Multi-Target Cold Chain Logistics Path Optimization and Algorithm Solution

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Abstract. Considering the high cost of fresh products in the distribution process, the goal of minimizing the cost of cold chain logistics distribution of fresh products is to fully consider all costs incurred in the process of fresh cold chain logistics distribution. On this basis, a customer satisfaction maximization function is introduced to build a multi-target path optimization model for cold chain logistics distribution of fresh products. The improved non-dominant sorting genetic algorithm (NSGA-II) is used to solve the model, and the designed algorithm can obtain the Pareto optimal solution in a short time. Therefore, the model built can effectively solve the problem of optimizing the distribution path of fresh cold chain logistics, and help fresh enterprises achieve a balance between reducing costs and improving customer satisfaction in the process of product distribution.

Keywords: Fresh Products, Cold Chain Logistics, Path Optimization, Customer Satisfaction, NSGA-II Algorithm.

1 INTRODUCTION

Due to the particularity of fresh products, the cost of distribution is extremely important. With the development of society, people pursue a high-quality life and have certain requirements for the quality of fresh products, so customer satisfaction is also very important.

Many scholars have conducted extensive research on the cold chain logistics path problem, which is more suitable for daily life in the vehicle routing problem (VRP). In the optimization of the cold chain logistics path, cost minimization is the main goal [1]. Under the concept of environmental protection, fuel consumption in the process of cold chain logistics transportation also needs to be considered [2]. To better solve the multi-path distribution problem, the punishment function and time window can be added to the model [3]. In the distribution of fresh products, it is necessary to ensure that the products are fresh and the loss is minimized [4]. The multi-objective model can solve the path optimization problem more comprehensively [5].

Due to the high-quality requirements for fresh products, customer satisfaction is just as important as distribution costs in the distribution path planning of these products. To reflect customer satisfaction, it's common to include punishing costs for delays. This article proposes a separate target function for measuring customer satisfaction. By taking into account the unique characteristics of fresh products, the first cost minimization

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target function is established, including vehicle fixed cost, transportation cost, refrigeration cost, cargo loss cost, carbon emission cost, and time penalty cost, and then take the maximum customer satisfaction as the second target function to build a fresh cold chain logistics vehicle path optimization dual target model. The improved NSGA-II algorithm is used to solve the model and provide a reference for the improvement and development of cold chain logistics distribution planning for fresh enterprises. The model effectively achieves a balance between cost and customer satisfaction.

2 MODEL INTRODUCTION

2.1 Model Description

This research paper aims to optimize the distribution path of fresh products in cold chain logistics. The distribution of fresh goods is done through a distribution center to multiple customers. The delivery vehicles have limited capacity, and customers have a specific time for the arrival of the vehicle. With this distribution process in place, a dual-objective optimization model is developed. The main goal is to reduce the total cost, which encompasses vehicle fixed costs, transportation costs, refrigeration costs, cargo loss costs, carbon emission costs, and time penalty costs. Additionally, it is important to prioritize customer satisfaction throughout the distribution process.

2.2 Conditional Hypothesis

1) After completing their tasks, all vehicles depart from and return to the distribution center.2) The location information of all nodes is known, and the customer's demand is known. 3) The vehicle should maintain a uniform speed during the distribution process. 4) Each customer point can only be delivered by one car, and it can only be delivered once. 5) The temperature of the vehicle remains unchanged during the distribution process, regardless of other factors, and the cost of loss is only related to time. 6) The vehicle's loading capacity during distribution cannot exceed its maximum rated load.

2.3 Symbol

The symbol interpretation is shown in Table 1.

Table 1. Description of the main symbols

Parameter	Symbol interpretation
N	All node collection (N=0, 1, 2, ...n; 0 represents the distribution center; 1, 2, ...n represents the customer, that is, the distribution node)
Q	Maximum rated load of the vehicle
m	Number of vehicles owned by the distribution center
k	Collection of all vehicles (K=1, 2, ...m)
d_{ij}	Distance from customer i to customer j
v	Average speed of the vehicle
q_i	Customer i 's demand for fresh goods

q_i	The remaining cargo load when the vehicle leaves the customer i
Q_{ij}	The carrying capacity of the vehicle at the time of between customers i and j
t_{ijk}	The travel time of the vehicle k from customer i to customer j
t_i	Customer i 's service time
t_{ik}	The moment when vehicle k arrives at the customer i
t_{0k}	Departure time of vehicle k from the distribution center 0
$[ET_i, LT_i]$	The customer i 's expected delivery time window
$[ET_i', LT_i']$	The customer i 's accepted delivery time window
ρ_0	Fuel consumption per unit distance when the vehicle is not loaded
ρ^*	Fuel consumption per unit distance when the vehicle is fully loaded
δ_1	The rot rate of unit products during vehicle driving
δ_2	The rate of unit product decay in the process of vehicle unloading
μ_1	Penalty cost per unit time for early arrival of vehicles
μ_2	Unit time penalty cost for vehicle being late
x_{ijk}	$x_{ijk} = \begin{cases} 1, \text{Vehicle } k \text{ drives from customer } i \text{ to customer } j \\ 0, \text{Otherwise} \end{cases}$
y_{ik}	$y_{ik} = \begin{cases} 1, \text{Customer } i \text{ delivers fresh goods by vehicle } k \\ 0, \text{Otherwise} \end{cases}$

3 MODEL CONSTRUCTION

3.1 Cost Calculation

(1) Fixed cost (C_1), which is related to the number of vehicles used. Among them, c_1 indicates the fixed cost of the unit vehicle.

$$C_1 = \sum_{k=1}^{m} \sum_{j=1}^{n} c_1 x_{0jk} \tag{1}$$

(2) The transportation cost (C_2) is directly proportional to the driving distance of the vehicle. Among them, c_2 indicates the driving cost of the unit distance of the vehicle.

$$C_2 = \sum_{k=1}^{m} \sum_{i=1}^{n} \sum_{j=0}^{n} c_2 x_{ijk} d_{ij} \tag{2}$$

(3) Refrigeration cost (C_3), including refrigeration cost (C_{31}) in transportation and refrigeration cost (C_{32}) in the unloading process. Among them, c_{31} represents the cost of refrigeration per unit of time during transportation; c_{32} represents the refrigeration cost per unit of time during the unloading process.

$$C_3 = C_{31} + C_{32} = \sum_{k=1}^{m} \sum_{i=0}^{n} \sum_{j=0}^{n} c_{31} x_{ijk} t_{ijk} + \sum_{k=1}^{m} \sum_{i=1}^{n} c_{32} y_{ik} t_i \tag{3}$$

(4) Loss cost of goods (C_4), because fresh products are perishable and have the characteristics of large loss, the quality will decline as the distribution time increases, resulting in the cost of loss of goods, including the cost of loss of goods in transportation (C_{41}) and the cost of loss of goods at the time of unloading (C_{42}). According to relevant literature [6], the periodic function of fresh product quality can be expressed as:

$Q_t = Q_0 e^{-\delta t}$. Among them, Q_t is the quality of fresh products at the moment; Q_0 is the quality of fresh products when they leave the distribution center; δ : it is the decay rate of the product. This article has assumed that the ambient temperature remains unchanged during transportation, and the quality of fresh products is only affected by time, so it can be regarded as a constant. Among them, p is the price per unit of product.

$$C_4 = C_{41} + C_{42} = \sum_{k=1}^{m}\sum_{i=1}^{n} p y_{ik}\left[q_i(1-e^{-\delta_1(t_{ik}-t_{0k})}) + Q_i(1-e^{-\delta_2 t_i})\right] \tag{4}$$

(5) Carbon emission cost (C_5), which is related to the fuel consumption of the vehicle, the driving distance of the vehicle, and the load of the vehicle. According to relevant literature [7], when the vehicle load is X, the fuel consumption per unit distance is $\rho(X)$, and the carbon emission generated by the vehicle during the driving between node i and node j is P. Among them, β : it indicates the carbon emission coefficient, that is, the carbon emission generated per unit of fuel consumption; c_0 indicates the cost per unit of carbon emission.

$$\rho(X) = \rho_0 + \frac{\rho^* - \rho_0}{Q} X \tag{5}$$

$$P = \beta(\rho_0 + \frac{\rho^* - \rho_0}{Q} Q_{ij}) d_{ij} \tag{6}$$

$$C_5 = \sum_{k=1}^{m}\sum_{i=0}^{n}\sum_{j=0}^{n} c_0 \beta(\rho_0 + \frac{\rho^* - \rho_0}{Q} Q_{ij}) d_{ij} x_{ijk} \tag{7}$$

(6) Time penalty cost (C_6), during the delivery process, the vehicle may not arrive within the customer's satisfactory time window, resulting in the time penalty cost. θ_{ik} : it indicates that the time penalty fee for the delivery of the vehicle k to the customer i. Among them, M is a great penalty value.

$$\theta_{ik} = \begin{cases} M, & t_{ik} < ET_i', t_{ik} > LT_i' \\ \mu_1(ET_i - t_{ik}), & ET_i' \le t_{ik} < ET_i \\ 0, & ET_i \le t_{ik} \le LT_i \\ \mu_2(t_{ik} - LT_i), & LT_i < t_{ik} \le LT_i' \end{cases} \tag{8}$$

$$C_6 = \sum_{k=1}^{m}\sum_{i=1}^{n} y_{ik}\theta_{ik} \tag{9}$$

3.2 Customer Satisfaction Function

When the delivery time of the vehicle is relatively punctual, the quality of the product is basically not damaged. At this time, the customer will feel that the service is better and the satisfaction is also high. On the contrary, when the delivery time of the vehicle is not ideal, the product quality will be more damaged, and then customer satisfaction will decline. Customer satisfaction is closely linked to the punctuality of the vehicle's arrival. The customer satisfaction function ($H(t_{ik})$) can be obtained as follows:

$$H(t_{ik}) = \begin{cases} 0, & t_{ik} < ET_i^{'}, t_{ik} > LT_i^{'} \\ \dfrac{t_{ik} - ET_i^{'}}{ET_I - ET_i^{'}}, & ET_i^{'} \le t_{ik} < ET_i \\ 1, & ET_i \le t_{ik} \le LT_i \\ \dfrac{LT_i^{'} - t_{ik}}{LT_i^{'} - LT_i}, & LT_i < t_{ik} < LT_i^{'} \end{cases} \tag{10}$$

3.3 Establishment of Dual-Objective Optimization Model

This paper aims to minimize the total cost of distribution and maximize customer satisfaction in the cold chain logistics distribution process for fresh products. To achieve this goal, a dual-objective optimization model has been developed as follows:

$$\min C = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 \tag{11}$$

$$\max Z = \frac{\sum_{i=1}^{n} [H(t_{ik}).q_i]}{\sum_{i=1}^{n} q_i} \tag{12}$$

Among them, formula (11) indicates that the total distribution cost is the smallest, Costs included are fixed cost, transportation cost, refrigeration cost, cargo loss cost, carbon emission cost, and time penalty cost; formula (12) indicates that customer satisfaction is the largest.

3.4 Conditional Constraints

The constraints are shown in Table 2.

Table 2. Conditional constraints

Conditional constraints	Formula representation
Carrying capacity constraints in the process of vehicle distribution	$\sum_{i=1}^{n} y_{ik} q \le Q,\ k = 1,2,...,m$
Each customer can only be delivered by one car	$\sum_{k=1}^{m} y_{ik} = 1,\ i = 1,2,\dots,n$
Every customer will be serviced by the vehicle once	$\sum_{i=0}^{n}\sum_{k=1}^{m} x_{ijk} = 1,\ j = 1,2,...,n$
The starting and ending points of each car are distribution centers	$\sum_{j=1}^{n} x_{0jk} = \sum_{j=1}^{n} x_{j0k} \le 1,\ k = 1,2,...,m$
Traffic constraints of vehicles at the customer's place	$\sum_{i=0}^{n} x_{ipk} = \sum_{j=0}^{n} x_{pjk},\ p = 1,2,...,n, k = 1,2,...,m$
Vehicle quantity constraints in the distribution center	$\sum_{k=1}^{m}\sum_{j=1}^{n} x_{0jk} \le m$
Continuous time constraints during the delivery process	$t_{jk} = t_{ik} + t_i + t_{ijk}$, $t_{ijk} = \frac{d_{ij}}{v}$

4 IMPROVE THE NSGA-II ALGORITHM TO SOLVE THE OPTIMAL PATH

4.1 Improved NSGA-II Algorithm

This paper adopts the non-dominated sorting genetic algorithm (NSGA-II) [8] as the core algorithm. The steps are as follows:

Step 1 Improve the method to generate the initial population. Generally, the initial solution construction of the algorithm is to randomly generate a line serial number arrangement to complete the construction. This algorithm improves the initial population construction method: first, generate 1-n customer points and disorderly arrange them, and then rearrange and assign customer points to each car according to customer needs and time window constraints. The rearrangement is carried out according to the time window of customer points under the premise of considering that the total customer demand does not exceed the vehicle capacity. Operation, put the customer in front of the time window in front of the vehicle route, and the customer in the back of the time window is moved to the back. When the total demand of the customer of a route exceeds the capacity of the vehicle, the route construction is completed, and the next car will repeat the process. Finally, all the routes are arranged and combined to obtain a chromosome. Repeat this process to get the initial population.

Step 2 Adaptability assessment and rapid non-dominant sequencing. Use the objective function as the adaptability measurement index, and then carry out non-dominant sorting. The sorting level of the optimal individual is 0, the sub-optimal sorting level is 1, and so on. Fast non-dominant sorting: for each individual i in the population, there are two parameters, n(i) and S(i). Among them, n(i) is the number of solutions in the population that are better than individual i, and S(i) is the set of solutions that are inferior to individual i. Generally, the advantages and disadvantages of individuals are judged by comparing their respective target function values. The core of fast non-dominant sorting is to stratify the individuals in the population according to the target value. The smaller n(i), the less it is dominated by other individuals. When non-dominant sorting, the individuals in the population are divided into corresponding levels.

Step 3 Crowding calculation. After fast non-dominant sorting, compare the advantages and disadvantages of individuals at the same level, and the congestion is used to evaluate the optimal target value.

Step 4 Select the operation. Select individuals according to the individual level and congestion, and ensure that the selected individual not only has the smallest series but also has the largest congestion among the individuals with the same series.

Step 5 Cross-operation.

The principle of multi-part matching intersection is as follows:

Father 1	1	2	3	4	5	6	7	8
Father 2	3	5	8	1	7	4	2	6

Randomly select two intersection positions a and b, such as a=3, b=5, and set the crossover fragment as:

Father 1	1	2	3	4	5	6	7	8
Father 2	3	5	8	1	7	4	2	6

Then the two paternal individuals become:

Father 1	1	2	3	1	7	6	7	8
Father 2	3	5	8	4	5	4	2	6

Then delete the duplicate genes and map them according to 1-4, 5-7:

Father 1	4	2	3	1	7	6	5	8
Father 2	3	7	8	4	5	1	2	6

Step 6 Variation is improved by using two different mutation methods. Reverse order variation: Select two positions and sort the middle sequence backward. Exchange mutation operation: randomly generate two positions, and then exchange the genes in these two positions.

After the iteration of the above process, the corresponding optimal solution is obtained.

4.2 Example Analysis

Experimental Parameters and Data. We started with a population of 100, and ran it for 100 iterations, with a crossover probability of 0.85 and mutation probability of 0.15. The actual data used in the model can be found in Table 3. The logistics distribution of fresh products involves numerous complex distribution paths. In this experiment, we are dealing with a scenario where a distribution center needs to deliver fresh products to 40 customer points (distribution nodes). We obtained the data from a map, and some of the data is listed in Table 4.

Table 3. The actual data used in the model

Parameter	Value	Parameter	Value
c_1	100 Yuan/vehicle	ρ^*	0.377 L/km
c_2	3.5 Yuan/km	β	2.9 kg/L
c_{31}	15 Yuan/h	c_0	0.5Yuan/kg
c_{32}	20 Yuan/h	μ_1	10 Yuan/h
p	30 Yuan/kg	μ_2	15 Yuan/h
δ_1	0.003	v	40 km/h
δ_2	0.005	Q	100 kg
ρ_0	0.1165 L/km		

Table 4. Distribution center data of some kind of fresh product

Serial number	Longitude (°)	Latitude (°)	Need (kg)	Expected time	Acceptable time	Service time(min)
0	111.56	24.01	0	6:00-11:00	6:00-11:00	0
1	111.54	23.92	14	7:00-8:45	6:45-9:05	18
2	111.61	23.92	18	7:00-9:00	6:45-9:15	20
3	111.59	23.93	14	6:30-8:25	6:15-8:40	13
4	111.6	23.92	24	6:40-8:30	6:20-9:00	18
5	111.58	23.98	14	6:45-8:25	6:30-8:40	12
…	…	…	…	…	…	…
37	111.6	24.02	18	6:45-8:20	6:15-8:45	15
38	111.67	23.92	20	6:25-8:30	6:15-8:50	17
39	111.51	23.88	14	6:50-8:30	6:35-8:40	12
40	111.82	24.06	18	6:45-8:30	6:15-8:45	15

Experimental Results. Run on the MATLAB simulation platform, edit the improved NSGA-II algorithm and the unimproved NSGA-II algorithm respectively, and solve the dual-objective optimization model built in this article. Figures 1 and 2 are the Pareto solution, Figures 3 and 4 are the optimal vehicle road map, and Table 5 is the vehicle distribution road map.

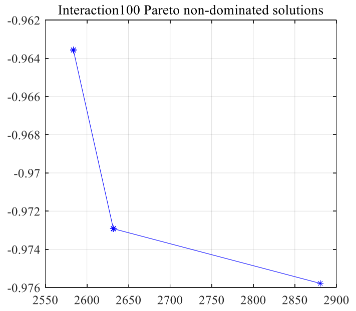

Fig. 1. Interaction 100 Pareto non-dominated solutions (Improved algorithm)

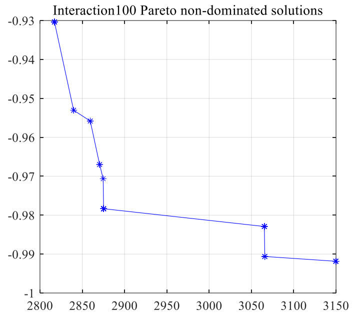

Fig. 2. Interaction 100 Pareto non-dominated solutions (Unimproved algorithm)

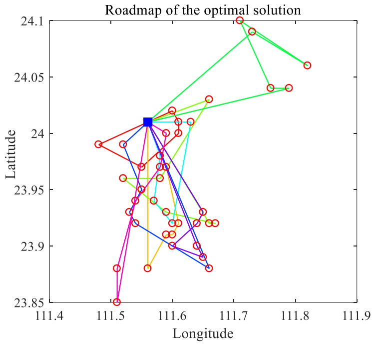

Fig. 3. Roadmap of the optimal solution (Improved algorithm)

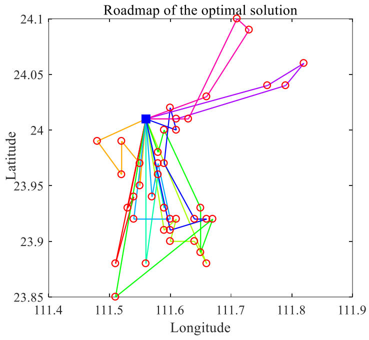

Fig. 4. Roadmap of the optimal solution (Unimproved algorithm)

Table 5. Vehicle distribution route

	Vehicle number	Vehicle distribution route		Vehicle number	Vehicle distribution route
Improve algorithm	1	0-31-13-22-15-37-0	Unimproved algorithms	1	0-39-25-23-0
	2	0-29-8-14-2-6-0		2	0-31-28-27-13-10-0
	3	0-16-38-3-28-17-30-0		3	0-20-34-12-2-8-0
	4	0-19-36-35-40-9-0		4	0-26-38-18-24-21-5-0
	5	0-33-4-11-5-0		5	0-3-17-29-0
	6	0-20-1-23-10-27-0		6	0-11-7-4-1-0
	7	0-34-18-12-32-24-0		7	0-22-37-6-32-16-14-0
	8	0-26-39-25-7-21-0		8	0-36-40-19-15-0
				9	0-30-9-35-33-0

The Pareto optimal solution obtained by the improved algorithm is: the minimum distribution cost is 2631.77 yuan, the maximum customer satisfaction is 97.30%, including a fixed cost of 800 yuan, the transportation cost is 1239.76 yuan, the refrigeration cost is 293.32 yuan, the loss cost is 181.47 yuan, and the carbon emission cost is 108.47 yuan, the penalty cost is 8.76 yuan. This result is further optimized compared with the unimproved algorithm. At this time, the distribution cost is optimally balanced with customer satisfaction.

5 CONCLUSIONS

This paper studies the problem of fresh cold chain logistics distribution, and establishes a dual-target optimization model with the lowest total distribution cost and the largest customer satisfaction. The improved NSGA-II algorithm is proposed, and the dual-target model is solved by using MATLAB software combined with examples, and the optimal balance between the total cost of cold chain logistics distribution of fresh products and customer satisfaction is obtained. It can help fresh food enterprises strike a balance between reducing distribution costs and improving customer satisfaction. The model proposed in this paper has good effectiveness and practicability in the practical problem of cold chain logistics path optimization.

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