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Optimization Model of Cold-Chain Logistics Network for Fresh Agricultural Products

—Taking Guangdong Province as an Example

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Abstract

Cold-chain demand of fresh agricultural products is increasing in China, while network layout of cold-chain logistics is in disorder and its cost is huge. To address this problem, this paper casts an optimal model of cold-chain logistics network and tackles it with genetic algorithms. This optimal model takes running total cost of logistics network as the objective, and embeds a nonlinear mixed integer programming including two assignment issues. The model determines optimal layout and logistics management for pre-cooling stations and logistics center for fresh agricultural products. Our main contribution is to consider construction cost and operation cost of cold chain logistics simultaneously. Case study illustrates the effectiveness of the model.

Keywords

Cold-Chain Logistics, Network Layout, Genetic Algorithms

1. Introduction

Guangdong has various characteristic fruits, such as lychee, banana, strawberry, dragon fruit, longan, etc., and its output of fruit is huge. The output of fruits such as cherry tomato, cucumber, cabbage and mustard, is also at the top in the list. In addition, there are many sea areas adjacent to Guangdong with various aquatic products, which provide a broad development prospects for cold-chain logistics. However, the cold-chain food is still self-producing and self-selling in most areas of Guangdong, and the refrigeration circulation rate is low comparing to some other provinces [1] [2]. The reason is that the layout of cold-chain logistics in Guangdong is unreasonable, and it is urgent and necessary to optimize the network of cold chain logistics, which includes network nodes, such as pre-cooling stations, distribution centers, etc. and network paths.

Some references have studied in similar issue. Xie and Zhao [3] studied the joint distribution model of cold chain logistics based on cloud logistics. They elaborated and analyzed the business system architecture and service model architecture of the joint distribution information platform of cold chain logistics based on cloud logistics. Harris, Mumford and Naim [4] proposed an efficient evolutionary multi-objective optimization model to the capacitated facility location-allocation problem (CFLP) for addressing large instances that considers flexibility at the allocation level, where financial costs and CO_2 emissions were considered simultaneously. Zheng, Li and Wu [5] proposed a novel location inventory routing (LIR) model to solve cold chain logistics network problem under uncertain demand environment. They introduced a multi-objective genetic algorithm (GA), non-dominated sorting in genetic algorithm II (NSGA-II) to solve the model due to the complex of LIR problem (LIRP).

Our main contribution in this paper is that, the construction cost and operation cost of cold chain logistics are also considered simultaneously, to establish network optimization model for cold chain logistics. Unlikely with the other research, we study the double layer structure of cold chain logistics network, that is, layer one is from places of origins to pre-cooling station while layer two is from pre-cooling station to distribution centers.

2. Problem Description

The planning of cold-chain network is to determine the layout and quantity of logistics distribution nodes, including producing area of agricultural products, pre-cooling stations, refrigeration house, distribution center, etc.

Different fresh agricultural products have different refrigerated transportation conditions, such as precooling mode, refrigerated transportation mode, temperature and humidity, etc. Aquatic products and vegetables are generally pre-cooled in the production area, and the pre-cooling method is relatively backward. Road and railway transportation are main methods of trans-regional transportation for vegetables. Generally, meat is pre-cooled in processing plants, and transport under frozen and chilled conditions. Aquatic products have two type of transportation after pre-cooling. The long-distance transportation of quick-frozen aquatic products is generally carried by railway, while the long-distance transportation of fresh aquatic products is mainly carried by air.

In view of different fresh agricultural products are not identical to the requirement of storage and transportation environment, so for a specific category (including aquatic products, vegetables, meat, fruits, etc.), this paper studies and constructs the logistics network of fresh agricultural products of this category, that is, to determine the transportation network between the origin, pre-cooling station and fresh distribution center.

The determination of the logistics network is mainly based on the cost of establishing precooling station, distribution center, storage cost and transportation cost of fresh agricultural products. At the same time, when constructing the logistics network of fresh agricultural products, we should take into account the transportation demand of producing area, the product demand of market, the storage capacity of precooling station and distribution center, etc. The determination of the logistics network takes establishment cost of pre-cooling station and distribution center, storage cost and transportation cost as the main objectives. Meanwhile, in the construction of fresh agricultural products logistics network, we should take into account the transportation needs of the origin, market demand for products, storage capacity of pre-cooling station and distribution center, and other factors.

3. Optimization Model of Cold Chain Logistics Network

3.1. Model Hypothesis

Before establishing an optimization model, the following assumptions are made for the fresh agricultural product logistics network:

1) Due to the huge investment for establishing a new cold chain logistics distribution center, we assume that the cold chain logistics distribution center has been completed and put into use, and there is no major change in the short term, that is, the location problem of distribution center of cold chain logistics is transformed into the selection problem of existing distribution center.

2) Assume that fresh agricultural produce at the production site will not be directly transported to the cold chain logistics distribution center even if the daily average supply is small, but will be sent to the pre-cooling station for pre-cooling before being transported to the cold chain logistics distribution center. For pre-cooling stations, the number of fresh agricultural products to be pre-cooled per day is called the average daily purchase volume.

3) Because fresh agricultural products have characteristic of diversity, seasonality and the dynamic of logistics operations, in order to accurately reflect the actual cost of unit supply, we takes 2 months as the cost accounting cycle.

4) Since the pre-cooling station has the function of temporarily storing for cold-chain food, and the procurement cycle of pre-cooling station or refrigeration storage is short, the centralized procurement cycle is set within one week in consideration of the capacity limitation.

3.2. Modeling of Cold Chain Logistics Network

The optimization model of the cold chain logistics network takes the total cost as objective function. The total cost accounting includes the rental cost, inventory cost, operation cost of logistics activities, and the transportation cost from the place of origin to the pre-cooling station and from pre-cooling station to distribution center. In terms of constraints, each place of origin will only select one pre-cooling station; each pre-cooling station also corresponds to a cold chain logistics distribution center; the distance from place of origin to pre-cooling station and the distance from pre-cooling station to cold chain logistics distribution center should not exceed its maximum limit; the quantity of fresh agricultural products received by pre-cooling station and cold chain logistics distribution center shall not exceed its maximum processing capacity; the quantity of fresh agricultural products processed by all pre-cooling stations is equal to the number of cold chain logistics distribution center. The optimization model of cold chain logistics network is established as follows:

Objective Function:

$$\min\left[60\sum_t C_t^L Z_T + 60\sum_j C_j^H \sum_i q_i^s X_{ij} + q_{jt} d_{jt}\left(C_{ij}+C_{jt}\right)\frac{60}{P_j}\times\sum_t Z_t \sum_j Y_j + q_{jt} C_t^S \frac{60}{P_j}\times\sum_t Z_t\sum_j Y_j + q_{jt}C_t^J\frac{60}{P_j}\times\sum_t Z_t\sum_j Y_j\right]$$

s.t.

$$\sum_j X_{ij} = 1,$$

$$\sum_t X_{jt} = 1,$$

$$d_{ij} X_{ij} \le L_{(i,j)\max},$$

$$d_{jt} X_{jt} \le D_{(i,j)\max},$$

$$\sum_j q_{ij} \le Q_j^H,$$

$$\sum_j q_{jt} \le Z_t Q_t,$$

$$\sum_j q_i^S X_{ij} P_j = \sum_t q_{jt}.$$

where,

i —the number of origin of agricultural products, $i \in [I]$;

j —the number of alternative pre-cooling stations, $j \in [J]$;

t —the number of alternative distribution centers, $t \in [T]$;

C_t^L denotes daily average rental cost cold-chain logistics distribution centers, (unit: RMB);

C_t^S denotes unit inventory cost of the cold-chain logistics distribution centers (unit: RMB);

C_t^J denotes the operating cost per unit logistics activity of cold chain logistics distribution center t (unit: RMB);

q_i^S denotes the average daily supply of production site i (unit: ton/day);

C_j^H denotes the unit processing cost of the pre-cooling station j (unit: RMB);

Q_j^H denotes the maximum processing capacity of pre-cooling station j (unit: tons);

Q_t denotes the maximum inventory capacity of the cold chain logistics distribution center t (unit: tons);

d_{ij} denotes the distance between production site i and pre-cooling station j (unit: km);

d_{jt} denotes the distance between pre-cooling station j and cold chain logistics distribution center t (unit: km);

$D_{(i,j)\max}$ denotes the maximum distance restriction (unit: km) from the place of production *i* to the pre-cooling station *j*;

$D_{(j,k)\max}$ denotes the maximum distance restriction (unit: km) from the pre-cooling station *j* to the cold-chain logistics distribution center *t*;

C_{ij} denotes the unit transportation cost (unit: RMB/ton·km) from the place of production *i* to the pre-cooling station *j*;

C_{jt} denotes the unit transportation cost (unit: RMB/ton·km) from the pre-cooling station *j* to the cold chain logistics distribution center *t*;

$Q_{\min}^{p}$ denotes the minimum number of pre-cooling stations;

$Q_{\min}^{D}$ denotes the minimum number of cold-chain logistics distribution centers;

$Q_{\max}^{D}$ denotes the maximum number of cold-chain logistics distribution centers;

q_{ij} denotes the supply quantity (unit: ton) from the production site to the pre-cooling station *j*;

q_{jt} denotes the periodic supply (unit: ton) from the pre-cooling station *j* to the cold-chain logistics distribution center *t*;

P_j denotes the centralized procurement cycle of the pre-cooling station *j*, namely, the time span from the beginning of procurement to car-loading (long distance);

X_{ij}, X_{jt}, Y_j, Z_t are 0 - 1 variables. If they are equal to 1, it means that a function works, while if they are equal to 0, it means that this function is unavailable.

4. Basic Idea of Genetic Algorithm

4.1. Evolutionary Process of Genetic Algorithms

Genetic algorithms (GA) is a mathematical algorithm that simulates the evolutionary process of organisms according to genetic mechanisms. The algorithm has the advantages of self-adaptability and global probabilistic search and its essence is an efficient, parallel and global search method, which can automatically acquire and accumulate information about the search space in the process of searching. The search process is controlled adaptively to obtain the optimal solution. In each generation of the genetic algorithm, individual selection is based on the fitness values of the individuals in the problem domain and the reconstruction method borrowed from natural genetics to generate a new approximate solution, which promotes the evolution of individuals in the population. The new individuals are more capable of adapting to the environment than the original individuals [6] [7] [8].

Genetic algorithm is a process of global optimization by using the idea of survival of the fittest and natural selection. In the process of genetics, the continuous replication, crossover and mutation of genes promote the continuous reproduction and evolution of the population. Finally, the optimal individual converges, and the process is shown in **Figure 1** [9] [10].

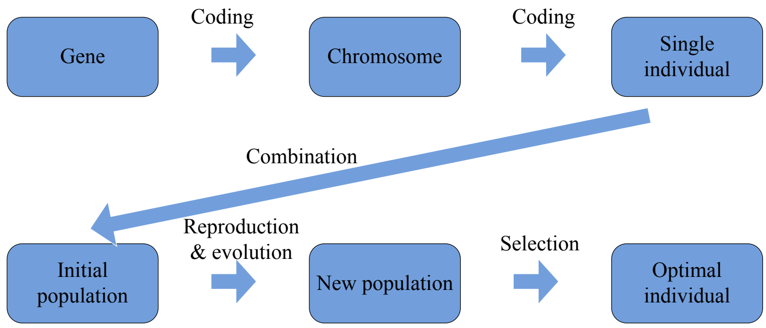

Figure 1. Evolutionary process of genetic algorithms.

As can be seen from **Figure 1**, first of all, the chromosome is encoded by the gene and is the carrier of the genetic material. Therefore, the internal performance and external performance of the individuals are determined by it, and the mapping process from internal performance to external performance is actually a genetic process. Secondly, when multiple individuals encoded by different chromosomes are combined into an initial population, according to the principle of survival of the fittest, by random selection, crossover and mutation operations, they evolve to a new population of the next generation with higher fitness to adapt to the environment. This process will make the individuals in the population have stronger environmental adaptability like natural evolution. After the optimization process is finished, the optimal individual in the last generation of the population will be selected to decode as the approximate optimal solution of the problem [10] [11]. The basic idea of this solution to the global optimization problem can be summarized as follows:

1) The objective function of the problem to be optimized is understood as the adaptability of a biological population to the environment;

2) The variables to be optimized are corresponding to the individuals of the biological population;

3) The algorithm for solving the optimization model is compared with the evolutionary process of the biological population.

4.2. Operational Steps of Genetic Algorithms

The genetic algorithm's operational flow consists of seven steps [12] [13] [14], as follows:

Step 1: Initialization. Firstly, the gene is encoded to form a chromosome, and then multiple individuals encoded by the chromosome are randomly selected to generate initial population;

Step 2: Evaluate individual's superiority and inferiority, that is, to determine the fitness function, to calculate the fitness value of the individuals, and to judge whether the optimization criterion is satisfied or not. If satisfied, it means that the final generation is reached, and the optimal solution can be decoded and output; if not, then turn to step three;

Step3: Determine the selection probability according to the fitness value, and execute the selection operator to enter the next generation from the preferred part of the existing population. The higher fitness it is, the more likely the individuals are to be copied;

Step 4: Determine the crossover probability, perform a crossover operator, and preferably select some individuals to enter the next generation;

Step 5: Determine the mutation probability, execute the mutation operator, and select new individuals to enter the new population;

Step 6: If the pre-set evolution times is reached in advance or the optimal individual is obtained in advance, or the optimal individual has not been improved in successive generations, then execute step seven, otherwise, return to step two;

Step 7: Output the individual with the optimal fitness in the population as the optimal solution or satisfactory solution to the model.

The basic operation process of the genetic algorithms is as follows [15]:

1) Initialization: Set the evolution number $t = 0$, set the maximum evolution number T, and randomly generate M individuals as the initial population P(0).

2) Individual evaluation: Calculate the fitness of each individual in the population P(t).

3) Selection operator: The selection operator is applied to the group. The purpose of the selection is to directly inherit the optimized individuals to the next generation or to generate a new individual through the pairing to regenerate to the next generation. The selection operator is based on the fitness assessment of the individuals in the group.

4) Crossover operator: The crossover operator is applied to the group. The so-called crossover refers to the operation of replacing the partial structure of two parent individuals to generate a new individual. The core function of the genetic algorithms is the crossover operator.

5) Mutation operator: The mutation operator is applied to the population, that is, changes the gene values on certain genomes of individuals in the population. The next generation population P(t + 1) was obtained after selection, crossover and mutation from population P(t).

6) Termination condition judgement: If t = T, the individual with the greatest fitness, which is obtained during the evolution process, is outputed as the optimal solution, and the calculation is terminated.

5. Examples

According to food production in Guangdong Province, the 8 palaces, Shenzhen, zhuhai, Huizhou, Foshan, Zhanjiang, Shantou, Dongguan and Shaoguan, aremain places of agricultural products, which will be coded as 1, 2, 3, 4, 5, 6, 7, and 8, respectively. Suppose that six alternative pre-cooling stations are given, which are coded as I, II, III, IV, V, VI, respectively. Besides the agricultural products logistics distribution center of Huizhou and Zhanjiang, another alternative distribution center of cold chain logistics is given, and they are coded as A, B, and C, respectively. The distances of the eight origins of Shenzhen, Zhuhai, Huizhou, Shunde, Zhanjiang, Shantou, Dongguan, Shaoguan to Guangzhou are shown in Table 1. According to the distance from the eight origins to Guangzhou, the maximum limit distance from the production site to the pre-cooling station and the maximum restricted distance from the pre-cooling station to the cold chain logistics distribution center are separately set to 70 km and 450 km. Considering the factors such as investment and construction costs, it is assumed that the number of cold chain logistics distribution centers M that can be leased is no more than two, and the number of pre-cooling stations N that can be used is no more than four. Then, we have $1 \le M \le 2$, $1 \le N \le 4$.

In this example, the distance from 8 origins to 6 alternative pre-cooling stations is shown in Table 2. At the same time, Table 2 also shows the daily supply quantity of each origin. All of these fresh agricultural products are sent to pre-cooling station for pre-cooling and then transported to the cold chain logistics distribution centers.

Using the MATLAB R2012 genetic algorithms toolbox to solve the model, through the multiple debugging of the parameters [16] [17], it is determined that the algorithm can reach the approximately optimal solution when running to the 98th generation, and finally the optimal layout of each node of the cold chain logistics network is obtained, as shown in Table 3. According to Table 3, under the constraints of different supply requirements of the eight production sites, and in order to minimize the total cost associated with cold chain logistics activities, the pre-cooling station should eventually choose IV and V, while the cold chain logistics distribution center chooses A and B, namely agricultural products logistics distribution center of Huizhou and Zhanjiang.

Table 1. Distance from the eight origin of cold chain fresh agricultural products to Guangzhou (unit: km).

	Shenzhen	zhuhai	Huizhou	Shunde	Shantou	Zhanjiang	Dongguan	Shaoguan
Guanzhou	139	116	140	15	527	466	82	227

Table 2. Distance from origins to pre-cooling station (unit: km) and average daily supply volume (unit: ton) for each origin.

i/j	I	II	III	IV	V	VI	Average daily supply
1	15	22	45	10	39	70	54
2	36	41	50	73	53	92	72
3	20	39	17	33	28	53	87
4	22	34	87	54	30	102	61
5	322	245	507	112	23	210	91
6	32	155	466	76	51	409	60
7	40	72	64	37	145	80	50
8	104	250	77	91	46	126	78

Table 3. Optimal solution of genetic algorithms.

No.	Place of origins	Pre-cooling station	Cold chain logistics distribution center
1	1, 7	IV	A
2	2, 3, 4, 5, 6, 8	V	B

6. Conclusion

The problem of cold chain logistics network layout optimization is a complex but significant problem. The fundamental goal is to solve the current network layout chaos and high cost-consuming for domestic cold chain logistics whose demand is growing. Therefore, this paper uses genetic algorithm to optimize the cold chain logistics network, so as to determine the layout of the pre-cooling station and the cold chain logistics distribution center in the cold chain logistics network, and solve transportation management issues from the production area to the pre-cooling station, and from the pre-cooling station to cold chain logistics distribution center in logistics network. The example shows that the established optimization model for cold chain logistics network can effectively solve the network layout problem and transportation management problem, and reduce the operating cost of cold chain logistics. The model also has good adaptability and reference to other logistics network layout problems. The future work is to collect more data in cold chain logistics in Guangdong and other provinces, and to apply this model to tackle these network layout problems.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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