from CDC i to retailer k
X_{iu}	Quantity of products transported from factory i to CDC u
X_{uj}^A	Quantity of Class A products transported from CDC u to RDC j
q_k^A	Dealer's demand for product A

3.1.2 Model Establishment

This section divides Company M's products into three major categories, and different transportation methods are adopted for different types of products, where the product flow for class A products is factory-CDC-RDC-retailer, and the product flow for class B and class C products is factory-CDC-retailer. A supply chain network facility location-allocation model is established with the goal of minimizing the total cost, which includes fixed cost, multi-stage transportation cost, inventory holding cost of warehouses, and carbon emission cost, while considering flow and service level constraints. The specific model is as follows:

Objective function

$$\text{Min } Z = FC + TC + HC + CC \tag{1}$$

$$FC = \sum_{i \in I} gd_i + \sum_{j \in J} F_j + \sum_{u \in U} G_u \tag{2}$$

$$TC = \sum_{i \in I} \sum_{u \in U} \left(\frac{X_{iu}}{x} \right) d_{iu} c_{iu} + \sum_{u \in U} \sum_{j \in J} \left(\frac{X_{uj}^A}{x} \right) d_{uj} c_{uj} + \sum_{j \in J} \sum_{k \in K} X_{jk}^A c_{jk} + \sum_{u \in U} \sum_{k \in K} X_{uk}^{BC} c_{uk} \tag{3}$$

$$HC = \sum_{i \in I \cup J \cup U} V_i wh \tag{4}$$

$$CC = \sum_{i \in I \cup J \cup U} E_i P + \sum_{i \in I} \sum_{u \in U} e_{iu} d_{iu} P + \sum_{j \in J} \sum_{k \in K} e_{jk} d_{jk} P + \sum_{u \in U} \sum_{k \in K} e_{uk} d_{uk} P \tag{5}$$

Constraint Conditions

$$\sum_{j \in J} X_{jk}^A \leq \sum_{u \in U} X_{uj}^A \quad (6)$$

$$\sum_{u \in U} X_{uk}^{BC} \leq \sum_{i \in I} X_{iu}^{BC} \quad (7)$$

$$\sum_{i \in I} X_{iu}^A \geq \sum_{u \in U} X_{uj}^A \quad (8)$$

$$\sum_{j \in J} \sum_{k \in K} (d_{jk} > 960 ? 0 : 1) q_k^A \geq \sum_{k \in K} q_k^A \cdot 95\% \quad (9)$$

$$X_{iu} \in Z; X_{uj}^A \in Z; X_{jk}^A \in Z; X_{uk}^{BC} \in Z \quad (10)$$

Where, Equation (1) represents the minimization of total cost, comprising fixed cost, transportation cost, inventory holding cost, and carbon emission cost. Equation (2) denotes the fixed cost; Equation (3) denotes the transportation cost; Equation (4) denotes the inventory holding cost; and Equation (5) denotes the carbon emission cost. Equation (6) specifies that the quantity of Class A products procured by RDCs from CDCs is no less than the quantity of Class A products supplied by RDC to retailers. Equation (7) indicates that the quantity of Class B and Class C products supplied by CDCs to dealers is no less than the quantity of Class B and Class C products delivered from factories to CDC. Equation (8) requires that the quantity of Class A products obtained by RDC from CDC is at least the quantity of Class A products supplied by factories to the CDC. Equation (9) imposes the constraint that the demand satisfaction rate for retailers under the “two-day delivery” service reaches 95%, taking a value of 0 if the distance from the RDC to the retailer exceeds 960 km and 1 otherwise. Equation (10) ensures that the quantities of transported products are integers.

3.2 Parameter Values in the Model

Given that certain parameter datasets are voluminous, only key parameters are presented in the main text to streamline the content and highlight core information. Specifically, the fixed operating cost are set at 500,000 yuan for the factory, 200,000 yuan for RDCs, and 350,000 yuan for CDCs. Inventory holding cost are 15% for the factory, 12% for CDCs, 18% for RDCs in Beijing and Shanghai, and 20% for RDCs in Chengdu, Xi'an, and Changsha. Furthermore, carbon emissions for transportation from factories to RDC and from factories to CDC are quantified at 0.00014847 kg/kg·km and 0.00029694 kg/kg·km, respectively. Detailed carbon emission data for

the factory, RDC, and CDC are provided in Table 6.

Table 6. Carbon Emissions by Facility

Facility type	Throughput ($\times 10^4$ units)	Carbon emissions (kg)
Factory	0-50	6000
	50-80	7500
	80-100	8000
	>100	9000
RDC	0-20	2000
	20-40	2500
	40-60	3000
	>60	4000
CDC	0-50	3000
	50-70	4000
	70-90	5000
	Above 90	6000

3.3 Model Solution and Analysis

Using the Supply Chain Modeling Master software to solve the established model, we can obtain the network structure graph of the supply chain, as shown in Figure 3. We find that CDC_Zhengzhou has no inflow and outflow of products, and it belongs to an idle CDC.

Based on the model's running results, we can obtain that the network optimization model with constrained optimization for CDC based on the service level of Class A products is compared with the various costs and service levels of the company's current situation in Table 6. From the cost perspective, the total cost of the original network is 70767044 yuan, and the optimized network is reduced to 58015687 yuan, with a decrease of 18.02%, showing significant effects in overall cost control. Among them, the optimization effect of transportation cost is the most prominent, with the original transportation cost of 62079368 yuan reduced to 47429876 yuan after optimization, with a decrease of 23.60%, becoming the core driving factor for the decrease in total cost. However, the optimization plan also leads to an upward trend in some cost, with the fixed operating cost increasing from 1500000 yuan to 2200000 yuan, with an increase of 46.67%; the inventory holding cost rising from 6844505 yuan to 7892033 yuan, with growth of 15.30%; at the same time, the carbon emission cost increased from 343170 yuan to 493777 yuan, with an increase of 43.89%, indicating that while the network optimization reduces transportation costs, it also increases investments in warehousing

operations, inventory reserves, and environmental emissions. In terms of logistics service timeliness, the overall product “two-day delivery” satisfaction rate has decreased from 84.5% to 79.4%, decrease of 6.04%, reflecting a weakening of overall delivery timeliness. However, for high-

value class A products, the quality of service has achieved significant improvement, with the “two-day delivery” satisfaction rate rising from 83.3% to 95%, an increase of 14.05%, demonstrating the resource allocation to core products through the optimized scheme.

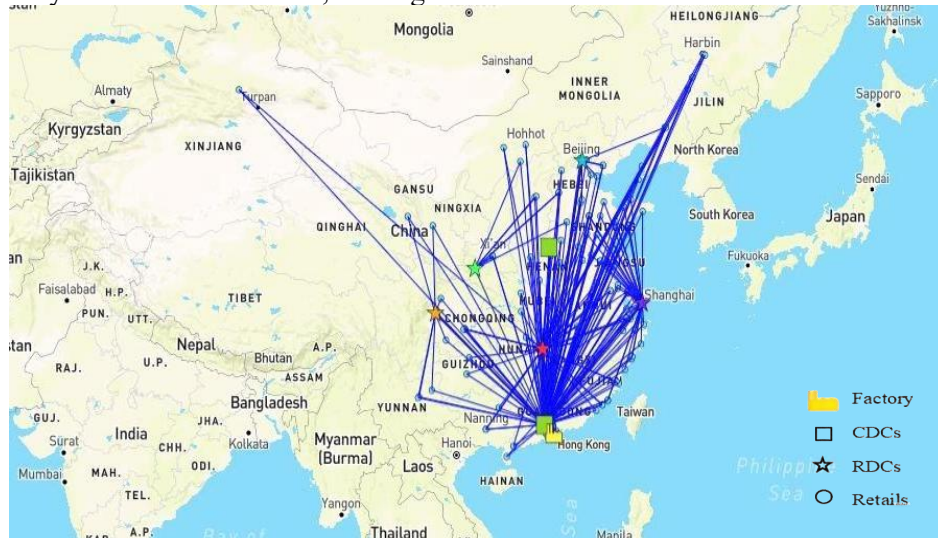


Figure 3. M Company’s Optimized Supply Chain Network

Table 6. Comparison of Cost and Service Levels Before and After Supply Chain Network Optimization

Scenario	Total cost	Fixed operating cost	Inventory holding cost	Carbon emission cost
Original network	70767044	1,500,000	6844505	343170
Optimize the network	58015687	2,200,000	7892033	493777
Proportion of increase or decrease	-18.02%	+46.67%	+15.30%	+43.89%
Scenario	Transport cost	Product “two-day delivery” satisfaction rate	Class A product “two-day delivery” satisfaction rate	
Original network	62079368	84.5%	83.3%	
Optimize the network	47429876	79.4%	95%	
Proportion of increase or decrease	-23.60%	-6.04%	+14.05%	

4. Conclusion

This study examines the supply chain network of Company M, focusing on product flow distribution, dealer demand fulfillment, “two-day delivery” satisfaction rates, and the cost structure comprising fixed, inventory, transportation, and carbon emission cost. Key problems identified include:

- (1) The company’s RDC layout is unreasonable, and the utilization rate of some RDCs is low, such as RDC_ Xi’an, indicating that the company’s operational status is not very good, and the inventory structure is not very reasonable.
- (2) High transportation costs driven by

unreasonable route selection and imbalanced product flow allocation from RDCs to retailers, which often disregards the proximity principle.

(3) The lack of a CDC, forcing long-distance shipments from factories to RDCs. Additionally, the model overlooks opportunities for production-sales synergy by not utilizing the proximity of certain retailers to factories or establishing dedicated CDC.

In response, this paper designs a revised distribution network that integrates a CDC. The new configuration allows direct distribution of products B and C from the CDC to retailers, while product A is routed via RDCs under a strict “two-day delivery” constraint. Comparison with the original network shows that the

optimization effectively controls total and transportation cost and enhances the timeliness of product A. However, it also results in higher fixed cost, inventory cost, and carbon emission cost, as well as a reduced overall satisfaction rate. Therefore, future efforts should aim to balance cost efficiency with service levels, aligning economic performance with low-carbon objectives.

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References

- [1] Fahimnia B, Sarkis J, Davarzani H. Green supply chain management: A review of the state of the art and future research directions. *International Journal of Production Economics*, 2015, 162: 101-114.
- [2] Benjaafar S, Yanzhi D, Taylor T. Carbon footprint and the management of supply chains: Insights from simple models. *IEEE Transactions on Automation Science and Engineering*, 2013, 10(4): 995-1008.
- [3] Daskin M S, Coullard C R, Shen Z J M. An inventory-location model: Formulation, solution algorithm and computational results. *Annals of Operations Research*, 2002, 110 (1-4): 83-106.
- [4] Rezapour S, Farahani R Z, Drezner Z. Strategic design of a green supply chain network with a risk averse perspective. *International Journal of Production Economics*, 2017, 183: 174-190.
- [5] Seyedkolaei A A, Nasseri S H. Facilities location in the supply chain network using an iterated local search algorithm. *Sustainability*, 2023, 15(6): 4872.
- [6] Jiang W X, Xiao Y, Guo H, et al. Location Selection of Logistics Distribution Center Based on P-Median Algorithm. *Logistics Technology*, 2022, 45(11): 21-24.
- [7] Govindan K, Ramezani M, Rostami B. Robust cross-docking location problem with uncertain supply and demand. *Decision Science Letters*, 2024, 13: 411-424.
- [8] Fahmy S A, Shalaby M, El-Kharbotly A. Dynamic multi-echelon facility location with inventory control and CODP positioning in supply chains. *Computers & Industrial Engineering*, 2024, 189: 109872.
- [9] Esmaeeli E, Ghasemi M. A hybrid GIS-clustering and metaheuristic optimization for cross-dock location problem in international logistics. *Computers & Industrial Engineering*, 2024, 189: 109215.
- [10] Zhang M, Yang C, Yang J. Location-Allocation Model of Low-Carbon Supply Chain Considering Carbon Emission. *Journal of Industrial Engineering and Engineering Management*, 2018, 32(3): 112-119.
- [11] Soleimani H, Govindan K, Saghafi S. Bi-objective closed-loop supply chain optimization considering environmental impacts. *Journal of Cleaner Production*, 2018, 189: 766-779.
- [12] Aksoy T, Demircioğlu H, Kahraman C. Multi-objective sustainable supply chain design under fuzzy uncertainty. *Journal of Cleaner Production*, 2020, 277: 124352.