Optimization of Cold Chain Logistics Based on Dynamic Planning Under Green Perspective

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Abstract: This paper improves the solving effect of path optimization through ameliorate the traditional genetic algorithm. As the optimization goal of the total cost of cold-chain distribution, with the constraint condition of vehicle load capacity and customers' requirement, build the optimal model. This research analyses the influence of temperature and time on refrigeration cost and cargo damage cost, and applies exponential function to describe the decay rule of fresh agricultural products. And this paper makes simulation experiment in different strategy algorithm through improving the choosing strategy, crossover strategy and mutation strategy in genetic algorithm, the result shows that improving strategy significantly impact the local solution accuracy and convergence speed of algorithm. Thus, it effectively avoid to sink into the problem of local optimum. This research provides a better plan of path optimization for distribution of cold-chain logistics. For practical cases, this paper chooses Nanjing Weigang Dairy Co., Ltd and 15 residential quarters in Nanjing as client site to analyse. In this case, through multiple runs to improve genetic algorithm, this paper gains a more economic and more friendly-environment way to distribution, dramatically reduces the total cost and carbon-dioxide emission, at the same time, also shortens the distribution time.

1 INTRODUCTION

With the improvement of economic growth and residents' life quality, the requirements of fresh agricultural products increase daily, prompting the quick development of cold-chain logistical industry (Xu, 2021). Particularly, not only vehicles would produce carbon emission, but also refrigerating equipments are the important source of it. Facing the global warming and the stress of carbon emission reduction, optimizing the distribution path of cold-chain logistics have become an urgent problem that need to be solved.

Cold-chain logistics encompass the entire process: manufacturing, consumption, disposal, storage, transportation, and sale of products under low-temperature conditions to ensure the safety and quality products. In whole supply chain, the transport link is crucial particularly, reasonable distribution path optimization not only can guarantee the quality of products and satisfy the needs of client, but also can reduce the logistical cost actively.

Based on its national circumstances, China, being a major agricultural country, has seen continuous increases in the production of agricultural products like vegetables, fruits, and meat (Xu, 2024).

In the current context of environmental policies, reducing the carbon emission have become the global focus (Cai et al., 2024; Hu et al., 2024; Wang et al., 2024). Especially in logistical industry, because cold-chain logistics have traits which are high energy consumption, high carbon emission, so its feature become the crucial point to optimize.

With the increasing global emphasis on environmental protection, green cold-chain logistics become the research highlights. Liu et al. developed an optimization model for cold-chain logistics distribution paths for fresh agricultural products,

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incorporating freshness deterioration penalties and carbon emission costs in addition to traditional fixed costs, fuel costs, and time window penalty costs (Liu et al., 2019). This study utilized an improved genetic algorithm based on taboo search and validated the model and algorithm with real-world cases, demonstrating that including eco-friendly factors in path optimization can promote sustainable cold-chain logistics development. Wang optimized cold-chain logistics distribution paths with time windows using a genetic algorithm, incorporating a penalty function and time window to accurately describe multi-path distribution problems, effectively reducing distribution costs and mileage (Wang, 2022). Lv et al. focused on the application of the simulated annealing algorithm (Lv et al., 2020). They enhanced the algorithm's local solution accuracy and convergence speed by adjusting the Metropolis Rules' acceptance rate, emphasizing the importance of algorithm parameter selection on optimization effectiveness and encouraging further development. Ni and Katarzyna optimized urban agricultural products' cold-chain distribution systems from a low-carbon perspective, analyzing factors affecting carbon emissions comprehensively (Ni and Katarzyna, 2024). They built a corresponding mathematical model and validated its feasibility and effectiveness by optimizing distribution paths using a genetic algorithm. The study of Pan and Gan focused on introduce optimization of cold-chain logistics distribution paths about carbon emission costs (Pan and Gan, 2016). Jia used ant colony heuristic algorithm and MATLAB to gain solution. Jia put forward the research about optimizing cold-chain logistics distribution path for agricultural product e-commerce from carbon neutral perspective, using ecological theory approach and combining Ant Colony Optimization (ACO) algorithm to explore cold-chain logistics distribution in city ecological systems, and the author sought to minimize operating costs while taking ecological and environmental considerations into account (Jia, 2022). Qian introduced a carbon tax into the model by constructing carbon emission functions while Zhou and Lu built a multi-objective model with time window (Qian, 2016; Zhou and Lu, 2019). Two researches all used genetics algorithm and ACO algorithm to build models to solve, and then validated the validity of model through actual cases.

2 HYPOTHESIS AND SYMBOL DESCRIPTION

2.1 Problem Hypothesis

Traditional logistics distribution optimization has primarily focused on minimizing economic costs, often overlooking environmental factors. However, with global emphasis on energy conservation and emission reduction policies, reducing carbon emissions during logistics distribution has become a critical research area. To define the research scope, this paper will establish some basic assumptions.

Hypothesis 1: Consider only one distribution centre. The deliver goods are all temperature sensitive products which customers need.

Hypothesis 2: Each delivery truck begins its route at the distribution center and returns there after completing its deliveries.

Hypothesis 3: All delivery trucks have the same known load capacity, and the total demand served by each truck must not exceed this capacity.

Hypothesis 4: It is assumed that the distribution trucks travel at the same speed at a constant rate, without taking into account the restrictions of vehicle flow and road conditions and natural disasters in the delivery process.

Hypothesis 5: To save delivery resources and improve vehicle utilization, each customer is served by one delivery truck, and each truck can provide delivery services to multiple customers.

Hypothesis 6: The geographic locations of the distribution center and customers are known. The quantities demanded by customers, the expected delivery service times, and the pickup and delivery service hours are known. Each delivery task must be completed within a service time frame acceptable to the customer. It is advisable to maintain all given values.

Based on these hypotheses： A fleet of vehicles used for transportation with identical refrigeration equipment starts from a fresh produce distribution centre, serving for several customers, and go back to delivery centre after completing the distribution tasks. Each specific location of the customer and the quantity of fresh produce required are predetermined. Each customer can be served only by a delivery truck. In the delivery process, fresh products may experience a decrease in freshness, which can lead to lower customer satisfaction and thus incur additional penalty costs. Even so the freshness of products can be considered in a perfect condition (100%). No customer will return the products because of the reduction of the freshness. On the premise of ensuring the need of customer products, following time window restrictions below the load capacity of each delivery truck, the research takes the penalty costs caused by carbon emission and the loss of freshness into consideration, aiming to plan a distribution route with the lowest total cost to maximize the distribution efficiency and minimize the cost of cold chain logistics enterprises.

2.2 Symbol Description

The correlation parameter quantity can be described as: There are M delivery trucks are available for deployment, and the truck is numbered as$1\sim$m. It defines a completely symmetric network diagram $\mathrm{G} = [v, \varepsilon]$, $v = \{0,1,2,\cdots,n,n+1\}$ represents a collection of all nodes, point 0 and point $n+1$ are considered as the delivery centers, $N' = \{1,2,\cdots,n\}$ represents a collection of all the customer, $\varepsilon = \{(i,j)|i,j \in N, i \neq j\}$ represents a collection of all the paths. Other symbols are shown in Table 1.

Table 1: Description of model symbols.

Symbol	Instruction
C	The overall cost of cold-chain logistics from an eco-friendly perspective
C_1	Fixed operating cost
C_2	Vehicle transportation cost
C_3	Refrigeration cost
C_4	Cost of goods loss
C_5	Time window cost
C_6	Cost of carbon emissions
P_1	Fixed cost of delivery vehicle delivery
s_1	Fuel cost per unit distance of the delivery vehicle
s_2	Cooling cost per unit distance travelled by the delivery vehicle
s_3	Cooling cost per unit time of unloading of delivery vehicle
s_4	Waiting cost of the delivery vehicle per unit time
s_5	Overtime cost of the delivery vehicle per unit of time
d_{ij}	Distance between customer point i and j
v	Speed of the delivery vehicle
T_j	Time required for the delivery vehicle to unload at the customer's point j
F_0	Initial freshness of goods
C	Maximum potential loss cost per unit of good
K	Attenuation index
c_0	Cost per unit of carbon emissions
e_0	Emission coefficient of CO_2
Q	Maximum cargo capacity of the delivery vehicle

3 MODELING PROCESS

3.1 Objective Function Analysis

This paper considers that the total cost of cold chain logistics and distribution of agricultural products includes the following components: fixed usage cost, vehicle transportation cost, refrigeration cost, cargo damage cost, time window cost, and carbon emission cost.

Fixed utilization cost: Fixed costs refer to the costs spent on vehicle wear and tear, maintenance, depreciation, and hiring drivers for distribution vehicles during the distribution process. Where the decision variables are:

$$x_{0j}^m = \begin{cases} 1, vehicle\ m\ travels\ from \\ center\ to\ customer\ point\ j \\ 0, vehicles\ not\ departed \end{cases} \quad (1)$$

Fixed cost of use is:

$$C_1 = \sum_{m=1}^{M} \sum_{j=0}^{n} x_{0j}^m \cdot P_1 \quad (2)$$

Vehicle Transportation Costs: These costs primarily pertain to the fuel expenses incurred during vehicle operation. They are proportional to the distance traveled by the vehicle and can be calculated accordingly, can be obtained as vehicle transportation costs:

$$C_2 = \sum_{m=1}^{M} \sum_{i=0}^{n+1} \sum_{j=0}^{n+1} x_{0j}^m \cdot s_1 \cdot d_{ij} \quad (3)$$

where s_1 is the cost of fuel consumption per unit distance traveled by the delivery vehicle and d_{ij} is the distance traveled by the vehicle between customer points i and j.

Refrigeration costs: Since all distribution vehicles are equipped with refrigeration equipment, which works mainly by consuming refrigerant, the refrigeration cost of the vehicle during transportation mainly refers to the total cost of refrigerant consumed by the refrigeration equipment. It is assumed that each delivery vehicle can deliver all the fresh food in the vehicle in only one transportation, and the refrigeration equipment will not work on the way back because there is no fresh food in the vehicle. Considering that the refrigerant consumption is affected by the external environment, it is necessary to calculate the total refrigeration cost by considering the refrigeration cost during transportation and unloading separately C_3. The cost of refrigeration during transportation is:

$$C_{31} = \sum_{m=1}^{M} \sum_{i=0}^{n} \sum_{j=0}^{n} x_{0j}^m \cdot s_2 \cdot d_{ij} \quad (4)$$

The cost of refrigeration during unloading is:

$$C_{32} = \sum_{m=1}^{M} \sum_{i=0}^{n} \sum_{j=0}^{n} x_{0j}^m \cdot s_3 \cdot T_j \quad (5)$$

where s_2 is the cost of refrigeration per unit distance traveled by the delivery truck, s_3 is the cost of refrigeration per unit time unloaded, and T_j is the time required to unload at the customer point j. Thus, the cost of refrigeration C_3 is:

$$C_3 = C_{31} + C_{32} \quad (6)$$

Cargo damage costs: Cargo damage cost refers to the corruption cost of fresh food due to time and temperature changes during transportation. Among them, the time-induced spoilage cost accompanies both transportation and unloading processes, while the temperature-induced spoilage cost mainly occurs in the unloading process. Therefore, it is necessary to consider the cargo spoilage costs in the two stages of transportation and unloading separately.

Meanwhile, this paper introduces the food spoilage function based on exponential decay to describe the process of food freshness decreasing with time, and assume that all delivery trucks are traveling at a uniform speed with speed v. The expense incurred due to damage to cargo during transportation is: $C_{41} = \sum_{m=1}^{M} \sum_{i=0}^{n} \sum_{j=0}^{n} x_{0j}^{m} \left[C \cdot \left(1 - F_0 \cdot e^{-K\frac{d_{ij}}{v}} \right) \right]$. The cost of cargo damage during unloading is: $C_{42} = \sum_{m=1}^{M} \sum_{i=0}^{n} \sum_{j=0}^{n} x_{0j}^{m} \left[C \cdot \left(1 - F_0 \cdot e^{-KT_j} \right) \right]$.

where F is the initial freshness (100%); C is the maximum potential cost of loss per unit of commodity, i.e., the cost at 100% freshness; and K is the decay index, which indicates the rate of decay of freshness over time, and whose value depends on the rate of spoilage of a particular food item and the storage conditions. Therefore, the cost of cargo damage C_4 is:

$$C_4 = C_{41} + C_{42} \quad (7)$$

Time Window Costs: These costs arise when a delivery vehicle fails to arrive at the customer's location within the specified time window. This includes waiting costs for vehicles that arrive too early and overtime costs for delayed arrivals.

$$C_5(i) = \begin{cases} s_4\left(i_s - t_i^k\right), 0 \le t_i^k < i_s \\ 0, i_s \le t_i^k \le i_e \\ s_5\left(t_i^k - i_e\right), i_e < t_i^k \end{cases} \quad (8)$$

Where s_4 is the waiting cost of the delivery truck per unit of time and s_5 is the overtime cost of the delivery truck per unit of time. Therefore, the time window cost C_5 is:

$$C_5 = \sum_{m=1}^{M} \sum_{i=0}^{n} C_5(i) \quad (9)$$

Carbon Emission Costs: According to the standards of green logistics, not only fuel costs but also carbon emission costs need to be considered when calculating costs. Carbon emission cost refers to the expense incurred from purchasing the necessary carbon emission allowances in the carbon trading market. The carbon emissions caused by the logistics process are mainly due to the direct and indirect carbon dioxide emissions brought about by the consumption of various energy sources and substances in the logistics process, so carbon dioxide emissions are an important part of the study of carbon emission costs. Specifically, the cost of carbon emissions is the product of the carbon dioxide emission factor of the fuel, the fuel consumption and the carbon trading price. The carbon emission cost $e(i,j)$ incurred by the distribution trucks traveling at customer point i and customer point j is:

$$e\left(y_{ij}\right) = c_0 e_0 \left[\emptyset_0 + \frac{(\emptyset^* - \emptyset_0)}{Q} y_{ij} \right] d_{ij} \quad (10)$$

where c_0 is the cost per unit of carbon emissions, e_0 is the CO_2 emission factor, $\emptyset_0$ and $\frac{\emptyset^* - \emptyset_0}{Q}$ are the intercept and slope, respectively. Q is the maximum load capacity of the delivery truck, and y_{ij} is the load capacity of the delivery truck between customer point i and customer point j. Thus, the cost of carbon emissions C_6 is:

$$C_6 = \sum_{i=0}^{n+1} \sum_{j=0}^{n+1} M \cdot e\left(x_{ij}\right) \quad (11)$$

3.2 Constraints Analysis

Combined with the real situation of the problem, the cold chain logistics optimization model under the specific green perspective makes the following constraints:

Constraint 1: All transport vehicles return to the distribution center uniformly after the distribution is completed.

$$\sum_{j=1}^{n} x_{ij}^{m} = \sum_{j=1}^{n} x_{ji}^{m} \le 1, i = 0, m = 1,2,\cdots,M \quad (12)$$

Constraint 2: Distribution is completed by one and only one transportation vehicle per customer point.

$$\sum_{m=1}^{M} \sum_{j=1}^{n+1} x_{ij}^{m} = 1, \forall i \in N' \quad (13)$$

Constraint 3: The load of all transportation vehicles shall not exceed the maximum load of the vehicle itself.

$$\sum_{m=1}^{M} y_{0j}^{m} \le MQ, \forall j \in N \quad (14)$$

3.3 Planning Model

In summary, this paper establishes a cold chain logistics optimization model under the green perspective, and the objective function is to minimize the total cost C of cold chain logistics and distribution:

$$Min\boldsymbol{C} = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 \quad (15)$$

$$s.t. \begin{cases} \sum_{j=1}^{n} x_{ij}^{m} = \sum_{j=1}^{n} x_{ji}^{m} \leq 1, i = 0, \\ \quad m = 1,2,\cdots,M \\ \sum_{m=1}^{M} \sum_{j=1}^{n+1} x_{ij}^{m} = 1, \forall i \in N' \\ \sum_{m=1}^{M} y_{0j}^{m} \leq MQ, \forall j \in N \end{cases} \tag{16}$$

4 METHODOLOGIES

By simulating biological evolution, genetic algorithm helps improve the quality of solutions. Genetic algorithm is widely used in path planning, scheduling, and resource allocation.

4.1 Genetic Algorithm Process

The vehicle path planning problem is a significant topic in operations research. Currently, heuristic algorithms are primarily used to address this problem, with genetic algorithms from modern heuristic methods being widely applied. Genetic algorithms are global probabilistic search methods that mimic biological evolution, combining survival of the fittest with random information exchange. Their core characteristics are reflected in basic genetic operations and population exploration strategies. Genetic algorithms begin with a population containing potential solutions, composed of a certain number of genetically coded individuals. Through continuous processes of selection, crossover, and mutation, individuals are optimized, passing excellent genes to the next generation to improve offspring adaptation. During this iterative evolution, the optimal or satisfactory solution to the problem is eventually decoded from the best individual in the final generation population. The specific operations of genetic algorithms are illustrated in Figure 1 below:

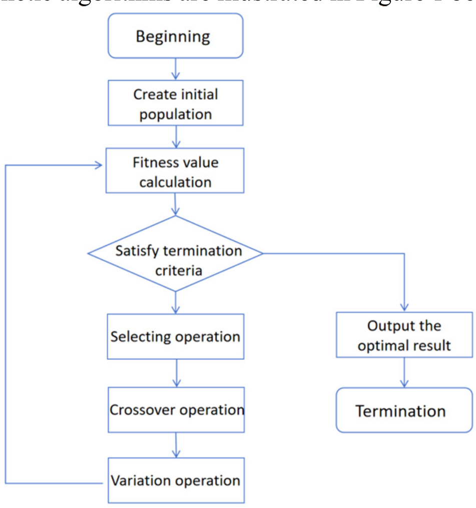

Figure 1: Brief flowchart of the genetic algorithm

4.2 Genetic Algorithm Design

According to the analysis above, the main steps of the genetic algorithm include encoding, initial population, fitness calculation, termination, choosing, crossover, variation.

Step 1: Encoding. Vehicle routing planning is a sequential optimization problem. Though the binary coding is widely used, it is not suitable to solve this kind of problems, because it can result in a large number of invalid solutions.

In the natural number coding method, No. 0 for Distribution Centre. M Cars start from the delivery center, delivering goods which is numbered as $1,2,\cdots,N$ to the fresh supermarket stores, and go back to the delivery centre. Once the number of a grocery store is determined, it will not be changed. The chromosome length of each distribution line is $M + N + 1$.

Step 2: Initial population. The beginning of the genetic algorithm is forming the initial population. If the scale of the population is too small, it may result in insufficient samples and affect the result of searching. If the scale is too large, the amount of computation will increase, which may extend convergence time. Thus, the author uses randomization to generate an initial population of 100.

Step 3: Fitness value calculation involves assessing each chromosome by its fitness value. A higher fitness value indicates an individual with better quality, whereas a lower fitness value signifies a poorer quality individual. Poorer individuals are eliminated through selection or competition. Expressed by the formula is $f_i = \frac{1}{z_i}$ and f_i represents the fitness value of the i^{th} chromosome.

Step 4: The termination principle determines when to stop the algorithm. If the termination criteria are met, evolution stops. If not, selection, crossover, and mutation are performed, followed by another fitness calculation. The individual with the best fitness value in the final generation, which corresponds to the lowest cost delivery path, is considered the optimal solution for path optimization in cold chain logistics from a green perspective.

Step 5: Selecting operation. Selecting operation is a process to select relatively good individuals from the parent population. The research uses roulette selection strategy, ensuring the differences and diversity of the progeny population individual, and can make full use of all available paths to improve bandwidth utilization.

To calculate the probability of selection P_i , it will use the fitness value f_i of individual i:

$$\mathrm{P}(i) = \frac{f_i}{\sum_{j=0}^{N-1} f_i} \quad (17)$$

Step 6: Crossover operation. Crossover operation in the genetic algorithm is to select a certain location in two or more individuals and swap or replace these positions to form new individuals. The multi-point crossover approach to crossover operations is used. It random selects multiple intersections and exchange the part between these points of the two individuals. The numbers and positions of the

Individuals can be different. The multi-point crossover approach can intersect more gene fragments and increase the Individual diversity according to Figure 2. The operation process is as follows:

Step 1: Segment and number two individuals of the parent-Parent entity 1: 1,2,3,4,5,6 ; Parent entity 2: 7,8,9,10,11,12.

Step 2: Find the corresponding customer location in two parent individuals to start the crossover operation: 2-8, 4-10, 6-12.

Step 3: Retain positions 1, 3, and 5 of parent entity 1 and positions 7, 9, and 11of parent entity 2.

Step 4: Form two new individuals.

Figure 2: Multipoint crossover.

Variation operation: Variation operation in the genetic algorithm is to replacement and change certain genes in the selected individual's chromosomes to form new individuals. According to the difference of the coding method, the Binary variation and real-valued variation are used in this research.

Binary variation: Choose a variable position randomly. Then change the value of the gene at the location of the mutation from "0" to "1", or change from "1" to "0" to create a new individual.

Real-valued variation: Use another random real number in the fixed scope to replace genetic value in the original variant position to generate a new individual.

Location-based mutation methods: First, two variation positions are randomly selected. Then the gene at the second mutation location was moved to the front of the first mutation location;

Variation based on order: First, two variation positions are randomly selected. Then exchange the genes on the two variation positions.

4.3 Example Analysis

In the optimization study of the delivery task of Nanjing Weigang Lotion Co. Ltd, the author used an improved genetic algorithm with parameter settings for 15 neighborhoods in Nanjing as customer points. The algorithm parameters are set as follows: population size ($P_s = 100$), crossover probability ($P_c = 0.82$), mutation probability ($P_m = 0.14$), and maximum number of iterations ($Mg = 500$).

Statistical analysis of 20 runs of the algorithm gives us the following average results:

The average results reveal that the total cost is approximately \$3,670.15, with a total time expenditure of about 490.29 minutes and a CO2 emission of 45.56 kilograms.

In all runs, the optimal distribution scenario consistently involves using five transportation vehicles. This scenario achieves a total cost of \$3,645.88, a total time of 470.92 minutes, and a CO2 emission of 42.89 kilograms.

These data suggest that the use of improved genetic algorithms can significantly optimize distribution efficiency while reducing total cost, distribution time, and environmental impact. Therefore, the author recommend that Nanjing Weigang Emulsion Co. consider implementing this strategy to improve distribution efficiency and environmental friendliness.

5 CONCLUSION

The distribution of fresh agricultural products not only require high efficiency, but also the quality and timeliness of products, it make that cold-chain logistics have higher cost than traditional logistics. Besides, not only vehicle, but also refrigerating equipment all would produce carbon emission. Thus, when facing the stress of global warming, optimizing the distribution path of cold-chain logistics have become the urgent problems.

Based on this, the paper considers various components contributing to the total cost of cold-chain logistics distribution for fresh agricultural products, including fixed-use costs, vehicle transportation costs, refrigeration costs, cargo damage costs, time-window costs, and carbon emission costs. By combining these factors with the actual conditions of the issue, the paper develops an optimization model aimed at minimizing the total cost from a green perspective. This research contributes to achieving green logistics and sustainable development by ensuring food freshness and quality while reducing carbon emissions. By utilizing MATLAB software, the study employs selection, crossover, and mutation operations to implement the genetic algorithm solving process. In the case study of Nanjing Weigang Dairy Co., Ltd.'s distribution mission, the research successfully reduced the total cost, overall time consumption, and carbon dioxide emissions to a certain extent, thereby enhancing distribution efficiency and environmental friendliness.

Although the contents of this paper could provide some reference value for cold-chain logistics distribution path for fresh agricultural products, and prompt green cold-chain logistics industry to have further development, the model built by this paper is confined to some hypothesis and constraint conditions, so this research also exist some deficiencies. In further research, the temperature outside the vehicle in actual distribution could be taken into cold-chain distribution account to optimize distribution path from deeper and more diverse directions.

AUTHORS CONTRIBUTION

All the authors contributed equally and their names were listed in alphabetical order.

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