A Decoding Method for Applying Swarm Intelligence Optimization Algorithm to Solve the Cold Chain Vehicle Logistics Routing Problem

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Abstract. In order to apply swarm intelligence optimization algorithms to solve cold chain vehicle routing problem efficacy and conveniently, a simplified decoding method was proposed. Based on the common encoding form in continuous space for swarm intelligence optimization algorithms, it divided the decoding process into three sections: decoding the service sequence of customers, assigning customer and determining the route of each vehicle, calculating circularly and outputting the whole plan. It did not need to design new encoding form and executed efficacy. Experiments with two different scale problem were introduced to test the performance of the decoding method applied in 9 algorithms. The results showed that the method can be used in swarm intelligence algorithms to solve the cold chain logistics vehicle routing problem. In addition, it also can be seen that different algorithms showed different performances due to their search mechanisms, although they were based on the same decoding method.

1. Introduction

With more than 80 years developing, the cold chain logistics has formed a modern system. Hsu [1] and Keizer [2] consider the influence factors such as perishability and energy consumption of products, and provide a model to reduce the cost of transportation. Based on analysing the time-limited vehicle routing and production scheduling problem of perishable products, Chen [3] et al. construct a nonlinear mathematical model and introduce a hybrid algorithm combining a heuristic algorithm and the Nelder-Mead method to solve the model. Kuo [4] et al. propose a multi-temperature distribution model based on the degree of perishability of fresh food related to temperature. With considering the characteristics of perishable food, Shi and Fu [5] introduce a time-varying factor of distribution network into the distribution location and transport path optimization research, and construct a simulation model under the time-varying conditions.

Although some swarm intelligence algorithms have been applied to solve the problem, their coding method is complex and inefficient. Thus, a simplified decoding method is proposed in this paper which keeps the basic encoding mode but introduces a heuristic method to realize the customer assignment and vehicle schedule for the cold chain logistics.

2. Vehicle routing optimization model for cold-chain distribution

2.1. Assumptions
2.1.1. Transportation cost
The cold chain logistics distribution process is that the products are distributed from a cold chain logistics distribution center to customers by refrigerated vehicles. It assumed that each customer’s demand and location are given. In addition, there is a time window constraint on the customer delivery time. Products can be delivered immediately if the vehicle’s arrival time is within the time window. If not, it can also be delivered, but penalty should be paid. The objective of the problem is to make an economical vehicle distribution plan to minimize the total cost.

2.1.2. Parameter definition
Based on the graph theory, the cold chain logistics network can be defined as: \( G=(V, D) \), where \( V=(v_0, v_1, v_2, \ldots, v_n) \) is the point set of the distribution center and customers. \( v_0 \) represents the distribution center, and \( v_i (i=1, 2, 3, \ldots, n) \) represents the \( i \)-th customer. \( D=((v_i, v_j): v_i, v_j) \) is the set of all path segments.

- \( m \): The number of delivery vehicles available at the distribution center;
- \( N \): Total number of customers;
- \( f_k \): The fixed cost of the \( k \)-th vehicle;
- \( Q_k \): The maximum load capacity of the \( k \)-th vehicle;
- \( c_{ij} \): The transportation cost of the vehicle on the road section \( (v_i, v_j) \);
- \( x_{ijk} \): if the \( k \)-th vehicle passes the \( (v_i, v_j) \) path, \( x_{ijk}=1 \); otherwise, \( x_{ijk}=0 \);
- \( y_{ik} \): if the \( k \)-th vehicle serves the customer \( i \), \( y_{ik}=1 \); otherwise, \( y_{ik}=0 \);
- \( d_{ij} \): The distance between customer \( i \) and customer \( j \);
- \( q_i \): The demand of customer \( i \);
- \( p \): The unit value of the product;
- \( t_0 \): The departure time of the \( k \)-th delivery vehicle from the distribution center;
- \( t_i \): The time when the \( k \)-th vehicle arrives at the customer \( i \);
- \( e_i, l_i (i=1, 2, 3, \ldots, n) \): The delivery time window that the customer \( i \) can actually accept.

2.2. The mathematical model

2.2.1. Transportation cost
In a cold chain logistics distribution process, transportation cost and customer satisfaction are the main influencing factors. The distribution costs involved in this study are shown as follows:

1) Transportation cost
Cold chain logistics has higher requirements for vehicles and refrigeration, thus its transportation cost is higher than general vehicles. Generally, the transportation costs of distribution vehicles include fuel consumption, maintenance costs, labour cost and so on, which are proportional to the distance of travel of the vehicle. The simplified formula used in this research is shown as follow:

\[
TC_i = \sum_{k=1}^{m} \sum_{i=0}^{n} \sum_{j=1}^{n} c_{ij}d_{ij}x_{ijk}
\]  

2) Penalty cost
Unlike general logistics, the goods quality is more time-sensitive in the cold chain logistics. Customers often have strict limits on delivery time in order to obtain higher income and service levels. However, in the actual distribution process, many unexpected events and factors, like traffic jams, weather changes, will disturb the distribution plan of a delivery vehicle. Therefore, the delivery time of cold chain products can be divided into: early delivery, on-time delivery, and delayed delivery according to the actual situations.
• Early delivery: when $t^k_i \leq e$, the vehicle arrives in advance. Arriving in advance will result in insufficient customer preparation, so it is necessary to pay a certain penalty fee. The penalty factor is set as $a$;
• On-time delivery: when $l \leq t^k_i \leq e$, the arrival time of the delivery vehicle is within the customer demand time window. The vehicle can complete its task without penalty;
• Delayed delivery: when $t^k_i \geq l$, the vehicle does not arrive on time, which will cause a certain loss to the customer. Thus, a certain penalty fee should be paid. The penalty factor is $b$;

In summary of the three situations, the penalty cost of customer $i$ can be expressed as:

$$TC_{2i} = pq_i [a \max(e - t^i_i, 0) + b \max(t^i_i - l, 0)]$$

The total penalty cost for all vehicles is as follows:

$$TC_2 = \sum_{k=1}^{m} \sum_{i=1}^{n} pq_i y_{ik} [a \max(e - t^i_i, 0) + b \max(t^i_i - l, 0)]$$

3) Fixed cost of vehicles
Fixed cost mainly refers to the inherent costs of dispatching each vehicle, including vehicle loss, labour cost and so on. Assuming that there are $m$ vehicles ($k=1, 2, \ldots, m$) to serve $n$ customers and the fixed cost of the $k$-th vehicle is $f_k$, the total fixed cost is:

$$TC_3 = \sum_{k=1}^{m} f_k$$

2.2.2. Model
According to the above cost analysis, the generalized function of the distribution vehicle routing problem of the cold chain logistics is defined as:

$$\min TC = TC_1 + TC_2 + TC_3$$

$$= \sum_{k=1}^{m} \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} d_{y_{ijk}} + \sum_{k=1}^{m} \sum_{i=1}^{n} pq_i [a \max(e - t^i_i, 0) + b \max(t^i_i - l, 0)] + \sum_{k=1}^{m} f_k$$

s.t.

$$\sum_{i=1}^{n} q_{y_{ijk}} \leq Q_k$$

$$\sum_{k=1}^{m} y_{ijk} = 1$$

$$\sum_{i=1}^{n} x_{ijk} = y_{ijk}$$

$$\sum_{j=1}^{n} x_{ijk} = y_{ijk}$$

$$E_i \leq t^k_i \leq L_i$$

Formula (6) represents the total load limits of a vehicle when servers its customers; formula (7) means that each vehicle can only serve one customer at a time; formula (8) and (9) means that if the vehicle passes a demand point, it must serve it; formula (10) indicates the time window limits.

3. Methodology
3.1. Swarm intelligence algorithm search characteristic analyses
In the search process of the swarm intelligence algorithm, each individual represents a feasible solution in the feasible domain space. Through collective cooperation, individuals constantly adjust their
positions and update information of feasible solutions. The quality evaluation of feasible solutions is based on the fitness function or the objective function. In the framework of swarm intelligence algorithm, global search and local search are two important components. Different swarm intelligence algorithms have different behavior mechanisms in global search and local search, but the computing framework is same. Therefore, the coding method design is universal when using swarm intelligence algorithm to optimize the problem.

3.2 Individual coding method

The cold chain distribution problem model belongs to the vehicle routing problem with capacity and time window constraints. It needs to arrange the number of vehicles and the distribution routes simultaneously under the constraints. Distribution routing optimization problem is also a discrete space optimization problem. To avoid changing individual coding rules, here proposes a decoding method with heuristic method to map the individual expression to the solution space of the problem, and then get the number of vehicles and the routing arrangements from the individual representation. For the individual structure in swarm intelligence algorithm, the individual expression still adopts the conventional continuous space coding method. Any individual can be represented as \( x = (x_1, x_2, \ldots, x_D)^T \), where \( i \) represents any individual and \( D \) represents the number of customers.

Based on the individual expression, the new decoding process is divided into three phases:

- **Phase 1:** Decode the service sequence of customers. The values on each dimension in the individual \( x \) are sorted to obtain an ordered integer array \( S \) as shown in Table 1. Each dimension number in \( S \) represents the customer’s number, and the integer \( s_j \) in each dimension is the assigned order for related customer.

| \( x_j \) | \( x_{i1} \) | \( x_{i2} \) | \( \ldots \) | \( x_{ij} \) | \( \ldots \) | \( x_{iD} \) |
|---|---|---|---|---|---|---|
| \( \downarrow \) |
| \( S \) | \( s_1 \) | \( s_2 \) | \( \ldots \) | \( s_j \) | \( \ldots \) | \( s_D \) |

- **Phase 2:** assign customer and determine the route \( R \) of each vehicle. In this phase, based on the constraints of vehicle capacity constraints, customer assignment is carried out according to the order got from \( S \). The process is described as Figure 1.

- **Phase 3:** output the plan \( p_i \). Based on the decoding results, calculate the number of vehicles and the order of the customers the vehicles served. Then output the plan.

It should be noted that swarm intelligence algorithms, especially those that search in continuous space, have much similarities in coding and searching forms. Therefore, the decoding processes are suitable for other swarm intelligence algorithm with the same characteristics to solve this type of the problem.

4. Case Study

4.1. Experimental setting

To test the performance of the encoding method, two different scale cases are introduced, which are medium-scale problems with 30 customers and large-scale problems with 50 customers. Information such as demand-point coordinate \((x_i, y_i)\), requirement, service time and service time window are given. According to the operational work and survey, the data of the above cases are generated randomly.

For comparing the performance of the encoding method in different algorithms for the cold-chain routing optimization problem, nine swarm intelligence algorithms are selected. The selected algorithms and settings are shown in Table 2, including CLPSO, BBO, FA, ABC, CS, BFO, BA, SNSO and GA. In all the experiments, the population number is 30.
Figure 1. The process of customer assignment method considering capacity constraints

| Alg. | Parameters | Alg. | Parameters |
|------|------------|------|------------|
| CLPSO | $c=1.5, \omega_{\text{max}}=0.95, \omega_{\text{min}}=0.4, m=5$ | BFO | $N_c=10, N_r=10, N_v=10, C=0.01, P_c=0.9$ |
| BBO  | $I=1$ | BA  | $\alpha=0.9, \gamma=0.5, r=0.5, A=0.25$ |
| FA   | $\alpha=0.5, \beta=0.2, \gamma=1$ | SNSO | $P_N=P_K=0.2$ |
| ABC  | $\text{limit}=100$ | GA  | $P_c=0.9, P_m=0.01$ |
| CS   | $P_a=0.25, \alpha=0.5, \beta=3/2$ |

4.2. Results and analysis

It can be seen from the statistical results (Table 3) that the accuracy of most algorithms is close in medium-scale case. Specially, the accuracy and stability of search solution gotten by ABC, CS, SNSO and GA are little better than other swarm algorithms. The average curves in figure 2 shows that ABC, CS, SNSO and GA converge rapidly in the early stage, which indicates that these algorithms have good global search ability in the early stage, and can quickly find the optimal region then to explore it.

Nevertheless, for the results of large-scale case (Table 4), it can be concluded that when the scale of the problem increases, the performances of algorithms are different. BBO, ABC and SNSO perform better and get the results than others. With the increase of the scale of problems, the difficulty of optimization is increased, and the requirement of searching ability of algorithms is also increased. The comparison of convergence curves (Figure 3) also shows that the BFO, BA and FA algorithms have insufficient continuous search ability in solving this problem. After some steps of local search in the early stage, the population of them are stagnated in the middle and later periods and cannot escape from the local extremum region. However, the convergence curves of BBO, ABC and SNSO continue to decline. It means that they can explore the solution space deeply, which leads to a higher accuracy than other algorithms.

Through the above analysis, conclusion can be drawn that the coding and decoding scheme designed in this paper is can be applied to solving the cold chain logistics distribution routing optimization problem for swarm intelligence algorithms. Most of the algorithms can get the near optimal solution and have good applicability.
5. Conclusion
In this paper, it aims at how to use swarm intelligence optimization algorithms to optimize the distribution of refrigerated vehicles in cold chain logistics. A new decoding method is designed by combining swarm intelligence algorithm with problem features. Through the experiments including the medium-scale and large-scale cases, 9 intelligent algorithms are used to solve the problem with the introduced method. The results show that the general model of the problem can be solved by using some swarm intelligence algorithms under the provide decoding method and performs efficiently.

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