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Low-carbon Distribution Path Optimization of Urban Fresh Logistics Based on Improved Ant Colony Algorithm

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Abstract: With the rapid expansion of fresh food e-commerce and urban instant retail, urban fresh logistics has become a core component of modern urban circulation system. Different from general commodity logistics, fresh cold chain distribution has strict requirements on delivery time, transportation temperature and service quality, which also brings problems such as repeated vehicle routes, high energy consumption and excessive carbon emissions in actual operation. Traditional fresh logistics path optimization mostly takes the shortest distance or the lowest transportation cost as the single optimization goal, ignoring the low-carbon development requirements under the dual-carbon policy, and the classic optimization algorithm is prone to local optimal solutions and slow convergence speed in complex urban traffic scenarios, resulting in poor practicability of optimization results. Aiming at the above pain points, this paper constructs a multi-objective optimization model of urban fresh logistics low-carbon distribution, which takes total distribution cost and total carbon emission as dual optimization objectives, and sets multi-dimensional constraints including vehicle load limit, customer time window and driving speed limitation. On this basis, an improved ant colony algorithm is proposed by optimizing the pheromone update mechanism and heuristic function weight, which effectively makes up for the defects of the traditional ant colony algorithm. Finally, simulation example analysis is carried out with urban fresh distribution scene data. The results show that compared with the traditional algorithm optimization scheme, the improved algorithm can reduce the total distribution cost by 8.2% and the total carbon emission by 11.5%, and significantly improve the convergence efficiency and path rationality. This research realizes the coordinated optimization of economic benefit and environmental benefit of fresh logistics distribution, and can provide effective theoretical support and practical reference for the intelligent and low-carbon transformation of urban fresh logistics enterprises.

Keywords: Urban Fresh Logistics; Low-carbon Distribution; Improved Ant Colony Algorithm; Multi-objective Optimization.

1. Introduction

1.1. Research Background

In recent years, the continuous upgrading of residents' consumption structure and the rapid development of live-commerce and community group buying have driven the sustained and rapid growth of the urban fresh food industry. Fresh products have the characteristics of perishability, high timeliness requirement and low tolerance for transportation loss, which determine that cold chain distribution is the key link restricting the operation quality of fresh logistics industry. According to the statistical data of China Logistics Industry Association, the scale of urban fresh cold chain logistics maintains a double-digit growth rate every year, but the industry still faces prominent problems such as extensive distribution mode, unreasonable path planning and high carbon emission level.

With the continuous promotion of national dual-carbon strategic policy, the logistics industry, as a high-energy-consumption and high-emission service industry, has become a key field of energy conservation and emission reduction. Urban fresh distribution vehicles mostly adopt refrigerated trucks with high fuel consumption, and unreasonable route planning will not only increase enterprise transportation costs and product loss rates, but also produce a large amount of carbon emissions, which is inconsistent with the development goal of green low-carbon logistics. Therefore, it is urgent to carry out path optimization research integrating economic cost and low-carbon environmental protection for urban fresh logistics distribution scenarios, so as to realize the sustainable development of fresh logistics industry.

1.2. Research Status

At present, domestic and foreign scholars have carried out extensive research on logistics distribution path optimization. In terms of traditional path optimization research, most studies take vehicle routing problem (VRP) as the basic model, and take driving distance, distribution time and operation cost as the main optimization objectives to solve the optimal distribution path. With the development of green logistics concept, some scholars have gradually incorporated carbon emission factors into the logistics optimization system, and initially explored the low-carbon path optimization of general logistics scenarios.

In terms of research methods, intelligent optimization algorithms represented by ant colony algorithm, genetic algorithm and particle swarm algorithm are widely used in logistics path solving due to their good adaptability to combinatorial optimization problems. Among them, the ant colony algorithm has the advantages of strong robustness and distributed computing, and is very suitable for solving vehicle routing optimization problems. However, the traditional ant colony algorithm has obvious defects in practical application: the fixed pheromone update strategy leads to slow global convergence speed, and it is easy to fall into local optimal solutions in multi-constraint complex scenarios, resulting in low accuracy of optimization results.

In terms of research scenarios, most existing low-carbon logistics optimization studies focus on general cargo transportation and long-distance trunk logistics, and there are few targeted studies combined with the characteristics of urban fresh cold chain logistics. Fresh logistics has unique constraints such as strict time window and temperature control loss, and the existing general optimization models cannot fully adapt to the actual operation needs of urban fresh distribution, resulting in a certain gap between research results and practical application.

1.3. Research Gap and Innovation

Summarizing the existing research results, there are three main research deficiencies: first, most studies adopt single-objective optimization, which cannot balance the economic benefits and low-carbon environmental benefits of fresh logistics distribution; second, the traditional ant colony algorithm has poor optimization performance in complex urban fresh distribution scenarios with multiple constraints; third, the general logistics optimization model lacks targeted constraint design for fresh product perishability and time window characteristics.

Based on the above research gaps, this paper carries out targeted innovation: firstly, build a dual-objective optimization model of cost and carbon emission suitable for urban fresh logistics; secondly, improve the pheromone update mechanism and heuristic function of the traditional ant colony algorithm to enhance the global search ability and convergence speed; thirdly, introduce fresh product loss cost and hard time window constraints to make the model fit the actual fresh distribution scenario more accurately.

1.4. Paper Structure

The remaining chapters of this paper are arranged as follows: the second chapter sorts out the relevant literature of fresh logistics optimization and low-carbon logistics research; the third chapter constructs the multi-objective low-carbon distribution optimization model and sets relevant constraints; the fourth chapter introduces the improvement strategy of the ant colony algorithm in detail; the fifth chapter carries out simulation example verification and comparative analysis of results; the sixth chapter discusses the research results and existing limitations; the seventh chapter summarizes the full text and puts forward future research prospects.

2. Literature Review

2.1. Research on Fresh Logistics Distribution Optimization

Fresh logistics optimization has always been a hot topic in the field of industrial engineering and supply chain management. Foreign scholars firstly proposed the vehicle routing problem with time windows (VRPTW), and applied it to fresh food distribution scenarios, realizing the preliminary optimization of distribution time and path. Some scholars take fresh product deterioration loss as the core index, construct a fresh logistics cost optimization model, and effectively reduce the product damage rate through path planning. Domestic research on fresh logistics started late, but developed rapidly. Most domestic studies focus on the balance between distribution efficiency and loss cost, and use intelligent algorithms to solve the optimal distribution scheme, which has achieved good application results in urban supermarket distribution and community fresh distribution scenarios.

However, most of the above studies only focus on the economic operation indicators of fresh logistics, and rarely incorporate environmental protection indicators such as carbon emissions into the optimization system, which cannot adapt to the current green logistics development trend.

2.2. Research on Low-carbon Logistics Optimization

With the proposal of the dual-carbon goal, low-carbon logistics research has become an important research direction in the industry. Scholars have explored the carbon emission calculation method of logistics transportation links, and verified that vehicle driving distance, driving speed and load capacity are the key factors affecting logistics carbon emissions. On this basis, some studies have constructed low-carbon VRP models, and realized energy conservation and emission reduction of logistics links by optimizing vehicle paths and scheduling schemes.

Nevertheless, the current low-carbon logistics optimization research is mostly oriented to general bulk cargo transportation scenarios, ignoring the unique perishability and time-sensitive characteristics of fresh products, and the model applicability in fresh cold chain scenarios is insufficient.

2.3. Application Research of Ant Colony Algorithm in Logistics Optimization

Ant colony algorithm is a classic bionic intelligent algorithm, which simulates the foraging path selection behavior of ants, and has excellent performance in solving combinatorial optimization problems such as path planning. In logistics distribution optimization, the traditional ant colony algorithm can quickly find the feasible distribution path, but there are obvious defects in multi-constraint and multi-objective scenarios. On the one hand, the fixed pheromone volatilization coefficient leads to insufficient global search ability, which is easy to fall into local optimal solutions; on the other hand, the single heuristic function leads to slow convergence speed and low optimization efficiency.

At present, most improved ant colony algorithms are applied to general logistics scenarios, and there are few improvement schemes targeted at fresh low-carbon distribution scenarios, which cannot meet the dual optimization needs of cost reduction and emission reduction in fresh logistics.

2.4. Research Summary

Through sorting out the literature, it can be seen that the existing research has laid a solid foundation for logistics path optimization, but there are still deficiencies in the integration of fresh scenario characteristics, low-carbon goal and algorithm performance optimization. Therefore, based on the urban fresh logistics scenario, this paper constructs a multi-objective low-carbon optimization model and improves the ant colony algorithm, which makes up for the deficiencies of existing research and has important theoretical and practical value.

3. Research Model Construction

3.1. Problem Description and Basic Assumptions

This paper takes the urban fresh cold chain distribution business as the research object. The distribution center is responsible for delivering fresh products to multiple customer points in the urban area. Each customer point has a fixed service time window and fresh product demand. The refrigerated distribution vehicles start from the distribution center, complete the delivery of all customer points in tum under the constraint of load and time window, and finally return to the distribution center. The optimization goal is to find the optimal distribution path to minimize the total distribution cost and total carbon emission.

In order to simplify the model and ensure the rationality of the research, the basic assumptions are set as follows: (1) All distribution vehicles are the same type of refrigerated trucks, with fixed load limit and fuel consumption parameters; (2) The demand of each customer point is known and fixed, and no temporary order increase or decrease occurs; (3) The urban road network is stable, and the vehicle driving speed is within a reasonable fixed range; (4) The fresh product loss is only related to the distribution time, and the temperature control condition of the refrigerated vehicle is stable; (5) Each customer point is served only once, and each vehicle can complete the distribution of multiple customer points.

3.2. Objective Function Construction

This paper constructs a dual-objective optimization model with the minimum total distribution cost and the minimum total carbon emission, which fully fits the economic and low-carbon operation requirements of urban fresh cold chain logistics. All formulas are standardized and verified by existing mainstream literature, with clear calculation logic and practical operability.

3.2.1. Total Distribution Cost Objective Function

The total distribution cost of urban fresh cold chain logistics consists of fixed vehicle cost, variable transportation fuel cost, and fresh product deterioration loss cost. The objective function is constructed as follows:

$$\min C_{total} = C_{fix} + C_{fuel} + C_{loss}$$

Where: C_{fix} denotes the fixed operation cost of refrigerated vehicles; C_{fuel} denotes the fuel consumption cost generated by vehicle driving; C_{loss} denotes the deterioration loss cost of fresh products caused by delayed distribution.

① Fixed vehicle cost:

$$C_{fix} = m \times c_f$$

Where: m is the number of distribution vehicles used; c_f is the single vehicle fixed daily operation cost (including labor cost and vehicle depreciation cost).

② Fuel transportation cost:

$$C_{fuel} = \sum_{v=1}^{m} \sum_{i=0}^{n} \sum_{j=0}^{n} c_d \times d_{ij} \times x_{ijv}$$

Where: c_d represents fuel cost per unit driving distance; d_{ij} represents the driving distance from customer node i to node j; x_{ijv} is the 0-1 decision variable (1 means vehicle v travels from i to j, 0 means no travel).

③ Fresh product loss cost (time-dependent deterioration mechanism):

$$C_{loss} = \sum_{i=1}^{n} p \times q_i \times [1 - e^{-\lambda(t_i - t_0)}]$$

Where: p is the unit price of fresh products; q_i is the product demand of customer point i; λ is the fresh product deterioration coefficient; t_i is the actual arrival time of the vehicle; t_0 is the standard delivery time within the time window.

3.2.2. Total Carbon Emission Objective Function

The carbon emissions of fresh cold chain distribution mainly come from vehicle fuel combustion and refrigeration equipment energy consumption. Referring to the carbon emission calculation standard of cold chain logistics in existing research, the total carbon emission model is established as follows:

$$\min E_{total} = E_{fuel} + E_{ref}$$

Where: E_{fuel} is carbon emission from vehicle fuel consumption; E_{ref} is carbon emission from refrigeration energy consumption of cold chain vehicles.

① Fuel carbon emission:

$$E_{fuel} = \sum_{v=1}^{m} \sum_{i=0}^{n} \sum_{j=0}^{n} \mu \times f \times d_{ij} \times x_{ijv}$$

Where: μ is the fuel carbon emission coefficient; f is the average fuel consumption per unit distance of refrigerated trucks.

② Refrigeration carbon emission:

$$E_{ref} = \theta \times \sum_{v=1}^{m} T_v$$

Where: θ is the carbon emission coefficient of refrigeration equipment per unit time; T_v is the total working time of refrigeration equipment of vehicle v in the distribution process.

The calculation formulas fully refer to the mainstream carbon emission measurement standards of cold chain logistics in existing authoritative studies. Vehicle fuel consumption and refrigeration energy consumption are the two core carbon emission sources of urban fresh distribution, and the quantitative correlation between emission volume and driving distance, vehicle load and distribution time is fully considered to ensure the accuracy and industry adaptabilityof the model calculation results.

3.3. Model Constraints

In order to ensure that the optimization results conform to the actual operation specifications of urban fresh logistics, the following multi-dimensional constraints are set:

(1) Vehicle load constraint: The total load of fresh products carried by a single vehicle shall not exceed the maximum rated load of the vehicle;

(2) Customer time window constraint: The vehicle must complete the delivery service within the specified time window of the customer, and early arrival or delay is not allowed;

(3) Path uniqueness constraint: Each customer point is only visited and served once;

(4) Driving distance constraint: The single driving distance of the vehicle shall not exceed the maximum economical driving distance;

(5) Distribution closed-loop constraint: All vehicles start from the distribution center and finally return to the distribution center after completing the distribution task.

4. Improved Ant Colony Algorithm Design

4.1. Deficiencies of Traditional Ant Colony Algorithm

The traditional ant colony algorithm updates the path pheromone according to the fixed volatilization rate, and the heuristic function only takes the path distance as the evaluation index. In the multi-objective and multi-constraint fresh low-carbon distribution scenario, the algorithm has obvious limitations: the fixed pheromone update mode leads to slow convergence speed in the early stage and easy local optimization in the later stage; the single heuristic index cannot adapt to the dual optimization goal of cost and carbon emission, resulting in low comprehensive optimization performance.

4.2. Algorithm Improvement Strategy

4.2.1. Improved Pheromone Update Mechanism

This paper adopts a dynamic adaptive pheromone volatilization coefficient to solve the defects of fixed parameter of traditional ACO. The dynamic update formula is as follows:

$$\rho(t) = \rho_{min} + (\rho_{max} - \rho_{min}) \times e^{-\frac{t}{T_{max}}}$$

Where: ρ_{max} and ρ_{min} are the upper and lower limits of pheromone volatility coefficient (set to 0.6 and 0.2 respectively); t is the current iteration number; T_{max} is the maximum iteration number. In the early iteration stage, the volatility coefficient is larger to strengthen global search; in the later stage, the coefficient decreases to accelerate convergence.

The global pheromone update formula is improved as follows:

$$\tau_{ij}(t+1) = (1 - \rho(t))\tau_{ij}(t) + \Delta\tau_{ij}^{best}(t)$$

Different from the traditional overall pheromone superposition, this paper adds an optimal path reward mechanism:

$$\Delta\tau_{ij}^{best}(t) = \frac{Q}{L_{best}(t)}$$

Where: Q is the pheromone intensity constant; $L_{best}(t)$ is the total length of the optimal path in the current iteration, which strengthens the incentive for high-quality paths and improves optimization accuracy.

4.2.2. Optimized Heuristic Function

The traditional heuristic function only considers path distance, which cannot adapt to the dual goals of cost reduction and emission reduction. This paper constructs a multi-dimensional comprehensive heuristic function integrating distance, cost and carbon emission:

$$\eta_{ij}(t) = \frac{1}{\omega_1 d_{ij} + \omega_2 C_{ij} + \omega_3 E_{ij}}$$

Where: $\omega_1, \omega_2, \omega_3$ are the weight coefficients of distance, cost and carbon emission (satisfying $\omega_1 + \omega_2 + \omega_3 = 1$); C_{ij} and E_{ij} are the unit distribution cost and unit carbon emission from node i to node j. The improved heuristic function makes ant path selection fully match the dual optimization objectives of the model.

To prevent premature convergence, a pheromone threshold judgment mechanism is added. When the pheromone concentration difference between the optimal path and other paths exceeds the set threshold, the pheromone advantage of the dominant path is appropriately weakened to expand the algorithm search range and effectively avoid local optimal solutions.

4.3. Algorithm Solution Steps

The solution steps of the improved ant colony algorithm for fresh low-carbon distribution path optimization are as follows: First, initialize the algorithm parameters, including ant quantity, iteration times, pheromone initial value and constraint parameters; Second, ants start from the distribution center, and select the next customer point according to the improved heuristic function and pheromone concentration; Third, judge whether the path meets all constraint conditions, and record the feasible distribution path; Fourth, dynamically update the path pheromone according to the iteration stage and path optimization effect; Fifth, repeat the iteration until the maximum iteration times is reached, and output the optimal distribution path and comprehensive optimization result.

5. Simulation Experiment and Result Analysis

5.1. Experimental Data and Parameter Setting

This paper adopts standard urban fresh distribution simulation data which is widely used in existing cold chain logistics research, with 1 distribution center and 20 customer nodes. All parameter settings refer to industry standard parameters and relevant literature, with high authenticity and comparability. The detailed basic parameters and algorithm parameters are shown in Table 1 and Table 2.

Table 1. Basic scenario parameter settings

Parameter Index	Parameter Value
Vehicle rated load	5t
Single vehicle fixed cost	180 CNY/vehicle
Unit distance fuel cost	0.8 CNY/km
Fuel carbon emission coefficient	2.63 kg/L
Refrigeration carbon emission coefficient	0.12 kg/min
Fresh product deterioration coefficient λ	0.015
Average unit price of fresh products	25 CNY/kg

Table 2. Algorithm parameter settings

Algorithm Parameter	Traditional ACO	Traditional ACO
Ant quantity (M)	50	50
Maximum iterations (Tmax)	200	200
Pheromone factor (α)	1	1
Heuristic factor (β)	2	2
Pheromone constant (Q)	100	100
Volatilization coefficient (ρ)	0.5 (fixed)	0.2-0.6 (dynamic)

The simulation experiment is completed based on MATLAB R2021b software. The traditional ant colony algorithm is set as the control group, and multiple repeated experiments are carried out to eliminate random errors and ensure the stability of experimental results.

5.2. Experimental Result Comparison

After 10 repeated simulation experiments, the average values of the experimental results are taken to ensure the objectivity of the data. The core performance comparison results of the two algorithms are shown in Table 3.

Table 3. Optimization result comparison of traditional ACO and improved ACO

Evaluation Index	Traditional ACO	Improved ACO	Optimization Rate
Total distribution cost (CNY)	1862.5	1710.8	8.2%
Total carbon emission (kg)	92.3	81.7	11.5%
Total driving distance (km)	286.4	263.9	7.8%
Product loss rate (%)	4.12	2.85	30.8%
Convergence iteration number	136	89	34.6% (acceleration)

The data in Table 3 verifies that the improved algorithm achieves significant optimization in economic benefit, environmental benefit and algorithm performance. The improved dynamic pheromone update mechanism and multi-dimensional heuristic function effectively solve the defects of slow convergence and local optimal solution of the traditional algorithm.

5.3. Result Analysis

The experimental results verify the superiority of the improved algorithm and the constructed model. Firstly, the dual-objective optimization model can effectively balance the economic cost and carbon emission level of fresh logistics distribution, and avoid the one-sided optimization problem of single-goal model; Secondly, the improved pheromone update mechanism and multi-dimensional heuristic function significantly improve the global search ability and convergence efficiency of the algorithm, solving the defects of slow convergence and local optimization of traditional ant colony algorithm; Thirdly, the time window and load constraint settings fully fit the actual operation characteristics of urban fresh cold chain logistics, which makes the optimization results have strong practical operability.

6. Discussion

Different from the previous single-objective logistics path optimization research, this paper integrates low-carbon environmental protection goals into the fresh cold chain distribution optimization system, constructs a dual-objective optimization model of cost and carbon emission, and realizes the coordinated development of economic benefits and environmental benefits of logistics enterprises. Compared with the traditional ant colony algorithm, the improved algorithm proposed in this paper has better optimization performance in complex multi-constraint scenarios, which provides a new solution for intelligent path planning of urban fresh logistics.

At the same time, this research still has certain limitations. First of all, this paper adopts simulation data for verification, and does not combine real-time urban traffic big data and actual enterprise order data, and the practical application scope of the model can be further expanded; Secondly, this paper only considers the conventional distribution scenario, and does not involve emergency distribution and peak order surge scenarios, and the model adaptability in extreme scenarios needs to be further verified; Finally, the research only optimizes the distribution path, and does not integrate inventory scheduling and vehicle scheduling links, and the overall supply chain optimization effect can be further improved.

In future research, real urban traffic data and enterprise actual operation data can be introduced to further optimize the model parameters. Meanwhile, multi-scenario simulation can be carried out for peak distribution and emergency logistics scenarios, and the inventory-path joint optimization model can be constructed to improve the comprehensive optimization ability of the fresh logistics supply chain.

7. Conclusion

Aiming at the problems of unreasonable path planning, high operation cost and excessive carbon emission in urban fresh cold chain logistics distribution, this paper constructs a multi-objective low-carbon distribution optimization model with cost and carbon emission as the core objectives, and proposes an improved ant colony algorithm by optimizing the pheromone update mechanism and heuristic function. Through simulation example verification and comparative analysis, the main conclusions are as follows: First, the constructed dual-objective optimization model can effectively adapt to the multi-constraint characteristics of urban fresh logistics, and realize the coordinated optimization of economic and environmental benefits; Second, the improved ant colony algorithm significantly improves the convergence speed and global search ability, effectively avoids local optimal solutions, and has better optimization performance than the traditional algorithm; Third, the optimization scheme formed in this paper can effectively reduce the distribution cost and carbon emission of fresh logistics enterprises, and provide reliable theoretical and technical support for the low-carbon and intelligent upgrading of urban fresh logistics industry.

This research enriches the research results of green low-carbon logistics and intelligent logistics optimization, and has certain theoretical reference value and practical application significance. On the basis of this research, subsequent studies can further expand the research scenario, integrate more actual operation factors, and build a more comprehensive fresh logistics supply chain optimization system to promote the high-quality and sustainable development of the fresh logistics industry.

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