

Research on Low-Carbon Scheduling Model and Algorithm Optimization of Multi-Temperature Zone Fresh Cold Chain

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Abstract:

The temperature of food storage environment is an important factor affecting the rate of change of freshness and food safety of fresh commodities. This paper investigates the variation of freshness decay rate under different optimal storage temperatures. Considering the cost of vehicle usage, loss cost of different kinds of fresh commodities, customer time window penalty cost, fuel consumption cost, carbon emission cost, and the traffic congestion that exists in the actual urban distribution, we establish a low-carbon cold chain network scheduling model aiming at the minimization of the logistics cost of the enterprise. Combining the C-W mileage-saving algorithm with genetic algorithm, the proposed multi-temperature zone fresh food cold chain scheduling model is proved to reduce the freshness loss of fresh food commodities, reduce the cost of the enterprise while reducing the carbon emission through simulation, and provide a reference for the decision-making of fresh food logistics enterprises.

Keywords:

Fresh Produce Cold Chain Logistics, Carbon Emission, Food Quality and Safety, Improved Genetic Algorithm, Vehicle Path Planning

1. Introduction

Yan Pang, Huali Luo [1] analyzed the green VRP model based on the traditional Vehicle Routing Problem at home and abroad, with the goal of reducing carbon emissions, and established different measurement models according to the different factors affecting carbon emissions. Kuo Y [2] considered the effect of load weight on the fuel consumption of transportation vehicles from the perspective of fuel consumption; Songyi Wang et al [3] introduced the carbon tax policy in the site selection-path problem of low-carbon cold chain logistics, and considered the impact on logistics costs as well as carbon emissions under the carbon tax policy. Teng Ren [4] improved the traditional ant colony algorithm with the objective of minimizing carbon emissions and considering the limitation of customer delivery time range.

Different from the previous static logistics vehicle transportation model, Maokang Du et al [5] fully consider the time-varying characteristics of the actual urban traffic network, and use adaptive genetic algorithms to solve the problem to improve customer satisfaction as much as possible. Hong Liu et al [6] based on the perishable and perishable characteristics of fresh products, on the basis of the Arrhenius deterioration equation and the deterioration function of the cold chain products, according to the relationship between the product quality of fresh commodities and the change of temperature, to establish a cold chain distribution optimization model to find the minimum degree of customer aversion and the minimum total cost. On this basis, Jing Wang et al [7] studied the impact of different temperature environments on the quality deterioration of fresh food based on the perspective of fresh food quality and safety, and established a multi-product phased fresh food cold chain operation model with multi-temperature control, which was solved by an improved particle swarm algorithm.

For the solution of cold chain logistics vehicle path problem, traditional heuristic algorithms such as forbidden search algorithm and ant colony algorithm have problems such as slow convergence speed and inability to perform global search, etc. Wenting Fang [8] utilizes the global search characteristics of A* algorithm and the collection of positive feedback mechanism of ant colony algorithm to improve and accelerate the algorithm search rate. Shuyun Wang [9] used K-means clustering algorithm to classify the customer nodes, and brought the clustering results into the ant colony algorithm as well as stochastic dynamic programming algorithm for updating and iterating to explore all the distribution paths that satisfy the conditions. Zhou [10] embedded a variable neighborhood search algorithm in NSGA-II algorithm to establish a dual-objective model with cost minimization and customer satisfaction maximization to strike a balance between multiple optimization objectives.

In this paper, to address the freshness loss problem of fresh commodities, the freshness decay function of different kinds of fresh commodities affected by temperature is established according to the T.T.T. theory [11]. A multi-temperature low-carbon cold chain logistics optimization model is constructed by considering different freshness decay rates of fresh commodities and time-varying traffic congestion.

2. Problem Description and Modeling

2.1. Description of the problem

Assuming that the unique distribution center and a number of customer points location, demand, time window and customer point service time according to the different limits of the range of randomly generated, according to the Shanghai local standard DB31/T388-2007 "Food Cold Chain Logistics Technology and Management Specification," the subdivided guidelines for the temperature requirements of the customer points required for the types of fresh commodities are classified as chilled commodities and frozen commodities. A number of multi-temperature refrigerated trucks are dispatched from the distribution center to distribute to all customer points. Subject to real-time traffic congestion. Under the premise of meeting the distribution needs of all customer points, the optimal distribution route scheme is sought to minimize the logistics cost of the whole process.

2.2. Symbol Definition

Table 1. Symbol List.

Parameter	Description
A	Set of the set of distribution points $A=\{0,1,2,\dots,N\}$, with a total of $N+1$ nodes, and 0 denotes the distribution center point, $i, j \in A$.
K	Set of a total of k logistics vehicles $K=\{1,2,\dots,k\}$.
V	denotes the average speed of logistics vehicle traveling.
Z	denotes the total cost of logistics and distribution.
M_0	denotes the deadweight of the multi-temperature refrigerated vehicle.
$M_{\max}$	denotes the maximum load capacity of the logistics vehicle.
d_{ij}	denotes the distance between customer point i and customer point j .
φ	denotes the fixed use cost of multi-temperature refrigerated trucks (unit: yuan/vehicle).
μ	denotes the fixed time cost of multi-temperature refrigerated truck use (unit: yuan/hour).
σ_1, σ_2	denote the energy consumption coefficients of compartment refrigeration of multi-temperature refrigerated vehicle in traveling, in loading and unloading respectively (unit: L/hour).
ρ	denotes the unit price of fresh products.
T	indicates the storage temperature of the refrigerated truck compartment.
θ_T	denotes the freshness coefficient of fresh commodities at T temperature at the corresponding time T .
F_{ij}^k	denotes the amount of fuel consumption (in L) generated by the k th refrigerated truck between node i and node j .
E_{ij}^k	denotes the carbon emission (in kg) generated by the k th refrigerated truck between node i and node j .
d_{ij}^k	denotes the distance traveled by the k th reefer truck from customer i to customer point j ($i, j \in A$).
λ_f	denotes the unit fuel consumption cost (unit: yuan/L).
λ_e	denotes the unit carbon tax cost (unit: yuan/kg).
ω_1, ω_2	denote the time-window penalty coefficients (unit: \$/hour) for the reefer trucks to arrive at the customer point early and late, respectively.
q_i	denotes the demand at customer point i (unit: kg).
q_{in}^k	denotes the mass of fresh produce left on board the k th refrigerated truck when it leaves customer i .
q_{ij}^k	denotes the load capacity of the k th refrigerated truck k when it is transported between nodes (i, j).
t_i	denotes the time at which the door of the refrigerated vehicle is opened for service at customer point i .
t_{ij}^k	denotes the traveling time of the k th refrigerated vehicle between nodes (i, j).
t_i^k	denotes the time when the k th reefer truck arrives at customer point i .
t_0^k	denotes the time when the k th refrigerated truck departs from the distribution center.
ET_i, LT_i	respectively, denote the hard time window agreed upon by customer i .
X_{ij}^k	1 if the k th vehicle passes through the section between customer point i and customer point j , 0 otherwise.
Y_i^k	1 if the k th reefer customer performs the service, 0 otherwise.

2.3. Fresh food cold chain scheduling objective function considering multi-temperature zones

The total logistics cost includes vehicle fixed use cost, cargo loss cost, time window cost, fuel consumption cost and carbon emission cost, respectively.

$$Z = Z_1 + Z_2 + Z_3 + Z_4 + Z_5 \quad (1)$$

2.3.1. Components of the total logistics cost function

(1) Vehicle fixed-use costs

The fixed cost of vehicle utilization Z_1 consists of the fixed departure cost of using the vehicle, the fixed time cost, and the waiting time cost of servicing the customer point.

$$Z_1 = \sum_{k=1}^K \sum_{i=0}^N \varphi + \sum_{k=1}^K \sum_{i=0}^N \sum_{j=0}^N \mu t_{ij}^k X_{ij}^k + \sum_{k=1}^K \sum_{i=0}^N \mu t_i Y_i^k \quad (2)$$

(2) Cost of loss of goods in multi-temperature zones

According to the empirical formula proposed by the Swedish chemist Arrhenius that allows for a more precise reaction rate versus temperature: $k = Ae^{\frac{-E_a}{RT}}$. In this paper, we assume product freshness $\rho = \rho_0 e^{-\theta_T t}$, where ρ_0 denotes the initial freshness of the product, which defaults to 1, $\theta_T = K_{\max} e^{\frac{-E_a}{RT}}$. $K_{\max}$: temperature-independent reaction rate constant (s⁻¹); E_a : activation energy (J*mol⁻¹); R : gas constant (J*mol⁻¹*K⁻¹), T : thermodynamic temperature (K). fresh commodities loss rate: $l_{qm} = [1 - e^{-\theta_T(t_i^k - t_0^k)}] * 100\%$. T can be set to 255K (-18°C) and 280K (7°C) for frozen and refrigerated goods with different needs at the customer point. The cost of loss of different goods for the customer point Z_2 is:

$$Z_2 = \sum_{k=1}^K \sum_{i=1}^N \rho q_i [1 - e^{-\theta_T(t_i^k - t_0^k)}] Y_i^k \quad (3)$$

(3) Time Window Penalty Costs

Fresh cold chain commodities require a high degree of timeliness, which is closely related to customer satisfaction, so there is a strict time window requirement for fresh food to reach the customer's point of delivery, and the delivery needs to be completed within the customer's specified time window $[ET_i, LT_i]$. Delivery staff according to the customer's different time windows for delivery. Considering the actual situation, in order to meet the overall distribution efficiency optimization, there may be individual customer points can not be completed according to the specified time delivery, resulting in early or delayed violation of the time window cost. According to the penalty function, the more time violations there are, the larger the total time window cost Z_3 is.

$$Z_3 = \begin{cases} \omega_1(ET_i - t_i^k), & t_i^k < ET_i \\ 0, & ET_i < t_i^k < LT_i \\ \omega_2(t_i^k - LT_i), & t_i^k > LT_i \end{cases}$$

$$Z_3 = \omega_1 \sum_{n=1}^N \text{Max}\{ET_i - t_i^k, 0\} + \omega_2 \sum_{i=1}^N \text{Max}\{t_i^k - LT_i, 0\} \quad (4)$$

(4) Fuel cost

The fuel consumption of multi-temperature refrigerated trucks comes from the driving process and compartment refrigeration generation, according to the study of

Qingting Li [12], the influence factors of refrigerated truck fuel consumption include compartment maintenance structure insulation performance, airtightness, refrigeration temperature, load, etc. In this paper, the focus is on considering the influence of load, refrigeration temperature, driving speed, vehicle parameters, etc. on the fuel consumption. According to the comprehensive mode emission model of Barth [13], it is assumed that the vehicle engine module coefficient is β_1 , the speed module coefficient is β_2 , and the load module coefficient is β_3 .

The amount of fuel consumption f_1 generated by the vehicle traveling is related to the speed v , load w , and distance traveled d by the equation:

$$f_1 = \sum_{k=1}^K \sum_{i=0}^N \sum_{j=0}^N \left[\frac{\beta_1 d_{ij}^k}{V} + \beta_2 d_{ij}^k V^2 + \beta_3 d_{ij}^k (M_0 + M_{\max}) \right] X_{ij}^k \quad (5)$$

Multi-temperature refrigerated trucks are refrigerated for the compartments to ensure that different commodities are at the optimal storage temperature generating a fuel consumption f_2 of:

$$f_2 = \sum_{k=1}^K \sum_{i=0}^N \sum_{j=0}^N \left(\frac{\sigma_1 d_{ij}^k}{V} + \sigma_2 d_{ij}^k t_i \right) X_{ij}^k \quad (6)$$

Total cost of fuel consumption for multi-temperature refrigerated trucks Z_4 .

$$Z_4 = \lambda_f (f_1 + f_2) \quad (7)$$

(5) Cost of carbon emissions

The carbon dioxide emissions produced by a refrigerated vehicle during traveling are proportional to the fuel consumption, and the carbon dioxide emission factor is φ . The fuel consumption of the vehicle, f_1 , f_2 , has been given. Therefore, the carbon emission cost Z_5 of a multi-temperature refrigerated vehicle is as follows.

$$Z_5 = \lambda_e \Psi (f_1 + f_2) \quad (8)$$

2.4. Mathematical model

In summary, the research objective of this paper is to minimize the cold chain logistics cost Z . The logistics cost Z includes the fixed use cost of multi-temperature reefer trucks, the cost of cargo loss, the cost of time window penalties, the cost of fuel consumption and the cost of carbon emissions, which are modeled as follows:

$$\text{Min} Z = Z_1 + Z_2 + Z_3 + Z_4 + Z_5 \quad (9)$$

$$\sum_{i=1}^N q_i Y_i^k < M_{\max}, \quad k \in K \quad (10)$$

$$\sum_{k=1}^K Y_i^k = 1, i \in [1, 2, 3, \dots, N] \quad (11)$$

$$\sum_{i=1}^N X_{i0}^k = \sum_{j=1}^N X_{0j}^k \leq 1, \quad k \in K \quad (12)$$

$$ET_i < t_i^k < LT_i \quad (13)$$

$$t_i + t_{ij}^k = t_j^k - t_i^k \quad (14)$$

$$\sum_{j=1}^N \sum_{k=1}^K x_{0j}^k \leq K \quad (15)$$

$$i, j \in A, k \in K \quad (16)$$

Eq. (9) indicates that the total logistics cost is minimum; Eq. (10) indicates that the total weight of fresh commodities carried by multi-temperature refrigerated trucks in a single delivery does not exceed the maximum load capacity of refrigerated trucks; Eq. (11) indicates that each customer can only be served by one vehicle; Eq. (12) indicates that the multi-temperature refrigerated trucks must be returned to the distribution center after serving the full range of customers; Eq. (13) indicates that the distribution needs to be completed within the customer's maximum tolerance limit; Eq. (14) indicates that the multi-temperature refrigerated trucks have continuity of distribution between two nodes; Eq. (15) indicates that the number of vehicles to carry out the service is not more than the total number of vehicles; Eq. (16) Points i and j belong to the set of distribution center points A , and k belongs to the set of logistics vehicles K .

3. Algorithm Design

In this paper, on the basis of genetic algorithm combined with C-W saving mileage algorithm, according to the distance from the distribution center to the customer points and the distance between the customer points, the total mileage of logistics vehicles is calculated as the initial population of genetic algorithm, on the basis of the initial population of individuals, generation by generation evolution, according to each generation of excellent fitness of the individual, according to the natural genetics genetic algorithms of selection, crossover, mutation, resulting in a new pooled population, the optimal fitness of the selected individual as the optimal solution, According to the genetic algorithm of natural genetics, selection, crossover and mutation are carried out in each generation to produce a new aggregate population, and the individual with the best fitness is selected as the optimal solution.

3.1. Algorithmic Process

According to the above chromosome coding method, the specific implementation process of the algorithm is as follows:

Step1: randomly generate DNA strands, generate population, initialize each variable and parameter;

Step2: Optimize the initial population P using the saving mileage algorithm for the population generated by Step1 to generate new DNA strands;

Step3: Calculate the individual fitness in different temperature zones according to the different freshness attenuation coefficients corresponding to different fresh commodities, and calculate the fitness value of each DNA strand in each generation of the population;

Step4: Select the parent population by fitness and eliminate individuals with low fitness, leaving individuals with high fitness;

Step5: generating new individuals using specific crossover probabilities and methods;

Step6: generating new individuals using specific mutation probabilities and methods;

Step7: Generate a new generation of population after crossover and mutation, and return to Step2. if the maximum number of iterations is reached, the optimal fitness value corresponding to the lowest logistics cost is output, and the iteration ends.

4. Calculus Analysis

4.1. Simulation data

In this paper, a randomly generated simulation example is used to verify the feasibility of the model and the improved genetic algorithm. Assuming that a distribution center point and twenty customer demand points are randomly generated in a square area of 50km×50km. According to the limited range of randomly generated customer point demand, time window, service time, multi-temperature zone into refrigerated and frozen two temperature zones, the customer point demand for fresh commodities in the frozen commodities and refrigerated commodities randomly selected between the specific data in Table 2, the rest of the model parameter data settings are shown in Table 3. Consider the actual road traffic congestion, Traffic is congested with an average speed of 20km/h during 7:45-8:45 and 11:00-12:00 hours and smooth with an average speed of 50km/h during 6:00-7:45 and 8:45-11:00 hours.

Table 2. Customer Information Sheet.

Coordinate Point	Horizontal Coordinate	Vertical Coordinate	Time Window	Serve Time (h)	Commodity Temperature Zone	Quantity Demanded (Kg)
distribution center	23.0	27.0				
Customer 1	1.0	33.0	(6,7)	0.5	Refrigeration	17.6
Customer 2	42.0	4.0	(7,12)	0.167	Refrigeration	12
Customer 3	35.0	1.0	(7,10)	0.25	Refrigeration	12.1
Customer 4	33.0	24.0	(7,9)	0.5	Frozen	2.2
Customer 5	31.0	4.0	(7,12)	0.5	Refrigeration	4.5
Customer 6	28.0	9.0	(6,7)	0.5	Refrigeration	9.5
Customer 7	48.0	4.0	(6,9)	0.167	Frozen	8.7
Customer 8	31.0	28.0	(8,13)	0.333	Refrigeration	36
Customer 9	4.0	6.0	(6,7)	0.167	Refrigeration	32.4
Customer 10	22.0	6.0	(7,10)	0.333	Refrigeration	19.1
Customer 11	40.0	50.0	(6,8)	0.167	Refrigeration	5.5
Customer 12	26.0	40.0	(6,11)	0.25	Frozen	11.3
Customer 13	43.0	47.0	(8,10)	0.167	Refrigeration	5.5
Customer 14	5.0	11.0	(8,10)	0.333	Frozen	13.7
Customer 15	50.0	34.0	(7,11)	0.333	Refrigeration	22.7
Customer 16	2.0	47.0	(7,11)	0.25	Refrigeration	1.8
Customer 17	35.0	30.0	(8,12)	0.25	Frozen	27.6
Customer 18	22.0	28.0	(8,11)	0.333	Frozen	16.8
Customer 19	27.0	34.0	(7,10)	0.5	Refrigeration	24.2
Customer 20	43.0	32.0	(6,10)	0.167	Frozen	5.5

Table 3. Model parameter values.

Model parameter	Retrieve a value	Model parameter	Retrieve a value	Model parameter	Retrieve a value	Model parameter	Retrieve a value	Model parameter	Retrieve a value
M_0	1930kg	$M_{\max}$	100kg	φ	200yuan/vehicle	σ_1	3L/h	σ_2	6L/h
ρ	10yuan/kg	λ_f	7yuan/L	λ_e	0.07yuan/kg	ω_1	6yuan/h	ω_2	9yuan/h
V	50km/h	β_1	1.004×10^{-3} L/h	β_2	3.896×10^{-7} L $\cdot$ h 2 /km 3	β_3	1.328×10^{-8} L/km $\cdot$ kg	Ψ	2.621 kg/L

4.2. Calculus Analysis

The improved genetic algorithm is run 20 times, and the average running time is 663.98s. where the total cost of the most program is shown in Figure 1. As can be seen in Figure 4, the minimum logistics cost is found in the 29th generation as is 3952.1, and the minimum cost of the population decreases gradually with the increase in the number of iterations.

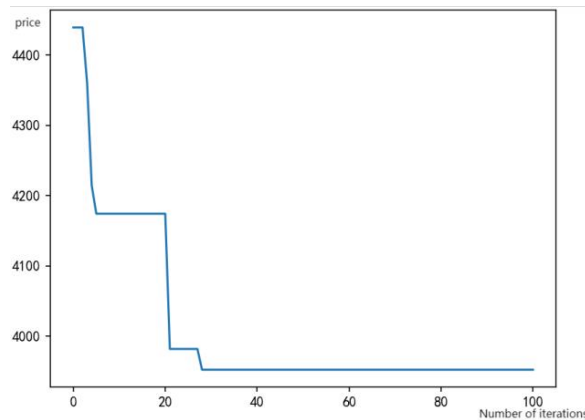


Figure 1. Improved Genetic Algorithm Optimal Total Cost.

Considering the distribution roadmap of multi-temperature cold chain trucks in different cases of customer demanded commodities is shown in Figure 2, and the optimal scheduling scheme is shown in Table 4.

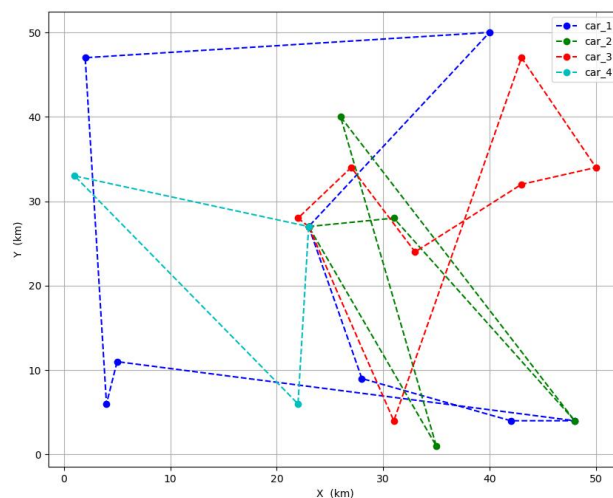


Figure 2. Improved Genetic Algorithm Vehicle Distribution Routes.

4.3. Comparison and Analysis of Experimental Results of Fresh Commodities in Dual Temperature Zones

In order to verify the effectiveness of the improved genetic algorithm after combining the C-W mileage-saving algorithm, this paper uses the traditional genetic algorithm for solving according to the same simulation model and compares the results. Traditional genetic algorithm optimal program total cost of \$4203.4, traditional genetic algorithm results in logistics routes as shown in Figure 6, through the Table 5. two algorithms to solve the optimal program total cost and solution time comparison can be seen, improve the genetic algorithm to reduce the total distance of 99.48km, compared with the original save 18.5% distance at the same time to reduce carbon emissions. The total cost of enterprise logistics saves 251.3 RMB, which is 5.98% lower than before. The difference between the two running times is not significant, and the performance of the improved genetic algorithm is significantly better than the traditional genetic algorithm, which can effectively solve the logistics scheduling problem of multi-temperature cold chain trucks.

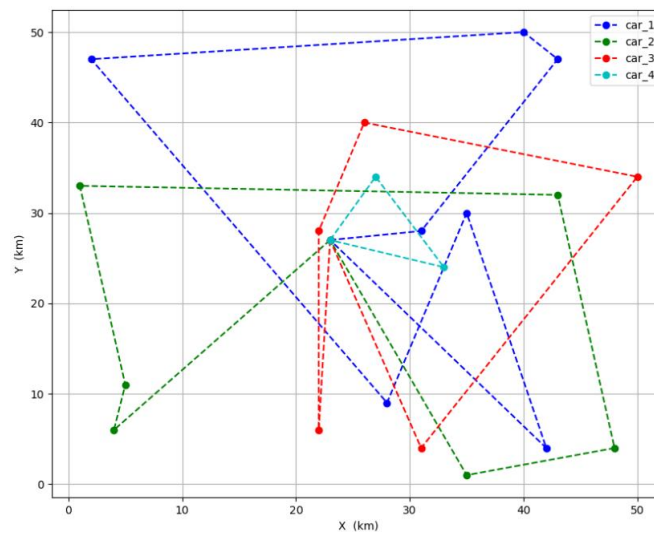


Figure 3. Traditional Genetic Algorithm Vehicle Distribution Routes.

Table 4. Dual-temperature zone refrigerated truck optimal distribution program.

Car	Improved Genetic Algorithm Optimal Path	Traditional Genetic Algorithm Optimal Path
1	0→6→2→7→14→9→16→11→0	0→8→13→11→16→6→17→2→0
2	0→8→17→12→3→0	0→9→14→1→20→7→3→0
3	0→18→19→4→20→15→13→5→0	0→10→18→12→15→5→0
4	0→10→1→0	0→19→4→0

Table 5. Improved Genetic Algorithm vs. Traditional Genetic Algorithm,

	Total distance	Total logistics costs	Running time
Improved genetic algorithms	438.38km	3952.1yuan	638.6s
Traditional genetic algorithms	537.86km	4203.4yuan	604.9s

4.4. Comparison and analysis of experimental results of fresh commodities in multi-temperature zones

In order to verify the effectiveness of the improved genetic algorithm for the cold chain logistics vehicle scheduling of multi-category fresh commodities demand, according to the Shanghai local standard DB31/T388-2007 “Food Cold Chain Logistics Technology and Management Specification” subdivided guideline

temperature requirements, the customer point of the customer information table of the customer point of the commodity temperature zone request from the original frozen and refrigerated two commodity temperature zone classifications, subdivided into three categories of different temperature zones, namely The optimal storage temperature for soybean products and fruits and vegetables is 1° to 10° , the optimal storage temperature for frozen split animal meat and frozen food is -18° , and the optimal storage temperature for aquatic products and boxed lunches is 0° to 4° .

Table 6. *Improved Genetic Algorithm vs. Traditional Genetic Algorithm Route.*

Car	Improved Genetic Algorithm Optimal Path	Traditional Genetic Algorithm Optimal Path
1	0→10→3→2→7→14→9→0	0→18→19→4→16→14→9→11→0
2	0→18→8→4→20→13→11→16→1→0	0→8→15→20→10→5→6→0
3	0→19→12→17→15→6→5→0	0→2→3→7→1→12→17→13→0

Table 7. *Improved Genetic Algorithm vs. Traditional Genetic Algorithm.*

	Total distance	Total logistics costs	Running time	Carbon footprint
Improved genetic algorithms for commodities with multiple temperature zones	354.052km	2730.641yuan	662.1s	143.916L
Conventional Genetic Algorithms for Commodities in Multiple Temperature Zones	476.504km	3065.405yuan	612.36s	171.594L

Table 6 shows the comparison of the algorithm routes under multi-temperature fresh commodities distribution. According to Table 7, comparing the solution results of the genetic algorithm before and after the improvement under the customer demand of multi-temperature fresh commodities, it can be found that the total cost of logistics of the enterprise is saved by 10.92%, and the total mileage of the delivery of cold-chain vehicles is reduced by 34.59% compared with the previous one, and the carbon emission is reduced by 16.13%, which means that the improved genetic algorithm can solve the practical problem of multi-temperature fresh commodity cold chain distribution efficiently.

5. Conclusions

In this paper, for the problem of coordinated planning of cold chain logistics distribution routes for fresh commodities in multi-temperature zones, while considering the vehicle scheduling model established under the actual road traffic congestion, a high-quality solution can be obtained by introducing the C-W mileage-saving algorithm into the genetic algorithm. The results show that the improved genetic algorithm reduces the enterprise logistics costs while effectively reducing carbon emissions, verifying the effectiveness and feasibility of the model. It provides a reference for creating a fresh and cold chain logistics enterprise with low-carbon logistics and green economy.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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