Optimization Study of Cold Chain Logistics Distribution Path Considering Carbon Emission and Time Window Constraints

Xue Wang[1*], Jun Wan[2], Jiancheng Huang[3]

[1]College Of Business Administration, Liaoning Technical University, Liaoning Province, Huludao, 125000, China
[2]Basic Teaching Department, Liaoning Technical University, Liaoning Province, Huludao, 125000, China
[3]College Of Business Administration, Liaoning Technical University, Liaoning Province, Huludao, 125000, China
[1*]lgdwangxue163.com;
[2]wanjunchina@vip.163.com
[3]huangjiancheng0604@163.com

Abstract. Aiming at the characteristics of cold chain logistics with high timeliness and high cost, taking into account the influence of temperature change on the decay rate of fresh food in the unloading process, the cost of carbon emission in the transportation process and cold storage process, and the cost of penalty for violating the time window, etc., we constructed a mathematical model aiming at the minimization of the total cost of transportation, and solved it with an improved adaptive genetic algorithm. Taking a district in Beijing as an example, we make decisions on transportation paths and vehicles, and analyze the results before and after optimization to verify the effectiveness of the model and algorithm. The results show that the total distribution cost after optimization is reduced by 15.36% compared with the pre-optimization, and the carbon emission cost is reduced by 8.70% compared with the pre-optimization, and the modified genetic algorithm has a significant effect in reducing the distribution cost and carbon emission cost, which can be reduced by means of reasonable arrangement of distribution paths and transportation vehicles.

Keywords: carbon emission; cold chain logistics; path optimization; genetic algorithm

1 INTRODUCTION

Since 2020, China has made clear the goal of "carbon peak and carbon neutrality", various industries have responded and actively promoted green development[1]. As a major emitter of carbon emissions in the field of transportation, in addition to vigorously developing new energy technologies, it is also an effective means to reduce carbon emissions by optimizing logistics and transportation routes. Especially in the field of cold

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chain logistics, due to its high energy consumption and high time efficiency, the optimization of its vehicle transport path has far-reaching significance for energy saving, emission reduction as well as the realization of sustainable economic and environmental development[2].

After Dantzig and Ramser[3]first proposed the vehicle path optimization problem in 1959, related scholars at home and abroad have studied the vehicle path optimization problem in the field of cold chain logistics by considering different scenarios, constraints, and research methods, etc. Zheng et al.[4]combined multimodal transportation with cold chain logistics, and used the timeliness of delivery and the freshness of the cold chain products to portray customer satisfaction, which is solved by an improved particle swarm algorithm. Qiu Jinhong et al[5]studied the multi-objective green vehicle path optimization problem with time window constraints and transport efficiency equilibrium. Xu Xiangbin et al[6]considered the effects of vehicle restriction and two-dimensional crate constraints on the vehicle path optimization problem.Yan[7]constructed a joint distribution model for cold chain logistics by taking the minimization of total cost as the objective function. With the development of modern economic technology, the influence of time factor is more and more concerned in the process of cold chain logistics and distribution of fresh agricultural products.Solomon and Desrosiers et al[8]firstly applied the constraints with time windows to the vehicle path, which provides useful guidelines for the path planning of fresh logistics vehicles in the future. Qian Li et al[9]constructed an optimal model with the objectives of minimizing the time window cost and minimizing the cargo loss rate, etc,and proposed an optimal solution by using the non-dominated sorted ant colony algorithm under the elite strategy. Shuyun Wang et al[10]constructed a cold chain product delivery path optimization model considering customer time window with the objective of satisfying customer time window requirements. Li[11]proposed a stochastic vehicle path problem with soft time windows and solved it. On the basis of comprehensively considering various factors such as transportation cost, carbon emission cost, and cargo damage cost. Jian Chen[12]systematically analyzed the various costs in the cold chain logistics and distribution process, and established a path optimization model with the maximization of the enterprise's economic efficiency as the objective function.Wang et al[13]established a cold chain logistics path optimization model with the minimization of the total cost on the basis of the carbon tax, and designed a recurrent evolutionary genetic algorithm to solve the model. An Lu et al[14]constructed an optimization model based on the quantum ant colony algorithm for the high carbon emission problem in cold chain logistics with the optimization objectives of minimizing the carbon emission cost and minimizing the comprehensive distribution cost.

In the past research, most scholars only consider the carbon emission factor or time window constraints, and there are few studies that comprehensively and comprehensively consider the joint influence of both and establish a mathematical model, based on this, this paper constructs a model for minimizing the total cost of distribution that considers the time window and carbon emission constraints, and adopts the optimized genetic algorithm to solve the problem, and verifies the validity of the model through actual cases.

2 PROBLEM DESCRIPTION AND MODELING

2.1 Problem Description and Assumptions.

The cold chain logistics path optimization problem studied in this paper introduces time window and carbon emission constraints on the basis of the traditional path optimization model. The problem can be described as follows: distributing goods from 1 distribution center to multiple customer points, the location of the customer points, the demand, the time window and other information is known, the vehicles uniformly start from the distribution center, while satisfying the constraints of customer demand, time window constraints, and vehicle loading, carbon emission cost is introduced into the total cost, and the distribution route is reasonably planned with the goal of minimizing the total cost.

The assumed conditions in the distribution transportation process are as follows:

(1) The number of refrigerated vehicles in distribution centers is limited, and refrigerated vehicles have capacity limitations and may not be overloaded;

(2) Considering traffic congestion, vehicles travel at different speeds at different times;

(3) With the passage of time, the freshness of the goods decreases, which will generate a certain cost of cargo damage;

(4) Refrigerated vehicles start and end at distribution centers.

2.2 Definition of Symbols

The relevant variables and meanings involved in this paper are shown in Table 1

Table 1. Definition of symbols

Variable name	Variable meaning
N	Numbering of all customer points,N={0,1,2,…,N}
K	Numbering of all vehicles，K={0,1,2,…,K}
i、j	Node indexes，i、j={1,2,3,…,N}
Q_{ij}	Quality of fresh produce remaining on board refrigerated vehicles as they leave customer sites i
$\gamma(q_{ij})$	Fuel consumption per unit distance of goods loaded in distribution vehicles from supermarket i to j
η	Carbon emissions per unit distance traveled by goods in vehicle distribution units
β	Constant
H	Compartment heat load of refrigerated trucks
ΔT	Temperature difference between inside and outside the cabin
H_r	Heat load when refrigerated truck is open
f_K	Fixed cost per refrigerated transport vehicle

P_1	Unit price of fresh produce
P_2	Refrigerated truck unit refrigeration cost
P_3	Unit price of fuel oil
M	Infinitely large constant
φ_1、φ_2	Penalty costs for vehicles arriving earlier and later than the time window
q_i	Demand for fresh produce at customer point i
d_{ij}	Straight-line distance between client points i and j
β_1	Spoilage rate of fresh produce at appropriate temperatures
β_2	Product spoilage rate when unloading and opening doors
t_0^K	The moment vehicle k arrives at customer point i from the distribution center
t_{si}	Service time required for customer dot i
t_f^K	The moment the vehicle k has served the last customer point
t_{ij}^K	Time required for vehicle k to travel from customer point i to j
$[t_{i,E}\ t_{i,L}]$、 $[t_{i,EE}\ t_{i,LL}]$	Customer point i's desired time window range to be served and acceptable time window range to be served
x_{ij}^K	0-1 Decision variable: refrigerated vehicle k departs from customer point i to j. This value is 1, otherwise it is 0
y_i^K	0-1 Decision variable: the value is 1 if refrigerated vehicle k serves customer i, and 0 otherwise
S_K	0-1 Decision variable: the value is 1 if refrigerated vehicle k is involved in the distribution, and 0 otherwise

2.3 Model Construction

Based on the parameters and variables defined above, a mathematical model is constructed with the objective of minimizing the total distribution cost.

$$Z_{\min} = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 \tag{1}$$

$$C_1 = \sum_{K=1}^{K} f_k s_K \tag{2}$$

$$C_2 = \sum_{K=1}^{K} \sum_{ij=0}^{N} P_3 \gamma(q_{ij}) x_{ij}^K d_{ij} \tag{3}$$

$$C_3 = \sum_{K=1}^{K} \sum_{i=0}^{N} y_i^K P_1 [q_i (1 - e^{-\beta_1 (t_i^K - t_0^K)}) + Q_{in} (1 - e^{-\beta_2 t_{si}})] \tag{4}$$

$$C_4 = \sum_{K=1}^{K} H \times (t_f^K - t_0^K) \times P_2 + \sum_{K=1}^{K} \sum_{i=0}^{N} P_2 H_r^{'} t_{si} y_i^K \tag{5}$$

$$C_5 = 2M + \varphi_1 \sum_{t=0}^{N} \max\{t_{i,E} - t_i, 0\} + \varphi_2 \sum_{t=0}^{N} \max\{t_i - t_{i,L}, 0\} \tag{6}$$

$$C_6 = C_{co_2}\sum_{K=1}^{K}\sum_{i,j=0}^{N} x_{ij}^{K} d_{ij}(\lambda\gamma(q_{ij})+\eta q_{ij}) \tag{7}$$

s.t.

$$\sum_{k=1}^{k} y_i^k = \begin{cases}1, & i=1,2,\ldots N\\ \mathrm{k}, & i=0\end{cases} \qquad \forall k\in K \tag{8}$$

$$\sum_{j=1}^{N} x_{ij}^k = \sum_{j=1}^{N} x_{ij}^k \le 1 \qquad i\text{=}0,\forall \mathrm{k}\in \mathrm{K} \tag{9}$$

$$\sum_{i,j=0}^{N} x_{ij} d_{ij} \le D \qquad \forall i,j\in N \tag{10}$$

$$\sum_{k=1}^{k}\sum_{i=1}^{N} y_i^k = N \qquad \forall i\in N,\forall k\in K \tag{11}$$

$$\sum_{i=1}^{N} y_i^k q_i \le Q_m \qquad \forall i\in n,\forall k\in K \tag{12}$$

$$t_j^k = \sum_{i=0}^{N}\sum_{k=1}^{k} t_i^k + t_{si} + t_{ij}^k \tag{13}$$

Equation (1) is the objective function, which indicates that the total distribution cost is minimized. Equation (2) represents the fixed cost of refrigerated transportation vehicles. Equation (3) represents the transportation cost of the vehicle. Equation (4) represents the cost of cargo damage. Equation (5) represents the refrigeration cost. Equation (6) represents penalty cost. Equation (7) represents the carbon emission cost. Equation (8) denotes that there are k distribution vehicles. Equation (9) indicates that the vehicles start from the distribution center and return to the distribution center after completing the distribution. Equation (10) denotes the vehicle traveling distance constraint. Equation (11) represents the number of customer points. Equation (12) denotes the vehicle load constraint. Equation (13) indicates that the distribution process is continuous.

3 ALGORITHM DESIGN

In order to solve the above objective function more efficiently, genetic algorithm is used, which has good global search ability and robustness, high search efficiency, and is very suitable for dealing with nonlinear optimization problems such as path planning, but it is prone to premature phenomenon and falling into local optimal solutions. Therefore, here the genetic algorithm cross-mutation approach is improved to protect the optimal solution by using the elite retention strategy. The flow of the algorithm is shown in Figure 1

3.1 Chromosome Coding

The algorithm is encoded in natural numbers, with number 0 denoting the distribution center and numbers 1,2…N being the individual customer points. When the number of customer points is N and the number of reefer trucks is K, the chromosome length is N+K+1.

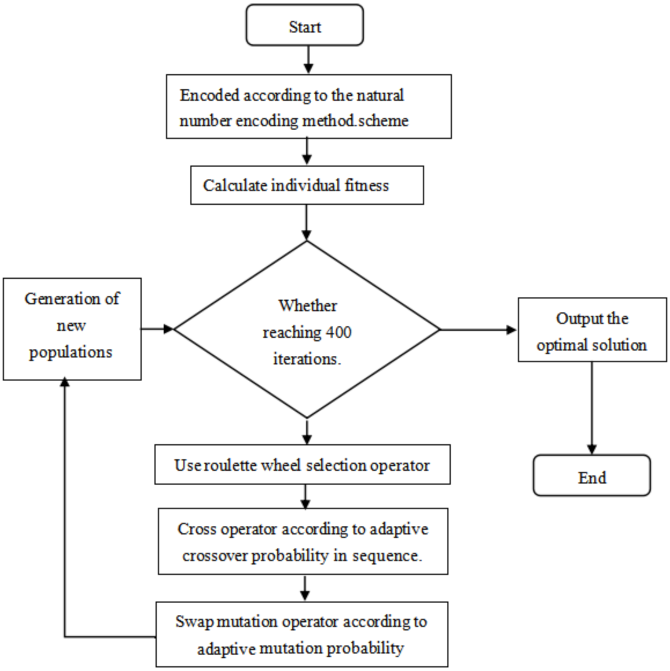


Fig. 1. algorithm flow chart of the algorithm

3.2 Initializing the Population

The random function generation method is used here to initialize the population, which is faster and less computationally difficult, so this method is taken to generate a population with an initial population size of 200.

3.3 Adaptation Function

Adaptation function is an important indicator to determine the degree of individual adaptation to the environment, the adaptability function is generally a positive number of the greater the value of the better, but this paper establishes the optimization objective is to minimize the total cost of distribution, so the inverse of the objective function as the adaptability function of this paper, the higher the value of adaptation. The function expression is shown in equation (14)

$$f_i = \frac{1}{c_i}(i = 1, 2 \ldots, N_p) \tag{14}$$

equation (14) fi is the fitness function of chromosome i; ci is the objective function of the chromosome; and Np is the population size.

3.4 Choosing an Operator

Selection operator operation selects individuals with high fitness from the population, the higher the fitness value, the higher the genetic probability will be selected individuals to form the parent population to reproduce the next generation, and then generate a new population for chromosome crossover and mutation operations. In this paper, the roulette method is used for the selection operation, comparing the fitness values of individuals through the selection probability formula, so as to select the good chromosomes into the next generation. The function expression is equation (15)

$$P_i = \frac{f_i}{\sum_{i=1}^{N} f_i} \tag{15}$$

3.5 Intersection Operator

After the crossover operation, the newly generated offspring need to be evaluated. If the newly generated offspring have better stress than the parent, the crossover offspring will be directly included in the next generation of the population; otherwise, mutation will be required.

3.6 Variational Operators

By comparing the fitness of the post-mutated chromosomes. If the fitness of the post-mutated chromosome is better than the fitness of the previous generation, it is directly incorporated into the next-generation population, and together with other chromosomes with higher fitness, it forms a new population; conversely, the chromosomes obtained from the previous generation after crossover are retained.

4 EXPERIMENT AND ANALYSIS

4.1 Basic Data

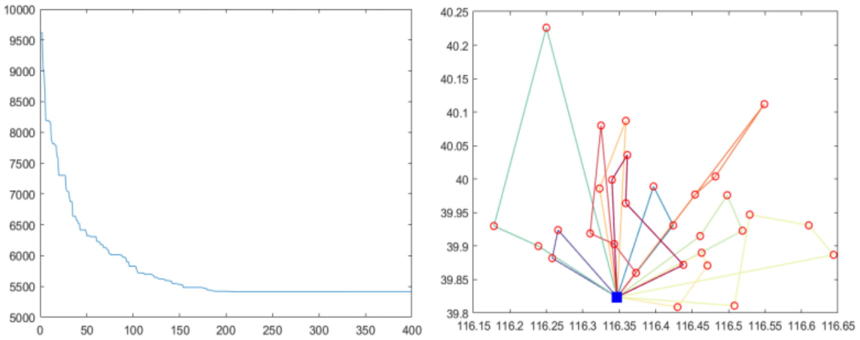
A fresh produce distribution center in a district of Beijing is taken as the object of study, and the distribution center needs to distribute fresh produce to 30 customer points. Distribution center and customer point information as shown in Table 2, the coordinates of the distribution center is (116.347,39.824), the distribution center has a total of 15 Foton Aoling refrigerated transport vehicles. Parameter settings: Fixed costs of vehicles fk=220yuan, Speed of refrigerated truck v=28km/h, Vehicle quality qm=1500kg, Price of fresh products P1=8 yuan/kg, Refrigerated vehicle unit refrigeration cost P2=2 yuan/h, Fuel price P3=6.8 yuan/L, Carbon dioxide emission factor λ=2.67kg/L, Carbon emission generated by the vehicle traveling unit distance. η= 0.00075kg/km, Degree of cracking of the compartment body β=0.08, Temperature difference between inside and outside the compartment ΔT=20°C, Penalty cost φ1=40 yuan/h, φ2=80yuan/h, Fuel consumption of the vehicle γ0=0.13 L/km, Heat transfer rate R=2.89W/(m2·k), Area of the carriage body exposed to solar radiation S=36m2, Volume of the carriage VK=4160mm×2180mm×2180mm, spoilage rate of fresh produce β1=0.002, β2=0.003, Door opening frequency coefficient ω=0.625.

Table 2. Customer information sheet

Number	Coordinates		Quantity demanded	Acceptable time window	expectation time window	Service time
0	116.347	39.824	0	05:30-17:00	05:30-17:30	0
1	116.361	40.036	450	05:55-09:50	06:10-09:20	15
2	116.323	39.986	430	06:05-10:20	06:30-09:50	14
3	116.31	39.919	520	06:00-09:30	06:25-09:10	14
4	116.343	39.903	550	06:15-10:20	06:45-09:50	10
5	116.438	39.872	510	06:30-10:05	07:00-09:50	13
6	116.373	39.86	495	06:15-10:20	06:45-09:50	11
7	116.424	39.931	460	06:00-09:20	06:15-09:05	13
8	116.454	39.977	490	06:30-10:20	07:00-10:05	14
9	116.239	39.9	475	06:15-09:50	06:30-09:35	9
10	116.471	39.871	415	05:45-09:35	06:00-09:20	11
11	116.644	39.887	560	06:00-10:20	06:30-09:35	14
12	116.519	39.923	290	05:55-09:50	06:15-09:35	9
13	116.325	40.08	660	06:15-10:20	06:30-09:50	10
14	116.549	40.112	545	06:15-09:50	06:30-10:05	11
15	116.34	39.999	330	06:00-09:50	06:30-09:35	13
16	116.266	39.924	500	06:05-10:30	06:30-10:05	12
171	116.359	40.087	520	06:15-10:20	06:25-10:05	9
18	116.482	40.004	500	06:00-09:50	06:15-09:35	14
19	116.463	39.89	550	06:35-10:35	07:00-10:05	8
20	116.359	39.964	485	05:45-10:05	06:05-09:20	9
21	116.61	39.931	525	06:00-09:30	06:30-09:00	9
22	116.178	39.93	390	06:20-10:05	06:40-09:35	11
23	116.461	39.915	480	06:30-10:30	07:00-09:35	10
24	116.397	39.989	510	05:45-09:30	06:10-09:00	12
25	116.529	39.947	440	06:20-09:40	06:40-09:20	11
26	116.508	39.811	425	06:00-10:00	06:15-09:35	13
27	116.258	39.882	465	06:05-09:55	06:30-09:30	11
28	116.25	40.226	500	05:50-09:40	06:20-09:10	10
29	116.43	39.809	455	06:30-10:20	07:00-09:35	11
30	116.498	39.976	530	05:55-09:30	06:15-09:10	15

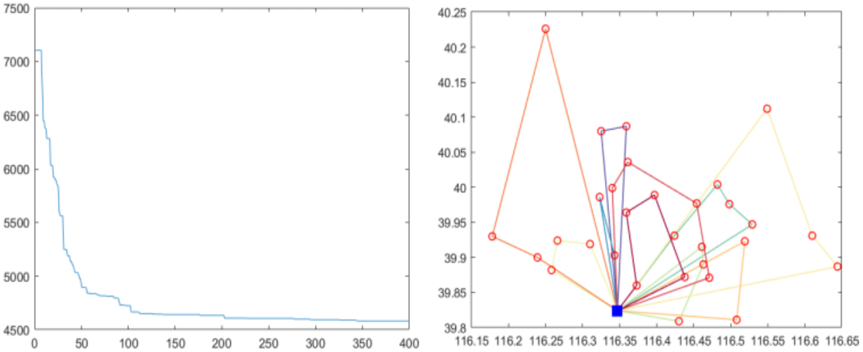
4.2 Comparative Analysis

Matlab R2019b software was used for programming, and simulation tests were carried out for the genetic algorithm before and after optimization using the above algorithm respectively. The population size is set to 100, the crossover probability is 0.9, the mutation probability is 0.1, and the maximum number of iterations is 400.After the simulation test, the optimal planning path of the calculus under the 2 algorithms is obtained. The running results are shown in Fig. 2 and Fig. 3, and the results are analyzed in Table 3 and Table 4.



（1）Genetic algorithm iteration graph （2）Vehicle distribution routes

Fig. 2. Schematic diagram of running results before algorithm optimization



（1）Genetic algorithm iteration graph （2）Vehicle distribution routes

Fig. 3. Schematic diagram of running results after algorithm optimization

Table 3. Optimal delivery route before and after algorithm optimization

Vehicle number	Before Optimization		After Optimization	
	Optimal path	Cost(yuan)	Optimal path	Cost(yuan)
1	0-16-27-0	401.819	0-13-17-0	395.369

2	0-24-7-0	415.527	0-2-4-0	333.694
3	0-9-22-18-0	705.204	0-7-18-30-25-0	477.352
4	0-23-30-12-0	549.335	0-29-19-23-0	391.566
5	0-26-25-21-11-0	787.155	0-3-16-27-0	360.19
6	0-29-10-19-0	453.687	0-14-21-11-0	665.056
7	0-2-17-0	439.943	0-26-12-0	473.253
8	0-8-18-14-0	633.004	0-9-22-28-0	578.38
9	0-6-4-3-13-0	482.861	0-15-1-8-10-0	484.216
10	0-5-20-1-15-0	535.799	0-6-20-24-5-0	414.499

Table 4. Comparison of results before and after optimization

Mode	Cost of carbon emissions /yuan	Total cost / yuan
Pre-optimization	9.2	5413.534
Post-optimisation	8.4	4581.945
Decrease in the same proportion	8.70%	15.36%

According to Figures 2 and 3 and Tables 3 and 4, it can be seen that before and after the optimization of the algorithm, the distribution center needs to send 10 refrigerated transport trucks to distribute goods to customers, but the algorithm before and after the optimization of the number of iterations and the arrangement of vehicle paths show obvious differences: in terms of the number of iterations, the genetic algorithm before optimization began to converge in the iteration to about 180 generations, and the optimization began to converge in about 120 generations, and the optimized The genetic algorithm convergence process is smoother, faster and more efficient; it can be seen that the optimized paths are all better than the pre-optimization, the carbon emission cost is reduced by 8.70%, and the total cost is reduced by 15.36% after optimization.

5 CONCLUSIONS

With the rapid development of the cold chain logistics industry, the cold chain logistics path optimization problem is studied based on the characteristics of high energy consumption and high time efficiency requirements of cold chain logistics. Firstly, on the basis of the traditional path optimization model, time window and carbon emission constraints are introduced. Second, the carbon emission cost was quantitatively analyzed, and the path optimization model was constructed, taking the minimization of total cost as the optimization objective. Finally,the model was solved using the improved genetic algorithm. The results show that the improved genetic algorithm has better adaptability and convergence for solving the distribution path optimization problem, improves the distribution efficiency, and further reduces the total distribution cost and carbon emission cost. It provides a relatively valuable reference for solving the current cold chain logistics distribution path optimization problem of Chinese enterprises.

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