Optimization Design of Automotive Parts Logistics Network Based on Facility Location-Routing

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Abstract: To address inefficiencies in Company X's automotive parts logistics network—caused by the rapid expansion and geographic dispersion of its suppliers (371 in East China, with uneven spatial distribution: concentrated in the Yangtze River Delta, scattered in northern Jiangsu/southern Zhejiang, and significant supply volume gaps) and the inherent limitations of the existing two-stage (supplier-central distribution center) structure—this study proposes a three-stage optimization framework (supplier-distribution center- central distribution center) by adding distribution centers to reduce costs and improve efficiency. Focusing on the East China network, the methodology is systematic: Firstly, K-means clustering was applied to analyze 371 suppliers, with 10 iterations identifying 6 candidate distribution centers (1 excluded for proximity to the central distribution center); Secondly, a linear programming model integrating fixed (distribution center), transportation, and transshipment costs is built to minimize total logistics expenses; Thirdly, a genetic algorithm optimizes milk-run routes to cut trip frequency. Empirical results show significant improvements: the optimized network selects Wuxi Huishan K1 (Fengwu Intelligent Manufacturing Park) and Shanghai Anting J1 (central distribution center) as collaborative nodes, restricts delivery radius to ≤300 km (down from over 500 km), saves 25,481 yuan in annual transportation costs, eases the original hub's load, and enhances vehicle scheduling efficiency. This study contributes threefold: (1) a "clustering-selection + model optimization" framework for supplier dispersion; (2) a cost-driven location model validated via sensitivity analysis of fixed/transshipment/transportation costs; (3) practical verification via Company X's case, providing references for similar automotive parts enterprises.

Keywords: Automotive Parts Logistics; Distribution Center Location; Location Decision-Making; Network Optimization

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1 Introduction

Amid the ongoing global transformations in the automotive industry and the rapid rise of new energy vehicles, the importance of automotive parts logistics has become increasingly apparent as a crucial link for efficient operation in the automotive manufacturing industry [1]. Automotive parts are characterized by a large variety, complex supply chains, and stringent transportation requirements. The efficiency of the logistics network directly influences the continuity of vehicle production and delivery schedules. As Company X expands its business scale, the number of suppliers and their geographic dispersion have increased, gradually exposing the limitations of the original two-stage logistics network (supplier-distribution center). A single central distribution center is unable to effectively cover long-distance suppliers, resulting in an excessively large delivery radius, high transportation costs, and a lack

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of logistical timeliness, severely restricting the overall effectiveness of the supply chain [2].

As the core link of automotive manufacturing, the efficient operation of parts logistics relies heavily on scientific network layout. The key issues currently faced by Company X include uneven supplier distribution. The supply chain is dense in the Yangtze River Delta region, but scattered in areas like northern Jiangsu and southern Zhejiang, with significant disparities in supply volumes. The current single distribution center, located in Shanghai, must serve a wide area including Jiangsu, Zhejiang, and Anhui. Some suppliers have a one-way pick-up distance exceeding 500 kilometers, which not only increases transportation costs but also results in delivery delays, negatively affecting downstream production plans. In this context, the existing two-stage logistics network is no longer sufficient for business development, and the introduction of a three-stage logistics network (supplier-distribution center-distribution hub) with additional distribution centers to optimize resource allocation becomes a key solution to improving logistics efficiency [3].

This paper takes the logistics network of X Company in East China as the research object. Aiming at the problems of wide supplier distribution and low distribution efficiency, it proposes to screen alternative distribution centers through the K-means algorithm, and construct a linear programming location model with the goal of minimizing costs and maximizing services and a milk-run model for distribution center path optimization to carry out quantitative analysis on alternative schemes. The research aims to optimize the logistics network structure through the rational location of distribution centers, reduce transportation costs, and improve the supply chain response speed, providing theoretical and practical references for the logistics network optimization of X Company and similar enterprises.

The full text is structured as follows: Chapter 2 reviews relevant domestic and foreign research, sorting out the theories and methods of distribution center location; Chapter 3 constructs the mathematical model of distribution center location and the milk-run pickup model, including model assumptions, parameter definitions, and constraint conditions; Chapter 4 combines the actual data of Company X to verify the effectiveness of the model through empirical analysis and derive the optimal location scheme; Chapter 5 summarizes the research conclusions and proposes future research directions.

2 Literature Review

The field of logistics network design has attracted significant research attention, with numerous studies focused on optimizing supply chain and logistics systems in various industries. Scholars have explored the problem from different perspectives, including cost minimization, service efficiency maximization, and route optimization.

Despite these advances, three gaps persist: (1) candidate site generation often lacks scientific support and assumes known alternatives, failing to accommodate dynamic supplier growth; (2) multi-cost coordination remains underexplored, with insufficient quantification of interactions among fixed, transportation, and transshipment costs; and (3) existing routing models seldom account for milk-run pickups, primarily addressing direct shipment scenarios. To address these gaps, this study focuses on Company X’s East China network, using K-means to generate candidate centers, building a linear programming model with multi-cost and radius constraints, and introducing a genetic algorithm-based milk-run optimization to integrate location and routing decisions for a robust, applicable logistics solution.

Scholars have proposed various theories and algorithms for location problems, focusing on model optimization, handling uncertainty, and enhancing efficiency. Xu et al. introduced the wolf pack algorithm by transforming the aggregation step size from deterministic to stochastic, improving global search capability [4, 5]. Szczepański et al. emphasized the need to combine mathematical models with sensitivity testing using Flexsim to assess robustness [6]. Lai proposed the MLDLP model for two-level facility location, integrating AHP and simplified swarm optimization to maximize facility utilization [7]. Ji et al. used a particle swarm optimization-based model to handle non-linear constraints, extending the applicability of traditional linear programming [8]. Majhi reviewed electric vehicle charging station location issues, offering methodological insights transferable to automotive parts networks [9]. Fazayeli explored time-window and fuzzy-demand constraints in multimodal networks using a two-part genetic algorithm [10]. Wu addressed the k-level soft capacity facility location problem with a dual-factor approximation approach [11]. He utilized grey prediction (1,1) and immune algorithms to optimize cold chain center sites, incorporating spoilage and time penalties [12]. Huang introduced satisfaction functions for time and quality into a fresh product delivery path model, solving it with an adaptive large neighborhood search algorithm [13].

In automotive logistics, studies have focused on supply chain coordination, cost control, and network adaptability. Yaobao et al. applied particle swarm optimization to warehouse siting considering transport and fixed costs [14-16]. Bahrami optimized storage strategies for small-to-medium parts manufacturers using VBA, improving picking time and space use [17, 18]. Mao proposed the MRPPL model to solve milk-run pickup problems, verifying the synergy between routing and layout [19-21]. Xi enhanced inventory demand forecasting with moving average improvements, supporting restocking decisions [22]. Zahiri addressed uncertainty in hazardous materials transport networks with heuristics adaptable to automotive logistics [23]. Li built an integrated carbon transaction-based LRIP model for cold chains, optimized with NSGA-II [24]. Diabat applied Lagrangian relaxation to joint inventory-location problems for strategic-tactical planning [25-27]. Zhang and Yu developed models and algorithms to improve cold chain and waste depot logistics under low-carbon or regional independence goals [28, 29]. Qiu used branch-and-price for carbon-constrained production-routing decisions [30].

In summary, research on the location problem of distribution centers in the automotive parts field is developing towards maturity. Through comprehensive collation and summary of research literature on distribution center location, many scholars have constructed numerous mathematical models and optimization algorithms, which are supported by numerous practical cases and mathematical calculations [31]. However, several key issues remain unresolved. Firstly, the generation logic for candidate distribution centers is insufficient. Most studies assume predefined candidate locations, yet they lack a scientifically based screening method derived from supplier distribution patterns. This leads to excessive reliance on experiential judgment during model input, making it difficult to adapt to the dynamic growth of automotive parts suppliers in real-world scenarios. Moreover, there is inadequate analysis of the interplay among multiple cost factors. The combined effects of fixed costs, transportation costs, and transshipment/handling costs have not been sufficiently quantified [32]. Specifically, when an increase in the number of suppliers necessitates an expanded distribution radius, how to strategically locate facilities to balance cost against time constraints requires deeper investigation. Additionally, existing routing optimization research primarily focuses on direct shipping from distribution centers, with limited consideration for milk run strategies. To address these challenges, this paper takes the East China network of Company X as its focus. We employ the K-means clustering algorithm to generate scientifically grounded candidate distribution centers. A linear programming model is then constructed that integrates multiple cost factors and distribution radius constraints. Furthermore, a dedicated milk run model for distribution centers is developed. The genetic algorithm is applied to optimize the milk run collection routes. The integrated approach aims to achieve synergistic optimization of facility location and transportation routing decisions. Ultimately, this research seeks to provide an integrated solution for automotive parts logistics network design, characterized by both theoretical robustness and practical applicability [33, 34].

3 Mathematical Modeling of Distribution Centers

3.1 Construction of the Location Model

3.1.1 Model Assumptions

The location model is built on the following assumptions:

The logistics network consists of three entities: automotive parts suppliers, distribution centers, and the central distribution center.

Candidate distribution centers are considered as discrete points.

There are no restrictions on the flow capacity through distribution centers or within storage.

The distance between suppliers and distribution centers, and between distribution centers and the central distribution center milk-run, is considered as straight-line (Euclidean) distance.

Unit freight rates and vehicle speeds are uniform for both the pickup and delivery stages.

Automotive parts are uniformly packaged and measured in cubic meters.

3.1.2 Parameter Definitions

The symbolic descriptions of the model are shown in Table 1.

Table 1 Parameter Definitions

Symbol	Meaning
F_j	Fixed cost of distribution center j
Z_j	0-1 decision variable, 1 if candidate distribution center j is selected, 0 otherwise
N	Number of candidate distribution centers
w_1	Unit freight rate from supplier to distribution center during transportation
w_2	Unit freight rate from distribution center to central distribution center during transportation
d_{ij}	Distance from supplier i to distribution center j
x_{ij}	Freight volume from supplier i to distribution center j
M	Number of suppliers
K	Number of central distribution centers
d_{jk}	Distance from distribution center j to central distribution center k
x_{jk}	Freight volume from distribution center j to central distribution center k
P_j	Unit transfer cost of goods at distribution center j
M_1	Unit stockout cost, an infinite large number
C_1	Stockout cost caused by excessively long delivery distance making delivery impossible
C_2	Fixed cost of constructing a distribution center
C_3	Transportation cost from supplier to distribution center
C_4	Transportation cost from distribution center to central distribution center
C_5	Transfer cost of distribution center
S_i	Supply volume of the i-th parts supplier
Q_k	Demand volume of the k-th central distribution center
β_{ki}	Whether vehicle k picks up goods from supplier i
∂_{ijk}	Decision on whether vehicle k undertakes transportation from supplier i to distribution center j

3.1.3 Construction of the Location Model

The basic model formula for distribution center location is as follows:

$$\text{Min } Z=C_1+C_2+C_3+C_4+C_5 \quad (1)$$

$$C_2=M_1\sum_{k=1}^{K}(Q_k-\sum_{j=1}^{N}x_{jk}) \quad (2)$$

$$C_2=\sum_{j=1}^{N}F_jZ_j \quad (3)$$

$$C_3=\sum_{i=1}^{M}\sum_{j=1}^{N}w_1d_{ij}x_{ij} \quad (4)$$

$$C_4=\sum_{j=1}^{N}\sum_{k=1}^{K}w_2d_{jk}x_{jk} \quad (5)$$

$$C_5=\sum_{i=1}^{M}\sum_{j=1}^{N}P_jx_{ij} \quad (6)$$

Formula (1) represents the objective function to minimize the location cost of automotive parts logistics distribution centers. Formula (2) represents the stockout cost, which is the difference between the total freight volume delivered by N distribution centers and the demand volume of the central distribution center. Since the production plan of the factory is continuous, to ensure the smooth implementation of the plan, no stockout is allowed, so the unit stockout cost is M_1. Formula (3) represents the fixed cost of constructing a distribution center. Formulas (4) and (5) represent the transportation cost from automotive parts supplier i to distribution center j and the transportation cost from distribution center j to central distribution center k, respectively. Formula (6) represents the transfer cost, which is the product of the unit transfer fee and the transfer volume.

The total objective function is as follows:

$$\text{Min Z} = M_1\sum_{k=1}^{K}(Q_k-\sum_{j=1}^{N}x_{jk})+\sum_{j=1}^{N}F_jZ_j+\sum_{i=1}^{M}\sum_{j=1}^{N}w_1d_{ij}x_{ij}Z_j+\sum_{j=1}^{N}\sum_{k=1}^{Z}w_2d_{jk}x_{jk}Z_j+\sum_{i=1}^{M}\sum_{j=1}^{N}P_jx_{ij}Z_j \quad (7)$$

The constraint conditions of the distribution center location model are as follows:

$$\sum_{j=1}^{N}Z_j \geq 1\ (j=1,2,3,\ldots,N) \quad (8)$$

$$Z_j \in \{0,1\}(j=1,2,3,\ldots,N) \quad (9)$$

$$\sum_{i=1}^{M}\sum_{j=1}^{N}x_{ij}Z_j=\sum_{j=1}^{N}\sum_{k=1}^{Z}x_{jk}Z_j \quad (10)$$

$$\sum_{i=1}^{M}\sum_{j=1}^{N}x_{ij}Z_j \leq S_i \quad (11)$$

$$\sum_{j=1}^{N}\sum_{k=1}^{Z}x_{jk}Z_j \leq Q_k \quad (12)$$

$$0 \leq d_{ij} \leq 300, 0 \leq d_{jk} \leq 300 \quad (13)$$

$$0 \leq x_{ij}, 0 \leq x_{jk} \quad (14)$$

Formula (8) indicates that at least one distribution center is selected, where $Z_j=1$ means selecting distribution center j, and $Z_j=0$ means not selecting distribution center j. Formula (9) indicates that distribution centers do not produce products but only undertake transfer functions. Formula (10) indicates that the supply volume Si of automotive parts suppliers is greater than or equal to the inflow volume of distribution centers. Formula (11) indicates that the demand volume Q_k of the central distribution center is greater than or equal to the outflow volume of distribution centers. Formula (12) represents the delivery distance constraint, restricting the delivery radius of each distribution center and central distribution center to within 300 km. Formula (14) represents the variable constraint that the transportation volume from each supplier to the distribution center and from each supplier to the central distribution center cannot be negative.

3.2 Construction of Distribution Center Milk-Run Model

The basic model formula for milk-run pickup at distribution centers is as follows [9]:

$$Min\ distance = \sum_k^a \sum_i^m \sum_j^n d_{ij}\, \partial_{ijk} \tag{15}$$

Formula (15) is the objective function to minimize the shortest distance, where d_{ij} is the distance from supplier i to distribution center j, and ∂_{ijk} is a decision 0-1 variable. ∂_{ijk}=1 means that decision k designates vehicle k to undertake transportation from supplier i to distribution center j, and ∂_{ijk}=0 means that decision k does not designate vehicle k to undertake transportation from supplier i to distribution center j, with a total of a vehicles.

The constraint conditions of the distribution center milk-run model are as follows:

$$\sum_i^m xi\beta_{ki} \le D \tag{16}$$

$$\sum_{k=1}^a \beta_{ki} = 1 \tag{17}$$

$$\sum_{i=0}^m \partial_{ijk} = \beta_{kj} \tag{18}$$

$$\sum_{j=0}^n \partial_{ijk} = \beta_{ki} \tag{19}$$

$$\sum_i^m x_{i+1}\beta_{ki} - \sum_i^m x_i\beta_{ki} = x_{i+1\mathrm{j}}\beta_{ki} \tag{20}$$

Equation (16) indicates that the transportation volume undertaken by vehicle k must be less than or equal to the loading capacity D of the vehicle, where β_{ki} is a decision variable. $\beta_{ki} = 1$ means that vehicle k picks up goods from supplier i, and $\beta_{ki} = 0$ means that vehicle k does not pick up goods from supplier i. Equation (17) indicates that supplier i can only be picked up by one vehicle. Equations (18) and (19) indicate that each supplier i is picked up by one vehicle. Equation (20) represents flow conservation, meaning that the goods picked up from the supplier each time should equal the goods from the supplier to the distribution center.

4 Empirical Analysis and Model Results

4.1 Analysis of Company X's Current Situation

4.1.1 X Existing Problems of Company X

Through the collection and collation of data on automotive parts suppliers of Company X, due to the unique geographical location and economic development level of East China, this paper takes East China as the analysis region for the case of Company X. According to data collection and collation, there are 371 automotive parts suppliers in East China, among which a supplier in Cixi, Zhejiang Province, has the highest annual supply volume of 37,874.39 m^3. A supplier in Ningbo, Zhejiang Province, has an annual supply volume of only 0.02 m^3, revealing significant uneven supply capacity among suppliers within East China. Meanwhile, scatter plots show that suppliers in East China are mainly concentrated in the Yangtze River Delta, while northern Jiangsu and southern Zhejiang have scattered suppliers, indicating that Company X faces large gaps in supply volume and scattered distribution. The specific supplier distribution is shown in Figure 1.

Taking East China as an example, Company X serves more than 1,000 suppliers, with over 300 located in East China. However, there is only one central distribution center in the region, located at No. 185 Yuandalu, Anting Town, Jiading District, Shanghai, responsible for the milk-run pickup tasks in the entire East China region, with a service scope covering the four provinces of Jiangsu, Zhejiang, Shanghai, and Anhui. The farthest one-way pickup distance from this center exceeds 500 kilometers, which not only significantly increases pickup transportation costs but also has a great impact on the timeliness of logistics distribution.

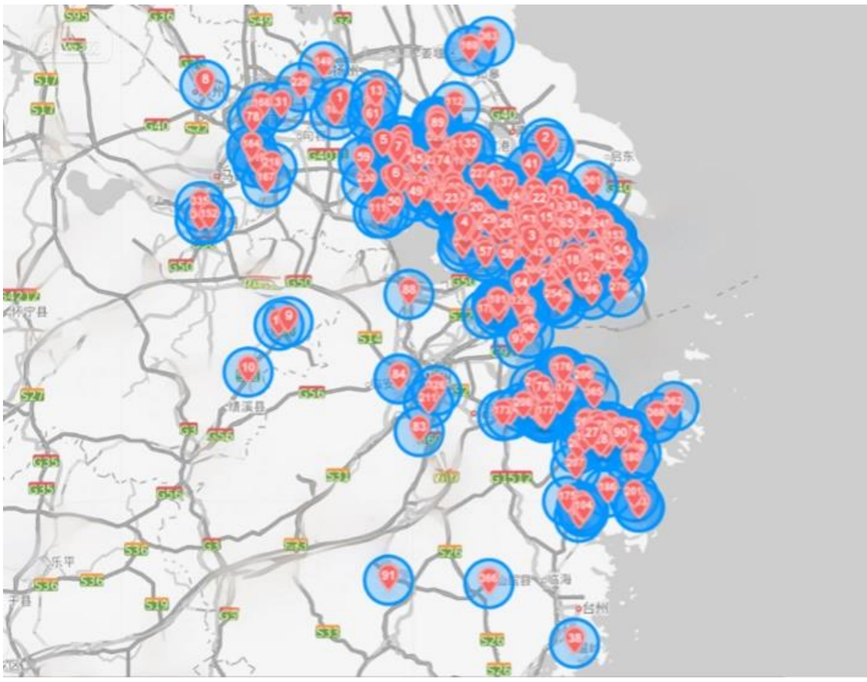

Figure 1 Distribution of Suppliers

4.1.2 Optimization of Company X's Logistics Network

Company X mainly adopts three types of off-site logistics pickup models, namely the ABC model, as shown in Figure 2.

Model A uses a point-to-point direct delivery method, suitable for situations where suppliers have a large quantity of goods and can achieve direct full-vehicle delivery. Model B is an end-to-end distribution system, mainly targeting situations with small goods quantities, numerous suppliers, long transportation distances, and inability to be fully loaded. It collects goods to off-site distribution centers or bases through milk-run operations, then distributes them to specific destinations through long-distance transportation and regional distribution networks. Model C is called the milk-run direct delivery model, suitable for medium-scale goods quantities and the number of suppliers. Through rotating pickup activities from multiple suppliers, it gathers enough goods to meet the demand for full-vehicle delivery before conducting long-distance direct transportation to the target location.

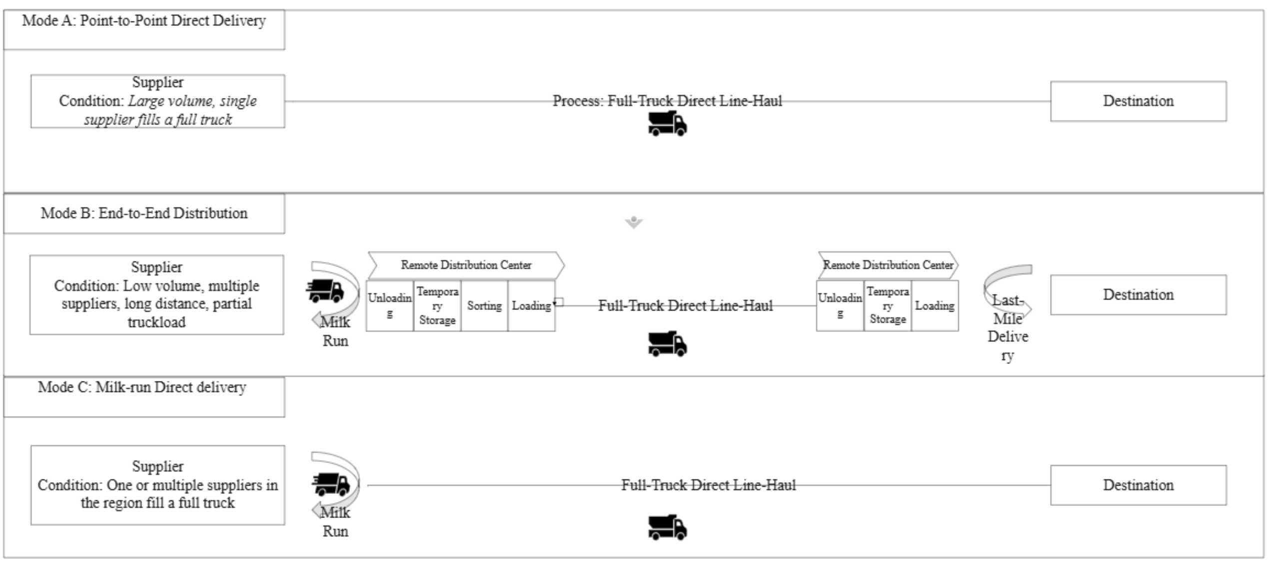

Figure 2 The Pick - up Mode of Company X

After in-depth analysis and comprehensive planning of the existing logistics network of Company X, this paper first transforms the original two-tier logistics network structure (i.e., supplier-to-central distribution center model) into a more efficient three-tier logistics network structure (first transporting from suppliers to newly established distribution centers, then distributing goods from distribution centers to central distribution centers), as shown in Figure 3.

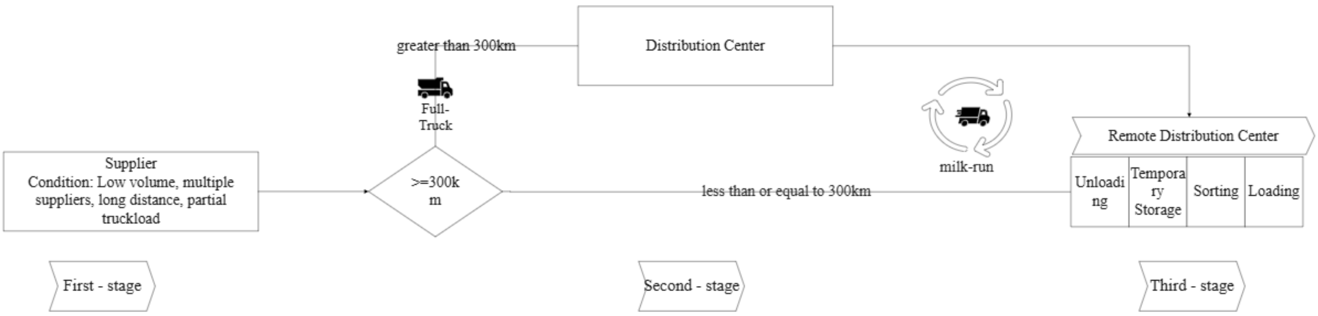

Figure 3 Three - stage Logistics network design

4.2 Data Analysis for Logistics Network Optimization of Company X

4.2.1 Determination of Candidate Distribution Centers

This paper uses the k-means clustering algorithm to cluster 371 suppliers, and through ten iterations, finally selects six candidate distribution center addresses and one central distribution center (the central distribution center also serves as a distribution center). Since candidate distribution center K2 is only 0.14 kilometers away from central distribution center J1, it is ignored in actual model calculations. The specific distribution is shown in Figure 4.

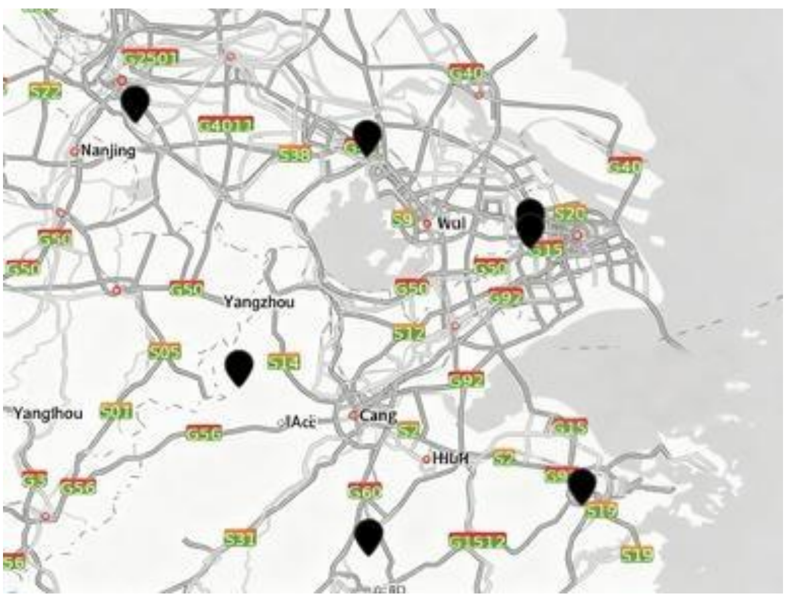

Figure 4 Map of Alternative Distribution Centers

4.2.2 Relevant Data Preparation

To facilitate distance calculation, we converted the distance positions of each supplier into latitude and longitude positions, as shown in Table 2. The latitude and longitude positions of the central distribution center in East China, located at No. 185 Yuandalu, Anting Town, Jiading District, Shanghai, are shown in Table 3. To convert latitude and longitude into specific distances, assuming the earth is a perfect sphere, this paper uses the Haversine formula to calculate the straight-line distance between two points. Convert latitude and longitude into radians and use the properties of trigonometric functions for calculation to obtain the straight-line distance between two points. Other relevant parameters are shown in Table 4.

Table 2 Locations of Candidate Distribution Centers

Serial Number	Automotive Parts Supplier	Longitude E	Latitude N
K1	Fengwu Intelligent Manufacturing Park, Huishan District, Wuxi City, Jiangsu Province	120.2318	31.7326
K2	X458 (Zhaozhong Highway), Qingpu District, Shanghai	121.1895	31.2444
K3	No. 181-a, Xinzhuang Road, Haishu District, Ningbo City, Zhejiang Province	121.4956	29.8715
K4	Wangkong Line, Anji County, Huzhou City, Zhejiang Province	119.4801	30.5115
K5	Tianmo Line, Jiangning District, Nanjing City, Jiangsu Province	118.8745	31.9140
K6	Zhuji City, Shaoxing City, Zhejiang Province	120.2485	29.5864
K7	No. 185 Yuandalu, Anting Town, Jiading District, Shanghai	121.1900	31.3200

Table 3 Location of the central distribution center

Serial Number	Central Distribution Center	Longitude E	Latitude N
J1	No. 185 Yuandalu, Anting Town, Jiading District, Shanghai	121.19	31.32

Table 4 Assignment of Other Parameters

Parameter Symbol	Location Parameter	Parameter Value
w_1	Unit freight rate from supplier to distribution center	¥2.5 /(m^3·km)
w_2	Unit freight rate from distribution center to central distribution center	¥1 /(m^3·km)
P_j	Transfer cost	¥0.2 /m^3
F_j	Fixed cost	¥5000000

4.2.3 Solution of the Location Model

Importing the data into the automotive parts logistics distribution center location model and using the LINGO solver for multiple iterations, the global optimal solution is finally obtained. The location result is selecting K1 and central distribution center J1 from the seven candidate distribution centers K1, K2, K3,..., K7 as the final location centers, with the minimum logistics total cost Z being 8,386,118 yuan. Finally, K1 distribution center: Fengwu Intelligent Manufacturing Park, Huishan District, Wuxi City, Jiangsu Province, and central distribution center J1: No. 185 Yuandalu, Anting Town, Jiading District, Shanghai, are selected. The distribution center selection is shown in Figure 5.

Figure 5 Final Location of Distribution Centers

4.2.4 Solution of the Milk-Run Model

Importing the data into the automotive parts logistics distribution center milk-run model, this paper assumes that the loading volume of a medium-sized automotive parts transport truck is 40 m^3, without restricting the number of vehicles in the distribution center. Milk-run pickup is carried out between each automotive parts distribution center and suppliers, where suppliers meeting or exceeding 40 m^3 are selected for direct delivery without considering milk-run pickup. Using Matlab to call the genetic algorithm for multiple iterations, the optimal milk-run pickup route planning is finally obtained as follows:

K1 distribution center: Fengwu Intelligent Manufacturing Park, Huishan District, Wuxi City, Jiangsu Province, are shown in Figure 6:

Delivery Route 1: K1-I6-I215-I10-K1
Delivery Route 2: K1-I75-K1
Delivery Route 3: K1-I35-I112-I125-K1
Delivery Route 4: K1-I79-I115-I13-I232-K1
Delivery Route 5: K1-I329-I340-K1
Delivery Route 6: K1-I337-K1
Delivery Route 7: K1-I132-I67-I357-K1
Delivery Route 8: K1-I74-K1

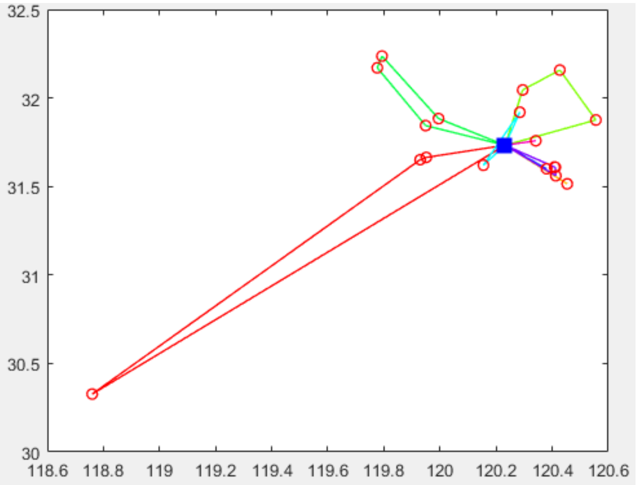

Figure 6 Optimal Routes for K1 Distribution Center

J1 central distribution center: No. 185 Yuandalu, Anting Town, Jiading District, Shanghai, are shown in Figure 7:

Delivery Route 1: J1-I51-J1
Delivery Route 2: J1-I71-J1
Delivery Route 3: J1-I359-I241-I87-I276-J1
Delivery Route 4: J1-I158-I282-I253-J1
Delivery Route 5: J1-I204-I207-I214-356-I176-J1
Delivery Route 6: J1-I86-I27-I311-J1
Delivery Route 7: J1-I53-I221-I330-I103-I136-I142-I265-J1
Delivery Route 8: J1-I351-I155-I227-I2-229-J1
Delivery Route 9: J1-I301-J1

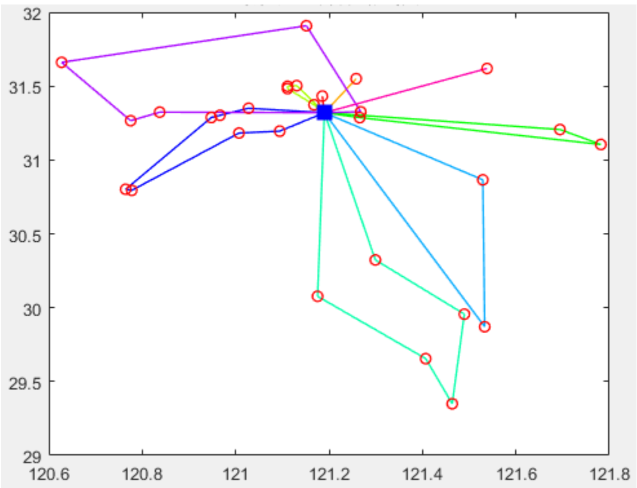

Figure 7 Optimal distribution routes for J1 central distribution center

4.2.4 Comparison and Data Analysis of Solution Results

In terms of total cost, through quantitative analysis and quantification of relevant factors, the minimum cost after constructing the distribution center is 8,386,118 yuan. The establishment of the distribution center effectively alleviates the pressure on vehicle and route arrangement of the original central distribution center in milk-run pickup. In the original logistics network of Company X in East China, the distribution tasks undertaken by the Shanghai central distribution center covered Jiangsu, Zhejiang, Shanghai, Fujian, and even parts of Zhengzhou and Anhui, with the farthest delivery radius exceeding 300 kilometers, leading to high transportation costs (annual transportation cost of 3,638,599 yuan) and low efficiency.

After optimization, the K1 distribution center (Huishan District, Wuxi) and J1 central distribution center were screened through the location model to operate collaboratively, controlling the delivery radius of all suppliers within 300 kilometers. K1 is mainly responsible for the milk-run pickup of scattered suppliers in Jiangsu and Anhui regions, sharing the transfer pressure of J1. The transportation cost was reduced to 3,386,118 yuan, saving 25,481 yuan annually. In addition, the delivery time was shortened, and the vehicle scheduling efficiency was improved, verifying the effectiveness of the two-stage optimization of "location-routing" in enhancing the efficiency of the logistics network.

Table 5 Influence of Fixed Costs on Distribution Center Selection

NO	F_i	DC	Transport Volume
1	5000000	K1	125978.1
		J1	793782
2	5	K1	87652.96
		K2	208457.2
		K3	5243.684
		K4	36880.14
		K5	12282.37
		J1	569243.8
3	50	K1	87652.96
		K2	208457.2
		K3	5243.684
		K4	36880.14
		K5	12282.37
		J1	569243.8
4	5000	K1	89097.95
		K4	36880.14
		J1	793782
5	50000	K1	89097.95
		K4	36880.14
		J1	793782
6	500000	K1	125978.1
		J1	793782
7	500000000	K1	125978.1
		J1	793782

As a core economic parameter for distribution center location, changes in fixed costs directly impact facility layout and transportation volume allocation strategies. Table 5 reveals:

1. Decision robustness under significant fixed cost increases: When fixed costs expanded 100-fold, the model consistently selected K1 distribution center, verifying that transportation cost savings from K1's locational advantages sufficiently offset high fixed cost investments and validating the model's effectiveness. 2. Decision divergence under significant fixed cost reductions: In extreme scenarios where fixed costs were compressed to 5–50 yuan, the model exhibited a multi-center decentralized layout (opening 6 centers) with fragmented transportation volume allocation. Although theoretically reducing transportation distances, this ignores real-world construction costs and holds only theoretical significance. It clearly reveals the trade-off between fixed and transportation costs: lowering fixed costs can increase facility quantity to optimize transportation efficiency, but excessive pursuit of dense layouts leads to resource waste; conversely, excessively high fixed costs suppress facility construction and intensify transportation pressure. 3. Cost response mechanism for transportation volume allocation: When Fj increases, transportation volume concentrates on efficient nodes (K1, J1) (No. 7), spreading fixed costs through scale transportation; when Fj decreases, transportation volume disperses to more nodes (No. 2), reducing variable costs by shortening transportation distances.

The study shows that fixed costs drive a positive correlation with transportation volume concentration. The K1 location in the benchmark scenario achieves an optimal trade-off between facility construction investment and transportation efficiency through quantitative balancing, providing cost-sensitive decision-making basis for Company X and similar enterprises. Within the fixed cost range of 5–10 million yuan, the K1+J1 dual-center model is a feasible solution balancing economy and network robustness.

Table 6 Influence of Transfer Costs on Distribution Center Selection

No	P_i	DC	Transport Volume
1	0.2	K1	125978.1
		J1	793782
2	2	K1	125978.1
		J1	793782
3	20	K1	125978.1
		J1	793782
4	2000	K1	87652.96
		K2	220079.5
		K3	5903.703
		K4	36880.14
		J1	569243.8
5	0.02	K1	125978.1
		J1	793782
6	0.002	K1	125978.1

As the unit cargo handling cost of distribution centers, transfer cost is a core parameter affecting the economy of the distribution model. Table 6 shows that its numerical changes significantly impact the layout of distribution centers and the allocation of transportation volume through the cost trade-off mechanism between "transfer and transportation".

1. In scenarios with low transfer costs, especially in the extreme low transfer cost case (No. 6), the economy of the distribution model is highlighted. The decision-making remains stable with the selection of J1 and K1, and the locational advantages still dominate the site selection, verifying the model's priority consideration for fixed costs and transportation efficiency. 2. At moderate costs (No. 2-3), constrained by the delivery radius (≤300 km), the model still maintains the K1+J1 layout, ensuring the timeliness of production plans by sacrificing part of the trans-

fer cost. 3. In the case of extreme costs (No. 4), when the transfer cost per container reaches as high as 2,000 yuan, the total transfer cost (transfer + transportation) exceeds the direct transportation cost, forcing the model to reduce transfer links and choose short-distance direct delivery or disperse to centers with low transfer costs. However, this value obviously exceeds the actual situation, reflecting the forced compromise in the trade-off between "transfer cost and transportation cost". There is a significant linkage mechanism between transfer cost and transportation cost: when (Pj < 200) yuan/m^3, the economy of transfer links is remarkable, and the model preferentially selects the distribution model; when (Pj > 200) yuan/m^3, it turns to "regional direct delivery" to reduce transfer expenses, and the transportation volume allocation presents a stepwise response characteristic of "stable in the low-sensitivity interval and dispersed in the high-sensitivity interval".

Table 7 Influence of Transportation Costs on Distribution Center Selection

No	w1	w2	DC	Transport Volume
1	1	1	J1	919760.1
2	1.5	1	K1	99099.59
			J1	820660.5
3	2.5	1	K1	125978.1
			J1	793782
4	5	1	K1	125978.1
			J1	793782
5	10	1	K1	194086
			J1	725674.1
6	15	1	K1	194599.8
			J1	725160.2
7	20	1	K1	195303.4
			J1	724456.7
8	2.5	0.5	K1	192768.9
			J1	726991.2
9	2.5	2	K1	88272.68
			J1	831487.4
10	2.5	3	J1	919760.1

As a core variable cost, transportation cost affects distribution center layout and transport volume allocation via dual freight rates: w1 (supplier to DC) and w2 (DC to central DC). Table 7 shows:

Supplier-side rate (w1) dictates facility density: Low w1 (≤2.5 yuan/m^3 ·km): Model prefers single-center direct delivery (No1) or regional distribution combined with direct delivery (No2) to cut costs by shortening distances. High w1 (≥5 yuan/m^3 ·km): Facilities concentrate at core nodes (K1+J1), with K1's transport share rising from 13.7% to 27% as w1 increases, balancing long-distance cost avoidance and scale effects.

Trunk rate (w2) regulates transfer scale: Low w2 (≤1 yuan/m^3 ·km): Regional distribution is enhanced (e.g., K1's volume hits 26.5% in No8) via low-cost trunks. High w2 (≥2 yuan/m^3 ·km): Volume shifts back to J1 direct delivery (K1's volume drops to 9.5% in No2), reflecting a ~1 yuan/m^3 ·km threshold for trunk cost impact on transfer decisions..

5 Conclusions

This study addresses the problems of scattered supplier distribution and low distribution efficiency in the East China automotive parts logistics network of Company X by constructing a three-tier logistics network. Through the K-means algorithm, candidate distribution centers were screened, and a linear programming model was used to determine the collaborative operation of a new distribution center in Huishan District, Wuxi (K1) and the Shanghai central distribution center (J1). The study further established a milk-run model for distribution centers and optimized pickup routes based on a genetic algorithm, controlling the supplier delivery radius within 300 kilometers, significantly shortening transportation distances, and reducing transportation costs by 25,481 yuan.

The "clustering screening-model optimization" framework constructed in this study provides a methodological reference for complex logistics network design, and the application of the milk-run model enhances the scientificity and economy of route planning. Future research can further integrate dynamic traffic data and green logistics indicators to explore optimization solutions for the special transportation needs of new energy automotive parts, promoting the intelligent and sustainable development of logistics networks.

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