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Research on Optimization of Fresh Cold Chain Logistics Distribution Route in Nanchong Considering Green Costs

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Abstract: In response to the practical needs of solving the distribution route problem in the fresh food cold chain logistics, this study adopts the ant colony algorithm to construct a distribution route selection strategy. By combining data analysis technology to mine key information such as customer demands, vehicle parameters, and distribution distances, and relying on the global optimization characteristics of the ant colony algorithm, an optimal planning scheme for Nanchong's logistics distribution routes with green costs as the key consideration is formulated. This scheme effectively reduces transportation costs and improves transportation efficiency.

Keywords: Cold chain logistics; Route optimization; Ant colony algorithm; Green costs.

1. Introduction

With the continuous improvement of national income and consumption levels, the demand for fresh products in China has increased significantly, putting forward higher requirements for the timeliness, safety, and greening of cold chain logistics. To ensure the freshness of products, the cold chain distribution process must rely on refrigeration equipment to maintain a low-temperature transportation environment. However, cold chain distribution not only increases fuel consumption but also exacerbates environmental pollution. In addition, the unreasonable planning of cold chain vehicle distribution paths will lead to delayed deliveries, increased product spoilage, and diminished customer satisfaction. Therefore, achieving timely and efficient distribution of refrigerated fresh goods while balancing environmental costs has become a focus of widespread attention in the industry.

Kuo, Y used the simulated annealing algorithm to optimize routes with the objectives of minimizing vehicle fuel consumption, shortest travel distance, and shortest travel time [1]. Bektas, T et al. constructed a multi-objective vehicle routing model integrating vehicle travel time, distance, and transportation costs, demonstrating that route optimization can effectively reduce carbon emissions [2]. Hariga et al. focused on multi-level supply chains, delving into how to minimize transportation costs and carbon emissions while ensuring sustainability [3]. Babagolzadeh et al. established a two-stage stochastic model to analyze the impact of cold chain logistics on carbon emissions under carbon tax policies and demand uncertainty [4]. Min Cong found through case analysis that considering carbon emissions can actually reduce total distribution costs, providing motivation for enterprises to practice green logistics [5]. Chen Yehong studied distribution route optimization based on a carbon emission assessment system [6]. Huang Xingxing et al. constructed a cold chain distribution route optimization model with carbon tax and carbon quota rules as important elements, while considering vehicle load capacity and time window constraints, to realize the optimization of fresh agricultural product distribution [7]. Feng Jie et al. conducted specialized research on relevant route issues targeting the actual scenario needs of homogeneous pure electric refrigerated trucks distributing fresh products to multiple customer points [8]. Yao Zhen et al. constructed a distribution route optimization model that considers soft time windows, customer satisfaction, and carbon emissions under the carbon tax system framework, solving the model through an improved genetic algorithm [9].

Existing research on constructing total cost optimization models mostly lacks the systematic integration of six key cost categories: fixed costs, transportation costs, cargo damage costs, refrigeration costs, disinfection costs, and carbon emission costs, usually focusing only on some of these factors. Therefore, grounded in contemporary developmental demands and adopting a green cost perspective, this study closely aligning with the characteristics of fresh produce, systematically incorporates all six cost elements for the first time. It constructs a mathematical model centered on minimizing total distribution costs, thereby addressing the shortcomings in cost factor integration found in existing literature while aligning closely with the sustainable development principles advocated by contemporary society.

2. Construction of Cold Chain Logistics Optimization Model Considering Green Costs

2.1. Problem Description

The optimization of fresh cold chain logistics transportation routes assumes that multiple customer demand points are served by vehicles dispatched from a single cold storage distribution center. The cold storage distribution center is equipped with multiple cold chain distribution vehicles of uniform specifications. After providing services to customers, the cold chain distribution vehicles return to the cold storage distribution center. Under the constraints of ensuring that the vehicle loading capacity meets requirements and customer cargo demands are satisfied, a cold chain logistics distribution route optimization model with optimal total distribution costs is constructed by integrating various distribution costs such as transportation, refrigeration, carbon emissions, fixed, disinfection, and cargo damage costs to find the optimal route arrangement.

2.2. Construction of Route Optimization Model

2.2.1. Green cost variables

(1) Transportation costs

The transportation costs of cold chain vehicles are primarily composed of fuel consumption expenses. An increase in vehicle transportation distance will directly lead to a linear rise in transportation costs.

Let F_1 be the transportation cost per unit distance of a cold chain distribution vehicle, d_{ij} be the driving distance between customer point i and customer point j, and X_{ij}^n be a binary variable indicating whether transportation vehicle n travels from customer point i to customer point j for distribution. If X_{ij}^n equals 1, vehicle n selects this route; otherwise, it does not. Then, the total transportation cost C_1 incurred by all cold chain distribution vehicles $N = \{1, \dots, n\}$ during the process is calculated as follows:

$$C_1 = \sum_1^N \sum_{i=1}^m \sum_{j=1}^m F_1 d_{ij} X_{ij}^n \quad (1)$$

(2) Refrigeration costs

Refrigeration costs refer to the total expenses incurred during the refrigeration process to achieve and maintain a certain low-temperature environment, primarily related to the cold chain vehicle transportation time. To comprehensively reflect the overall refrigeration costs, the costs incurred during transportation and unloading processes need to be evaluated and calculated separately. Let F_2 be the refrigeration cost per unit time of a cold chain distribution vehicle during driving, and T_{ij}^n be the time required for the cold chain distribution vehicle n to travel from customer point i to customer point j. Then, the refrigeration cost C_{21} during transportation is as follows:

$$C_{21} = \sum_1^N \sum_{i=1}^m \sum_{j=1}^m F_2 T_{ij}^n X_{ij}^n \quad (2)$$

LetF_3 be the refrigeration cost per unit time of a cold chain distribution vehicle when unloading goods, T_i^n be the service time (i.e., unloading time) of the cold chain transportation vehicle n for customer point i, and X_i^n be a variable indicating whether the cold chain distribution vehicle n serves customer point i. Then, the refrigeration cost C_{22} during unloading is:

$$C_{22} = \sum_1^N \sum_{i=1}^m \sum_{j=1}^m F_3 T_i^n X_i^n \quad (3)$$

Therefore, the total refrigeration cost C_2 is:

$$C_2 = C_{21} + C_{22} = \sum_1^N \sum_{i=1}^m \sum_{j=1}^m \left(F_2 T_{ij}^n X_{ij}^n + F_3 T_i^n X_i^n\right) \quad (4)$$

(3) Carbon emission costs

Carbon emission costs refer to the aggregate economic expenditures incurred by logistics enterprises throughout the entire fresh produce distribution chain due to carbon dioxide and other greenhouse gas emissions generated from consuming fuels, electricity, and other energy sources, or from using refrigerants [10]. Its core principle is to internalize the "environmental external costs", forcing enterprises to reduce carbon emissions in alignment with national low-carbon environmental policies and green development requirements.

The fuel consumption of refrigerated trucks primarily correlates with the vehicle's distribution distance and the load weight of fresh products [11]. Let Q be the curb weight of the cold chain distribution vehicle, W_1 be the fuel consumption per unit distance when the vehicle is unloaded, W_2 be the fuel consumption per unit distance when the vehicle is fully loaded. With load weight denoted as x, the fuel consumption per unit distance $W(x)$ can be expressed as:

$$W(x) = W_1 + \frac{W_2 - W_1}{Q} x \quad (5)$$

And Carbon emissions = Fuel consumption × Carbon dioxide emission factor. Let Q_{ij} be the weight of goods delivered between customer point i and customer point j, and K be the carbon dioxide emission factor. Then, the carbon emissions E_1 generated by the vehicle when traveling between customer points i and j can be expressed as:

$$E_1 = W(Q_{ij}) d_{ij} K \quad (6)$$

During distribution, the carbon dioxide emissions generated by refrigerants are related to the vehicle's cargo load, distribution distance, etc. Let L be the carbon dioxide emissions per unit distance of the refrigerant. Then, the emissions E_2 generated by refrigeration when the vehicle travels between customer points i and j can be expressed as:

$$E_2 = L d_{ij} Q_{ij} \quad (7)$$

The total carbon dioxide emissions generated during the distribution of cold chain trucks is $E = E_1 + E_2$. Let λ be the carbon tax, the total carbon emission cost C_3 incurred during fresh product distribution can be calculated using the carbon emission cost formula [12]: Carbon emission cost = Carbon tax × Carbon emissions

$$C_3 = \lambda E = \lambda(E_1 + E_2) = \lambda \sum_1^N \sum_{i=1}^m \sum_{j=1}^m d_{ij} X_{ij} \left[W(Q_{ij})K + L Q_{ij}\right] \quad (8)$$

2.2.2. Other cost variables

(1) Fixed costs

Fixed costs refer to costs that remain relatively stable over a given period and within a specific operational scope, unaffected by short-term fluctuations in business volume such as transportation mileage, delivery order volume, or loading capacity. Let F_4 be the fixed cost per cold chain distribution vehicle. Then, the fixed cost C_4 is:

$$C_4 = N F_4 \quad (9)$$

(2) Disinfection Costs

Disinfection costs refer to the total expenses invested by enterprises in the disinfection and sterilization links to ensure the hygiene and safety of goods and logistics links, reduce the risk of pathogen or pollutant transmission and infection, and meet consumers' demand for clean and safe shopping. Let F_5 be the disinfection cost per cold chain distribution vehicle and personnel, and F_6 be the inspection cost per unit of goods. Then, the disinfection cost C_5 is:

$$C_5 = \sum_1^N (F_5 + F_6) \quad (10)$$

(3) Cargo Damage Costs

Cargo damage costs refer to expenses incurred by logistics companies due to improper handling during pre-transportation disinfection operations, or damage and spoilage resulting from collisions and compression during transportation and loading/unloading that compromise product quality.

Let Q_j be the load of delivered goods when arriving at customer point j, δ_1 be the cargo loss rate during disinfection, and F_7 be the price per unit of product. Then, the cargo damage cost C_{61} during pre-transportation disinfection is:

$$C_{61} = \sum_1^N \sum_{i=1}^m \sum_{j=1}^m Q_j \, \delta_1 F_7 \tag{11}$$

Let δ_2 be the cargo loss rate during transportation. Then, the cargo damage cost C_{62} during transportation is:

$$C_{62} = \sum_1^N \sum_{i=1}^m \sum_{j=1}^m Q_{ij} F_7 \, X_{ij}^n \left(1 - e^{-\delta_2 T_{ij}^n}\right) \tag{12}$$

Let Y_i^n be a binary variable indicating whether transportation vehicle n distributes to customer point i, and δ_3 be the cargo loss rate during unloading. Then, the cargo damage cost C_{63} during unloading is:

$$C_{63} = \sum_1^N \sum_{i=1}^m \sum_{j=1}^m Q_{ij} F_7 Y_i^n \left(1 - e^{-\delta_3 T_{ij}^n}\right) \tag{13}$$

Therefore, the total cargo damage cost C_6 is:

$$C_6 = C_{61} + C_{62} + C_{63} \tag{14}$$

2.3. Establishment of Objective Function

Total cost = Transportation cost + Refrigeration cost + Carbon emission cost + Fixed cost + Disinfection cost + Cargo damage cost, i.e., $C = C_1 + C_2 + C_3 + C_4 + C_5 + C_6$.

To sum up, the objective function for optimizing the distribution route of fresh cold chain products can be established as:

$$minC = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 \tag{15}$$

The constraints are as follows:

$$\sum_1^N Y_i^n = \begin{cases} 1, i = 2,3,4, \dots, m \\ N, i = 1 \end{cases} \tag{16}$$

$$\sum_{j=2}^m X_{ij}^n = \sum_{j=2}^m X_{ij}^n \leq 1, i = 1, n = 1,2,3, \dots n \tag{17}$$

$$\sum_{i=2}^m Y_i^n Q_i \leq Q_1 \tag{18}$$

$$\sum_1^N \sum_{j=2}^m X_{ij}^n \leq N, i = 1 \tag{19}$$

Equation (16) indicates that the distribution center is equipped with N vehicles, and each customer point is served by only one vehicle, ensuring clear distribution responsibility and preventing duplicate services. Equation (17) indicates that distribution vehicles depart from the distribution center, complete transportation tasks on time according to customer cargo demands, and return safely to the distribution center upon task completion. Equation (18) indicates that the actual load of the distribution vehicle shall not exceed its maximum load capacity limit. Equation (19) indicates that the number of vehicles participating in the distribution operation shall not exceed the total number of vehicles deployable by the distribution center.

3. Algorithm Design

3.1. Algorithm Principle

The ant colony algorithm is a bionic algorithm that imitates the behavior of ant colonies in exploring routes when foraging in nature. Individual ants initially explore routes from the nest to food sources randomly, secreting pheromones along their routes as they travel. Since shorter routes offer higher efficiency for round trips, these routes accumulate higher pheromone concentrations over time. Subsequent ants preferentially choose paths with higher pheromone density. Simultaneously, to avoid falling into local optimality, the pheromones on the routes will volatilize slowly over time to retain the possibility of exploring new routes. After each iteration, additional pheromones are strategically deposited along the optimal route to reinforce its guiding role. Ultimately, the ant colony converges through a pattern of individual random search, indirect communication via pheromones, and collaboration. This process integrates individual experiences into collective intelligence, gradually uncovering optimal solutions to complex optimization problems.

3.2. Algorithm Flow

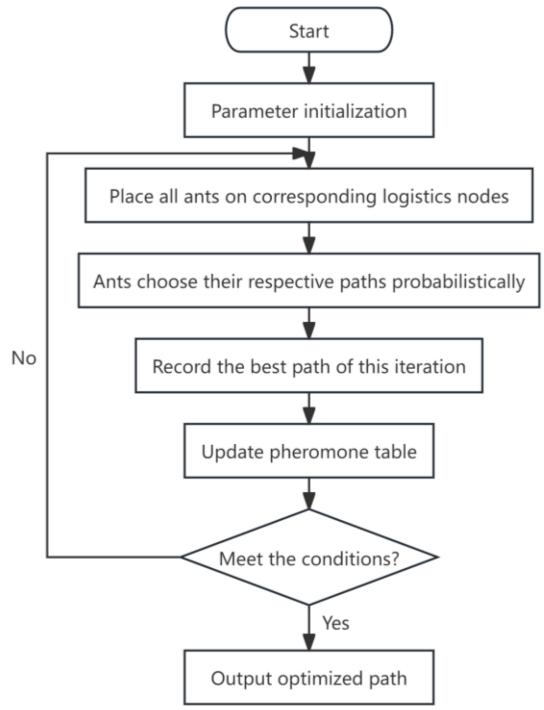

Figure 1. Flow chart of ant colony algorithm

4. Case Analysis

As a core agricultural product distribution center in northeastern Sichuan, Nanchong has made significant progress in the construction of cold chain logistics infrastructure in recent years. However, the current circulation rate of fresh cold chains remains low, and the sector faces challenges such as inadequate green cost management, insufficient operational coordination, and lagging route optimization technology. Against the background of large-scale cold chain infrastructure construction in Nanchong, establishing a distribution route optimization model that integrates a green cost quantification mechanism to achieve synergistic economic efficiency and low-carbon goals has become an urgent issue.

This study takes a fresh cold chain transportation and logistics company in Nanchong as an example, this study determines the location of the cold storage distribution center and each customer point, as well as the distances between the cold storage distribution center and each customer point, and between each pair of customer points through data collection, organization, and field investigation. For the convenience of the study, the shortest straight-line distance on the map is used as the distribution distance without considering actual traffic conditions and other factors. The basic demand information of each customer is shown in Table 1.

The foundational parameters in the model are derived from a fresh produce cold chain transportation logistics company in Nanchong City. The basic parameter settings are shown in Table 2.

Table 1. Customer logistics demand information

Customer Code	Demand / t	Service Time / min	Customer Code	Demand / t	Service Time / min
1	0.3	15	14	0.3	15
2	0.4	10	15	0.2	20
3	0.3	15	16	0.2	10
4	0.4	15	17	0.3	10
5	0.2	20	18	0.4	15
6	0.2	10	19	0.2	10
7	0.5	20	20	0.4	10
8	0.3	15	21	0.3	20
9	0.4	20	22	0.2	20
10	0.3	15	23	0.3	15
11	0.2	20	24	0.5	10
12	0.4	10	25	0.2	15
13	0.2	20	26	0.3	20

Table 2. Table of relevant parameters

Name	Numerical Value
Total number of customer points (M)	26
Number of refrigerated trucks (N)	5
Transportation cost per unit distance of cold chain distribution vehicle (F_1)	CNY 5/km
Refrigeration cost per unit time of cold chain distribution vehicle during driving (F_2)	CNY 12/h
Refrigeration cost per unit time of cold chain distribution vehicle when unloading (F_3)	CNY 16/h
Fixed cost per cold chain distribution vehicle (F_4)	CNY 250
Disinfection cost per cold chain distribution vehicle and personnel (F_5)	CNY 20
Inspection cost per unit of goods (F_6)	CNY 18
Price per unit of product (F_7)	CNY 10000/t
Carbon tax (λ)	CNY 0.3/kg
Cargo loss rate during disinfection (δ_1)	0.004
Cargo loss rate during transportation (δ_2)	0.003
Cargo loss rate during unloading (δ_3)	0.004
Carbon dioxide emission factor (K)	2.8kg/L
Driving speed of fully loaded cold chain distribution vehicle (V)	50km/h
Fuel consumption per unit distance when vehicle is unloaded (W_1)	0.12L/km
Fuel consumption per unit distance when vehicle is fully loaded (W_2)	0.38L/km
Carbon dioxide emissions of refrigerant per unit weight of goods per unit distance (L)	7.5×10-6kh/(kg·km)

Figure 2 shows the minimum total cost obtained by simulation. As illustrated, the algorithm demonstrates rapid convergence during the initial iteration phase, accelerating computational speed while continuously advancing toward the optimal solution. After 127 iterations, the minimum total cost reached was 5,338.81 yuan.

As shown in Figure 3, the optimal distribution scheme has 5 distribution routes. This plan rationally schedules distribution routes based on customer locations, goods demand, and expected receiving times, resulting in an optimal total mileage of 534.04 km.

The optimal distribution routes are listed in Table 3. By distributing to customers according to this routes, the cold chain transportation and logistics enterprise can achieve the minimum total transportation cost.

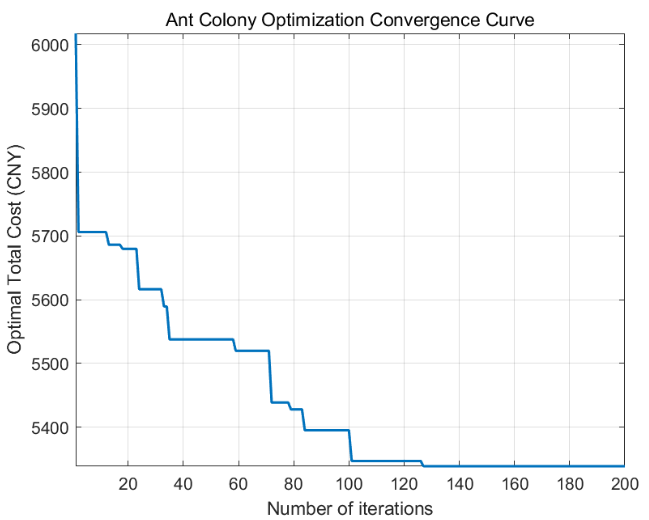

Figure 2. Ant colony algorithm convergence curve

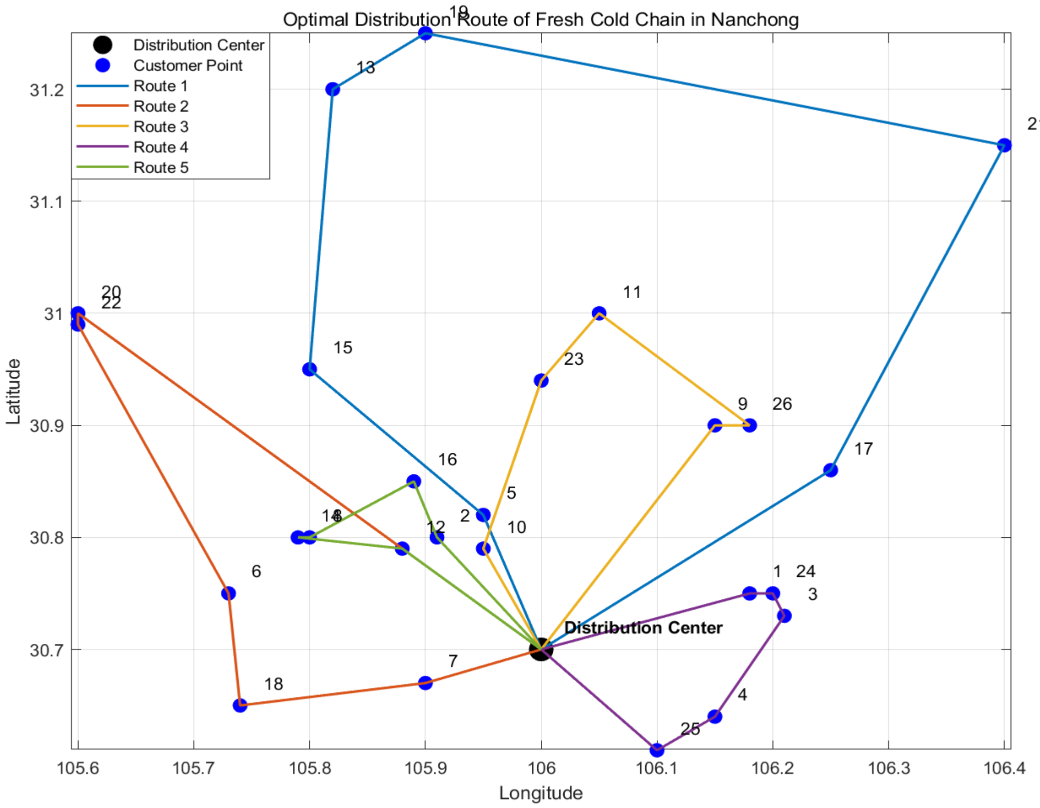

Figure 3. Optimal distribution route figure

Table 3. Optimal distribution route table

Distribution Route	Route	Load / t
Route 1	Distribution Center→5→15→13→19→21→17→Distribution Center	1.40
Route 2	Distribution Center→7→18→6→22→20→Distribution Center	1.70
Route 3	Distribution Center→10→23→11→26→9→Distribution Center	1.50
Route 4	Distribution Center→25→4→3→24→1→Distribution Center	1.70
Route 5	Distribution Center→12→14→8→16→2→Distribution Center	1.60

5. Conclusion

Rapid economic growth and rising living standards have driven continuous expansion in logistics demand, while green development principles have gradually become an industry consensus. This study focuses on optimizing distribution routes for fresh cold-chain products, constructing a distribution route optimization model that incorporates green costs and solving it using ant colony optimization. The findings indicate that in planning delivery routes for fresh cold-chain products, a comprehensive optimization approach can be adopted across economic, environmental, and social dimensions. This approach balances total costs with carbon emissions to formulate optimal delivery strategies that integrate internal economic benefits with external ecological benefits. Such strategies not only help enterprises maximize profits but also provide society with safer, greener, and more efficient logistics services, thereby effectively implementing the principles of green development.

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