Research on Route Optimization for Dairy Cold Chain Logistics Based on Hybrid Genetic Algorithm

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Abstract. Due to the perishable nature of dairy products, dairy cold chain logistics has high requirements for temperature control and distribution timeliness. This paper aims to optimize urban dairy cold chain logistics to minimize the total distribution cost by reducing delivery time, lowering cargo loss, and ensuring the quality of dairy products. First, a multi-objective mathematical model is constructed that integrates fixed cost, transportation cost, cargo damage cost, refrigeration cost, penalty cost, and carbon emission cost, while fully considering the perish ability of dairy products during transportation and loading/unloading. Second, a hybrid genetic algorithm combining the A* algorithm and genetic algorithm is designed to solve the model. Finally, the results show that the hybrid genetic algorithm outperforms the single genetic algorithm in cost reduction, which verifies the effectiveness of the proposed algorithm.

Keywords: Cold chain logistics; Route optimization; Genetic algorithm; A* algorithm

1 Introduction

With the improvement of residents' living standards and the popularization of healthy diet concepts, the market demand for dairy products continues to rise[1]. In 2025, the market scale of China's dairy industry has exceeded 550 billion RMB. Cold Chain Distribution (CCD), as a core link for ensuring dairy product quality[2], its efficiency and economy directly restrict the sustainable development of the industry. The costs of Cold Chain Logistics (CCL) are far higher than conventional logistics, especially in fuel consumption and carbon emission. Hence, optimizing distribution routes to cut operational costs and energy consumption is crucial for corporate sustainable development and environmental protection[3].

Urban CCL route optimization is a classic NP-hard problem[4]. Featuring multi-constraint and multi-objective characteristics, such problems cannot be solved by time-exact algorithms. Heuristic Algorithm (HA) serves as an effective solution with reliable performance[5]. Genetic Algorithm (GA) possesses powerful global search ability and high robustness, which is widely applied in Vehicle Routing Problem (VRP)[6]. Jiang Y Q et al.[7] adopted GA for calculation, greatly reducing distribution costs and carbon emission costs. Ge X L et al.[8] established a fresh food distribution

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model with time window constraints and fresh loss factors, and solved the model with improved GA.

2 Problem Description and Model Establishment

2.1 Problem Description and Assumptions

Under urban distribution conditions, only one distribution center is usually arranged[9]. This paper studies the route optimization of single-depot cold chain logistics for dairy products. Vehicles depart from a single distribution center, serve multiple customers, and return to the depot. The main constraints include limited fleet size and vehicle capacity, time-dependent cargo loss caused by perish ability, and dynamic vehicle speed under traffic congestion. All parameters are listed in Table 1.

2.2 Symbols and Parameters

Table 1. Specific Parameters

Parameters	Meaning	Parameters	Meaning
N	Set composed of distribution centers and customers	κ_2	Door-open fuel consumption
K	Set of available refrigerated vehicles	s_j	Standard unloading time for a single customer
Q	Maximum load weight limit for a single delivery	α	Penalty for arriving earlier
f_k	Fixed startup cost for single vehicle scheduling	β	Penalty for arriving after the latest allowable arrival time
v	Avg. speed in daytime congestion	δ	Time window tolerance
D	Maximum travel distance per delivery task	M	penalty for violating soft time or physical constraints
c_1	No-load unit mileage cost of vehicles	S_k	1 = vehicle K for distribution; 0 = otherwise.
ω	Unit load energy efficiency adjustment coefficient	x_{ij}^k	1 =vehicle K travels from node i to node j, 0 = otherwise.
c_3	Carbon tax price	y_j^k	1=customer j distributed by vehicle K; 0 = otherwise.
ξ	Carbon emission conversion factor of fuel consumption	Q_{ij}	Real-time load capacity of the vehicle on arc (i,j)
$\bar{\rho}$	Average fuel consumption rate during vehicle operation	q_j	Delivery demand weight of customer node j
$\bar{\varphi}$	Average fuel consumption rate of the refrigeration unit	d_{ij}	Section length between node i and node j
P	Market unit price of delivered goods	t_{ij}	Actual travel time from node i to node j
c_2	Fuel unit price	E_j	The earliest expected arrival time for customer j
c_f	Full-load unit mileage rate of the vehicle	L_j	The latest expected arrival time for customer j
c_e	No-load unit mileage rate of the vehicle	T_k	Total task duration of vehicle k
θ_1	deterioration rate of goods under closed-door driving state	t_i^k	Arrival time of vehicle k at customer i
κ_1	Fuel consumption of refrigeration unit under closed-door		

2.3 Mathematical Model

(1)Fixed Cost

Fixed cost refers to the fixed expenses incurred when refrigerated vehicles are dispatched from the distribution center to deliver goods to each service node. The functional formula is shown below.(1):

$$Z_1=\sum_{k=1}^{K} f_k \cdot S_k \tag{1}$$

(2)Transportation Cost

Transportation cost is mainly composed of fuel consumption cost, which is related not only to the driving distance during CCL delivery, but also to the vehicle load capacity.(2):

$$Z_2=\sum_{k=1}^{K}\sum_{i=0}^{n}\sum_{j=0}^{n}\left(c_1+\omega\cdot Q_{ij}\right)\cdot d_{ij}\cdot x_{ij}^{k} \tag{2}$$

$$\omega=\frac{c_f-c_e}{Q}$$

(3)Cargo Damage Cost

Due to the high temperature sensitivity of dairy products, the cargo damage cost in CCL transportation mainly stems from temperature fluctuations caused by door opening during unloading. Thus, cargo damage is divided into two stages: transportation and unloading. The relevant function formula is shown below.(3):

$$Z_3=P\sum_{k=1}^{K}\left(\sum_{i=0}^{n}\sum_{j=1}^{n} x_{ij}^{k}\cdot Q_{ij}\cdot\Delta_{ij}^{(1)}+\sum_{j=1}^{n} y_j^k\cdot q_j\cdot\Delta_j^{(2)}\right) \tag{3}$$

$$\Delta_{ij}^{(1)}=1-e^{-\theta_1 t_{ij}},\quad \Delta_j^{(2)}=1-e^{-\theta_2 s_j}$$

(4)Refrigeration Cost

Refrigeration cost refers to the expenses incurred to maintain a constant low-temperature environment inside refrigerated carriages and guarantee product quality. The functional formula is shown below.(4):

$$\mathrm{Z_4=c_2\cdot\sum_{k=1}^{K}\left(\sum_{i=0}^{n}\sum_{j=0}^{n}x_{ij}^{k}\cdot t_{ij}\cdot\kappa_1+\sum_{j=1}^{n}y_j^k\cdot s_j\cdot\kappa_2\right)} \tag{4}$$

(5)Penalty Cost

Penalty cost is formulated to ensure the timeliness of CCL distribution. This paper sets a time tolerance buffer. A linear fine will be charged within the buffer range, while a heavy fine will be imposed once exceeding the buffer limit. The functional formula is shown as follows.(5):

$$Z_5=\sum_{k=1}^{K}\sum_{j=1}^{n} y_j^k\cdot\Psi\left(t_j^k\right) \tag{5}$$

$$\Psi\left(t_j^k\right)=\begin{cases} M, & t_j^k<E_j-\delta \\ \alpha\left(E_j-t_j^k\right), & E_j-\delta\le t_j^k<E_j \\ 0, & E_j\le t_j^k\le L_j \\ \beta\left(t_j^k-L_j\right), & L_j<t_j^k\le L_j+\delta \\ M, & t_j^k>L_j+\delta \end{cases}$$

(6)Carbon Emission Cost

Carbon emission cost is mainly composed of two parts: one derives from fuel consumption in CCL operations, and the other comes from the operation of refrigeration units. The functional formula is shown below.(6):

$$Z_6 = c_3 \cdot \xi \cdot \sum_{k=1}^{K} \left(\sum_{i=0}^{n} \sum_{j=0}^{n} x_{ij}^{k} \cdot d_{ij} \cdot \bar{\rho} + T_k \cdot \bar{\varphi} \right) \tag{6}$$

$$T_k = \sum_{i \in N} \sum_{j \in N} x_{ij}^{k} \cdot t_{ij} + \sum_{j \in C} y_j^{k} \cdot s_j$$

The objective function integrates the above six types of costs, which can be expressed as Formula.(7):

$$\min Z = Z_1 + Z_2 + Z_3 + Z_4 + Z_5 + Z_6 \tag{7}$$

$$\sum_{k=1}^{K} f_k \cdot S_k + \sum_{k=1}^{K} \sum_{i=0}^{n} \sum_{j=0}^{n} \left(c_1 + \omega \cdot Q_{ij} \right) \cdot d_{ij} \cdot x_{ij}^{k} + P \sum_{k=1}^{K} \left(\sum_{i=0}^{n} \sum_{j=1}^{n} x_{ij}^{k} \cdot Q_{ij} \cdot \Delta_{ij}^{(1)} + \sum_{j=1}^{n} y_j^{k} \cdot q_j \cdot \Delta_j^{(2)} \right) + c_2 \cdot \sum_{k=1}^{K} \left(\sum_{i=0}^{n} \sum_{j=0}^{n} x_{ij}^{k} \cdot t_{ij} \cdot \kappa_1 + \sum_{j=1}^{n} y_j^{k} \cdot s_j \cdot \kappa_2 \right) \sum_{k=1}^{K} \sum_{j=1}^{n} y_j^{k} \cdot \Psi(a_j)$$
$$+ c_3 \cdot \xi \cdot \sum_{k=1}^{K} \left(\sum_{i=0}^{n} \sum_{j=0}^{n} x_{ij}^{k} \cdot d_{ij} \cdot \bar{\rho} + T_k \cdot \bar{\varphi} \right)$$

The constraints of the model are presented from Formula (8) to Formula (10).

$$\sum_{k \in K} y_j^{k} = 1, \quad \sum_{i \in N} x_{ij}^{k} = y_j^{k}, \quad \forall j \in C \tag{8}$$

$$\sum_{i \in N} x_{ij}^{k} = \sum_{l \in N} x_{jl}^{k}, \quad \forall j \in N, \forall k \in K \tag{9}$$

$$\sum_{j \in C} x_{0j}^{k} = \sum_{i \in C} x_{i0}^{k} \leq 1, \quad \forall k \in K \tag{10}$$

Among them, Equation (8) indicates that each customer node can only be served by one refrigerated vehicle for a single delivery. If a customer is assigned to a certain vehicle, the vehicle has a unique access route to this node; otherwise, no access route exists. Equation (9) denotes that refrigerated vehicles must depart from any customer node after arrival and return to the depot after leaving it. Equation (10) ensures that all dispatched vehicles start from the distribution center, complete CCL tasks and return to the depot, and each vehicle performs at most one closed-loop transportation task within the decision cycle.

3 Algorithm Design

3.1 Initial Population Setting

The heuristic function serves as the core of the A* algorithm, and its expression is shown in Equation (11):

$$f(n) = g(n) + h(n) \tag{11}$$

Where $g(n)$ represents the actual cost from the current distribution point a to customer point n, and $h(n)$ represents the conservative estimated cost from customer point n to the unserved customers. Euclidean distance is adopted to calculate the distance between distribution points in this paper. Firstly, the starting point of the path is set as the distribution center, and all distribution points are included in the open list. The termination condition of the algorithm is defined as the open list being empty, that is, all customer points have been allocated. The heuristic function is used to calculate the fn value of all distribution points, and the distribution point with the minimum value is selected to add to S[k]. Then, the load capacity constraint is checked. If the constraint is exceeded, the path is closed and a new vehicle is dispatched for delivery. If the constraint is satisfied, the current path is taken as a chromosome of the genetic algorithm.

3.2 Population Initialization

To balance population diversity and computational efficiency, the initial population size is set to 50 in this study. In Genetic Algorithm (GA), the fitness function is adopted to evaluate the quality of chromosomes, and individuals with higher fitness are more likely to be selected. To minimize the total CCL distribution cost, the reciprocal cost method is applied for the fitness function. The relevant formula is shown in Equation (12):

$$\mathrm{fitness}(i)=\frac{1}{\min Z(i)} \tag{12}$$

3.3 Selection Operator

This study combines the elitist preservation strategy with roulette wheel selection. The roulette wheel selection determines individual selection probability based on fitness values, guiding the algorithm to evolve toward the minimum total CCL cost. The elitist preservation strategy retains the top 10% of optimal chromosomes in each generation and directly passes them to the next iteration, reducing the loss risk of high-quality individuals and improving overall algorithm efficiency.

3.4 Crossover Operator

A pair of chromosomes are randomly selected from the parents. Taking vehicle segmentation as the random crossover point, the segmented sequences at the crossover points are exchanged to generate two offspring. All offspring shall be verified against relevant constraints; qualified individuals are retained, otherwise the crossover operation will be repeated.

3.5 Mutation Operator

Randomly select one chromosome from the parent generation, and reverse the sequence between two random codes on the chromosome.

Randomly select one chromosome from the parent generation, pick two random nodes a and b on the chromosome, and insert node a before node b.

After the above mutation operations, check whether the chromosome meets all constraints and calculate its fitness value. If the mutated chromosome has a higher fitness, it will be directly passed on to the next generation; otherwise, the original chromosome after crossover will be retained.

4 Case Solution and Analysis

This paper takes a dairy processing enterprise in Jinshui District, Zhengzhou City, Henan Province as the research object. The enterprise provides distribution services for 20 surrounding supermarkets. The relevant information of the distribution center and customer nodes is shown in the figure. The enterprise is equipped with 6 refrigerated vehicles with a load capacity of 3 tons for CCL delivery.The fixed cost of each refrigerated vehicle is 200 RMB/unit, with an average driving speed of 40 km/h. The transportation cost under no-load and full-load conditions is 2 RMB/km and 3 RMB/km respectively. The refrigerant consumption cost during transportation and handling is 6.24 RMB/h and 11.7 RMB/h. The deterioration rate of dairy products in the above two stages is 0.002 and 0.006. The unit price of dairy products is 15 RMB/kg, the fuel price is 7.8 RMB/L, and the vehicle carbon emission coefficient is 2.63 kg/L with a carbon tax of 0.05 RMB/kg. The penalty cost for early arrival and late arrival beyond the acceptable time window is 30 RMB/h and 50 RMB/h respectively.

Table 2. customer information

Numbering	Supermarket type	Coordinate	Demand/kg	Acceptable time	Desired time	Service time (min)
0	Distribution Center	(7.4, 8.1)	0	00:00–12:00	00:00–12:00	0
1	Large supermarket	(3.2, 12.6)	420	07:30–12:00	08:00–11:30	22
2	Large supermarket	(5.8, 11.3)	360	07:00–11:30	07:30–11:00	18
3	Medium-sized supermarket	(9.5, 13.1)	280	08:00–13:00	08:30–12:30	20
4	Large supermarket	(11.2, 10.8)	450	08:30–13:30	09:00–12:30	25
5	Medium-sized supermarket	(13.4, 9.6)	260	07:30–11:30	08:00–11:00	16
6	Large supermarket	(12.1, 7.2)	500	09:00–15:00	09:30–14:30	30
7	Medium-sized supermarket	(10.3, 5.4)	240	08:00–12:00	08:30–11:30	15
8	Large supermarket	(8.6, 4.8)	410	07:30–12:30	08:00–11:30	24
9	Medium-sized supermarket	(6.1, 5.2)	220	08:00–11:00	08:30–11:00	14
10	Large supermarket	(4.3, 6.7)	380	07:30–12:30	08:00–11:30	20
11	Medium-sized supermarket	(2.8, 8.9)	200	08:30–12:00	09:00–11:30	12
12	Large supermarket	(1.9, 10.4)	460	09:00–14:00	09:30–13:30	28
13	Medium-sized supermarket	(3.7, 3.5)	230	07:30–11:30	08:00–11:00	15
14	Large supermarket	(5.6, 2.4)	400	08:00–13:00	08:30–12:00	26
15	Medium-sized supermarket	(7.9, 1.8)	210	07:30–11:30	08:00–11:00	10
16	Large supermarket	(9.8, 2.9)	430	09:00–14:00	09:30–13:30	27
17	Medium-sized supermarket	(11.6, 3.8)	250	08:00–12:00	08:30–12:00	18
18	Large supermarket	(13.2, 5.1)	480	09:00–14:00	09:30–13:30	29
19	Medium-sized supermarket	(14.1, 7.9)	260	08:30–12:00	09:00–11:30	17
20	Large supermarket	(12.8, 12.4)	520	09:00–15:00	09:30–14:30	30

Based on the data in Table 2, simulation experiments are conducted on the GA and the hybrid combined algorithm in this paper. Relevant parameters are set as follows: an initial population size of 50, a crossover probability of 0.8, a mutation probability of 0.05, and a maximum iteration number of 200. Each algorithm runs independently for 10 times to acquire the optimal routes of the case. The operation results are shown in the figure, and the relevant analysis is listed in the table.

Table 3. Optimal Routes Before and After Algorithm Optimization

Genetic Algorithm				Combined Algorithm			
Vehicle	Optimal Route	Mileage / km	Cost / Yuan	Vehicle	Optimal Route	Mileage / km	Cost / Yuan
1	0-12-1-2-3-20-0	28.6	406.1	1	0-12-3-1-2-11-4-0	32.4	386.1
2	0-11-10-9-8-7-0	23.7	329.9	2	0-10-6-16-14-9-20-0	35.2	404
3	0-13-14-15-16-17	26.2	340.4	3	0-13-7-15-8-17-18-0	30.8	362.4
4	0-18-19-5-4-6	30.1	383.3	4	0-19-5-0	9.8	246.8

Table 4. Result Analysis

State	Total distance / km	Total delivery time / h	Total cost / Yuan
Genetic Algorithm	116.8	9.96	1649.9
Hybrid Algorithm	108.2	9.64	1399.3
Reduce in proportion	7.4%	3.2%	15.2%

Table 5. Performance Analysis

State	Number of iterations to convergence	Average running time/s	Standard deviation of solution results
Genetic Algorithm	120	28.6	47.2
Hybrid Algorithm	80	21.3	18.5
Reduce in proportion	33.3%	25.5%	60.8%

Tables 3 to 5 show that the hybrid GA proposed in this paper performs significantly better than the single GA in urban CCL distribution problems. Relying on the high-efficiency heuristic search of the A* algorithm, this hybrid algorithm supplies high-quality initial populations for GA and remedies the defects of random initialization. While ensuring global optimality and completeness, it improves the overall operational efficiency. By collaboratively optimizing costs in transportation, cargo damage, refrigeration and other links, it ultimately reduces the total cost by 15.2%, the total travel distance by 7.4%, and the total delivery time by 3.2%, thereby improving customer satisfaction. Meanwhile, the number of iterations decreased by 33.3%, the average running time decreased by 25.5%, and the algorithm stability increased by 60.8%.

5 Sensitivity Analysis of Carbon Emissions

To verify the response pattern and robustness of the model under changes in carbon tax policy, other parameters are fixed, and only the carbon tax price is adjusted to calculate the changes in total driving mileage, carbon emissions, carbon emission cost, transportation cost, and total cost. The results are shown in Table 6:

Table 6. Sensitivity Analysis

Carbon Tax / (Yuan·kg^{-1})	Carbon Emissions / kg	Total Distribution Cost / Yuan
0.02	67.82	1402.55
0.05	67.56	1399.30
0.10	67.31	1398.12
0.15	66.99	1395.76
0.20	66.74	1393.23

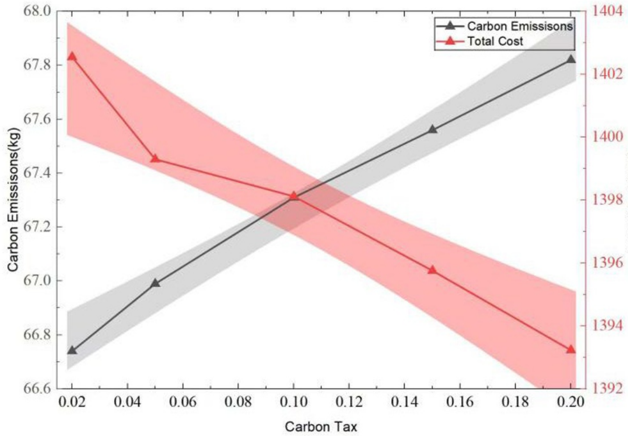

Fig. 1. Trend of total cost and the carbon tax price

As shown in the Figure 1, with the gradual increase in carbon tax price, the model automatically tends to select distribution routes with shorter mileage and lower fuel consumption. The total driving mileage decreases slightly with the rise of carbon tax, reflecting the green optimization orientation. Carbon emission cost increases approximately linearly with the carbon tax, but its impact on the overall total cost is moderate due to its low proportion in the total cost. When the carbon tax is increased from 0.02 yuan/kg to 0.20 yuan/kg (a 10-fold increase), the algorithm can output feasible solutions satisfying the constraints of vehicle load and time windows, and the path structure remains stable. This indicates that the model in this paper has good sensitivity and robustness to changes in carbon emission cost, and can adapt to future carbon tax policy adjustments and the requirements of green and low-carbon development.

6 Conclusion

With the rapid development of the CCL industry, rational route planning is critical for enterprises to cut costs and boost efficiency. Targeting this issue, this paper proposes a hybrid algorithm integrating the A* algorithm and GA to optimize distribution routes. A multi-objective function covering delivery cost, cargo damage and carbon emissions is constructed, with constraints such as vehicle load capacity and time windows incorporated. The A* algorithm is adopted to generate high-quality initial populations, addressing the random initialization defect of GA and enhancing solving efficiency. Comparative analysis verifies the effectiveness of the improved algorithm, which can provide theoretical support and decision-making references for similar enterprises.

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