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Bi-level programming model and genetic simulated annealing algorithm for inland collection and distribution system optimization under uncertain demand

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ABSTRACT

With the continuous improvement of users' expectation of transportation quality and the continuous improvement of the transportation system in China, the inland collection system plays an increasingly important role in port development. Based on the demand change, this paper measures the disturbance of the demand change to the inland collection and distribution system from ports and customers, it establishes bi-level programming model for transportation route and transportation mode selection. The upper layer establishes the stochastic opportunity constrained programming model with the minimum cost of collection and distribution, the lower layer builds an optimization model with the goal of maximum customer satisfaction. The genetic simulated annealing algorithm is used to solve the bi-level programming model combined with specific examples and compared with genetic algorithm. The result shows that genetic simulated annealing algorithm can not only obtain the optimal solution, but also improve the speed of global convergence. The genetic simulated annealing algorithm is an effective algorithm to solve the bi-level programming model with multiple targets.

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1. Introduction

With the rapid development of world economy and continuous growth of the trade volume, container transport industry in china has also entered the new peak of development. The throughput of container terminals has increased dramatically and the inland container transport network plays an increasingly important role in the container transportation system.

The inland collection and distribution system plays an important role in the development of port and hinterland. Therefore, many scholars at home and abroad have done a lot of researches on it. Zhang (2011), and Zhou X. *et al.* (2017) proposed the current port collection and distribution system problems and analysis, and its development status in-depth discussion [1, 2]. Tang and Tan (2009) discussed some shortcomings and corresponding development countermeasures to hinder it [3]. Based on the theory of sustainable development and related policies, Iannone (2012) proposed the model of inland container transport network planning based on the situation of infrastructure resource construction and the service level of nodes and lines [4]. Combined with the status quo of international railway intermodal transport, Sun (2016) put forward multimodal transport bill of lading and international rail transport waybill docking mode, multimodal transport bill of lading operation mechanism [5]. Du and Evans (2008) proposed logistics network transport management which mainly involves the choices of transport mode, the determination of transport routes, etc. [6]. Chang (2008) studied the optimal transport path selection problem in international multimodal transport networks [7].

On this basis, some experts and scholars combined with freight distribution optimization issues to study the specific operations of the organization in the process of related issues. In the study of maritime and inland transport portfolio problems, Arnone *et al*. (2014) established a linear programming model based on port service frequency and customs time to solve the problem of cargo flow distribution optimization for large sparse networks [8]. Under the combined consideration of various feasible paths and modes of transport, Luo and Grigalunas (2003) constructed a traffic distribution model for port collection and distribution systems [9]. Aiming at the distribution of freight container multimodal transportation problem, Chen and Sun (2015) constructed a freight distribution model based on super-network, and introduced the variational inequality theory, and implemented the improved projection algorithm [10]. To solve the problem of the Dominican inland container transport system, Zehendner and Feillet (2014) built a mixed integer programming model with the minimum transit time [11]. Dong (2007) established a comprehensive optimization model of the port collection and distribution system to solve the single cargo, multi-cargo and multi-transport mode combined transport problem [12]. Aiming at the transportation of goods in the integrated transportation network, Liu *et al*. (2016) constructed an integrated transport network design optimization model considering the construction of financial constraints [13]. Nossack and Pesch (2013), Feng *et al*. (2010), Wang and Yun (2013), and Sterzik and Kopfer (2013) introduced the concept of time benefit and established a model with the goal of minimizing the cost of time [14-17]. For the multi-objective logistics network optimization problem, Pishvaee *et al*. (2010) introduced the time window factor [18]. Huang (2013) and Wu (2014) construct the transportation network decision model of mixed axis mode with the goal of minimizing the cost, and used the heuristic greedy algorithm to solve it, and then used the branch and delimitation method to solve the scheme [19, 20].

All of the above studies are about the optimization of the recent inland collection and distribution system when the demands are certain. The mathematical model is established and solved from the angle of the port and the carrier in most of the researches. Ports provide freight services for many large enterprises. To make itself bigger, stronger and farther, ports have to reduce transportation cost, but also improve the customer satisfaction. Involve this into the decision-making process by measuring, which has a very important influence on the decision result. Considering the change of freight demand, the paper integrates customer satisfaction into decision making and constructs a bi-level programming model of transportation route and mode of transportation. Through the mutual influence between the port and the customer, the optimal solution to improve customer satisfaction can be achieved while reducing the transportation cost.

2. Problem description

The mathematical model studied in this paper is described as follows: Cities can transport export goods to the ports by two ways. One is directly from the city to the port. The other is from the city to the port through the transit station. Different transport nodes lead to different driving distance of the path. There are two alternative modes of transport, namely, railway and highway. Because the modes of transportation are different, the unit price and the speed of the transportation are thus different. In order to reduce the transportation cost and improve the customer satisfaction, choosing the best transportation route and the mode of transportation and making the optimal allocation of goods is necessary. The number of each transport node is shown in Table 1.

According to the problems studied in this paper, the following assumptions are made:

- Operation ability and capacity can meet the freight traffic for a period of time;
- This article only considers one type of goods;
- This article only considers two transportation ways-railway and highway;
- Planning period is one year, and during the period, the cargo demand obeys a certain probability distribution.

Variables and parameters required in this article:

a the number of cities;
b the number of transfer stations;
c the number of ports;
i the serial number of city and transit station;
j the serial number of transit station and port;
m the inland transportation ways, m = 1 indicates the choice of rail transport m = 2 indicates the choice of road transportation;
x_{ij}^m the cargo volume from the transport node i to the transport node j by using the transport mode m;
ε_i represents city i's random cargo needs, the distribution function is $\emptyset_i(\cdot)$;
C_{ij}^m the transportation costs of transporting the unit goods from the transport node i to the transport node j by using the transport mode m;
CI_i the operating costs of the container handling unit of the transfer station i;
CP_j the operating costs of the container handling unit of the port j;
S_{ij} the distance from the transport node i to the transport node j;
V_a the relationship between the average velocity and the maximum velocity;
D_{ij}^m the congestion time from the transport node i to the transport node j by using the transport mode m;
V_{ij}^m the transport speed of the transport mode m from the transport node i to the transport node j;
t_{ij}^m represents that the transport time required from the transport node i to the transport node j by the transport mode m;
T represents that the total time required for goods shipped to the port from the city;
Q^m the amount of container carried by the unit vehicle of the transport mode m;
n_{ij}^m represents that the number of available vehicles from the transport node i to the transport node j by using the transport mode m;
α_i $(0 \leq \alpha_i \leq 1)$ represents that the confidence level of the incident that the freight volume meets the transportation demand generated by the city;
ET represents that the earliest service time was agreed between the customer and the port;
LT represents that the latest service time was agreed between the customer and the port.

Table 1 The serial number of each transport node in the container distribution network

Node	Numbering			Quantity
City	1	2	a	a
Transfer station	a+1	a+2	b	a+b
Port	a+b+1	a+b+2	c	a+b+c

3. Used methods

3.1 Bi-level programming model

(1) Model structure

In the process of distribution of goods, the collecting and distributing cost in the ports mainly consists of transportation costs and operating costs. As a result, they are used to describe the cost of inland collection and distribution system in the upper model. However, the lower model is analyzed from the customer's perspective. It aims to maximize customer satisfaction and introduces the route travel time to describe. When the ports provides the freight service for customers, they make decisions aiming at the least collecting and distributing cost. On the premise of this, the customers make the decision with the shortest route time within the time limit agreed with the port. At the same time, the customer's service time has an impact on the decision of the port. Through the mutual influence of the two, the optimal freight transport scheme is obtained. The optimized model structure is shown in Fig. 1.

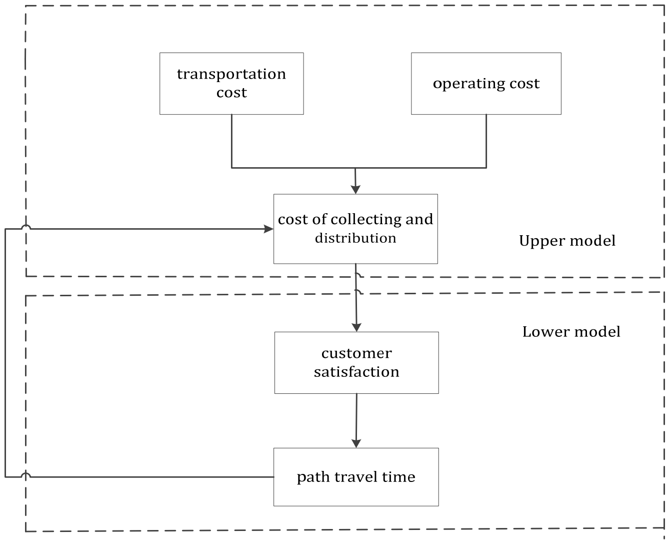

Fig. 1 Model structure

(2) Upper model

The upper model (U) is analyzed from the perspective of the port, taking the minimum cost of the port set as the goal, the target function is set as follows:

$$minf(x) = \sum_{i=1}^{a}\sum_{j=a+1}^{a+b+c}\sum_{m} C_{ij}^{m}\cdot x_{ij}^{m} + \sum_{i=a+1}^{a+b}\sum_{j=a+b+1}^{a+b+c}\sum_{m}\left(C_{ij}^{m} + CI_i\right)\cdot x_{ij}^{m} + \sum_{i=a+1}^{a+b}\sum_{j=a+b+1}^{a+b+c}\sum_{m} CP_j\cdot x_{ij}^{m}$$

Among them, the first item indicates the total cost of transportation to the port and inland container station; the second item represents the sum of the transportation cost from the inland container transfer station to the port and the operating cost of the inland container transfer station to handle the container cargo; the third term indicates the operating costs of the container port for handling all containerized cargo.

Constraint condition:

$$\mathrm{Pr}_i\left\{\sum_{j=a+1}^{a+b+c}\sum_{m} x_{ij}^{m} \geq \varepsilon_i\right\} \geq \alpha_i, i = 1, 2, \cdots, a \tag{1}$$

$$x_{ij}^{m} \leq Q^{m} n_{ij}^{m} \tag{2}$$

$$\sum_{i=1}^{a}\sum_{j=a+1}^{a+b}\sum_{m} x_{ij}^{m} = \sum_{i=a+1}^{a+b}\sum_{j=a+b+1}^{a+b+c}\sum_{m} x_{ij}^{m} \tag{3}$$

$$\text{When } i = 1, 2, \cdots, a, j = a + 1, a + 2, \cdots, a + b + c \tag{4}$$

$$\text{When } i = a + 1, a + 2, \cdots, a + b, j = a + b + 1, a + b + 2, \cdots, a + b + c \tag{5}$$

Constraint condition (Eq. 1) indicates that the amount of goods transported to the port by the city satisfies the demand for transport demand arising from the city should not be lower than the given confidence level. Constraint condition (Eq. 2) indicates that the operational capacity of the port can meet the volume of goods shipped to the port by the city. Constraint condition (Eq. 3) express the amount of goods transported to the transfer station is equal to the amount of the goods transported to the port by the transfer station. Constraint condition (Eq. 4) express the transfer station or the port is the terminal point when city is the starting point. Constraint condition (Eq. 5) represents that the port is the terminal point when the transfer station is the starting point.

(3) Lower model
The lower model (L) takes the customer satisfaction as the goal, and introduces the path driving time to carry on the characterization. Within the service time agreed between the customer and the port, the shortest route time is the target, and the objective function is set as follows:

$$minT = \sum_{i=1}^{a}\sum_{j=a+1}^{a+b+c}\sum_{m} t_{ij}^{m} + \sum_{i=a+1}^{a+b}\sum_{j=a+b+1}^{a+b+c}\sum_{m} t_{ij}^{m}$$
$$= \sum_{i=1}^{a}\sum_{j=a+1}^{a+b+c}\sum_{m}\left(\frac{S_{ij}}{V_a \cdot V_{ij}^{m}} + D_{ij}^{m}\right) + \sum_{i=a+1}^{a+b}\sum_{j=a+b+1}^{a+b+c}\sum_{m}\left(\frac{S_{ij}}{V_a \cdot V_{ij}^{m}} + D_{ij}^{m}\right)$$

Among them, the first item indicates transportation time from the city to the port and inland container transfer station; the second term indicates the transportation time from the inland container transfer station to the port.

Constraint condition:

$$\Pr\{ET \le T \le LT\} \ge 85\ \% \tag{6}$$

$$\text{When } i = 1, 2,\cdots, a, j = a+1, a+2,\cdots, a+b+c \tag{7}$$

$$\text{When } i = a+1, a+2,\cdots, a+b, j = a+b+1, a+b+2,\cdots, a+b+c \tag{8}$$

Constraint condition (Eq. 6) indicates that the travel time of the path is not less than 85 % within the service time range. Constraint condition (Eq. 7) indicates that the transfer station or port is the end point when the city is the starting point. Constraint condition (Eq. 8) means that the port is the terminal point when the transfer station is the starting point and

3.2 Bi-level programming model solving steps

(1) Determine the demand
In the random opportunity constraint condition (Eq. 1), ε_i represents the random demand for city i goods. The confidence level $\alpha_i (0 \le \alpha_i \le 1)$ to be achieved for each city i, there is always a number K_i, so that $\Pr_i\{K_i \ge \varepsilon_i\} \ge \alpha_i, i = 1, 2, \cdots, a$ established.

So, the sufficient and necessary conditions for the establishment of constrained condition Eq. 1 is:

$$\sum_{j=a+1}^{a+b+c}\sum_{m} x_{ij}^{m} \ge K_i\,,\ \ i = 1,2,\cdots,a.$$

Thus, the key to making the constraint a deterministic constraint is to express the critical value K_i with a known distribution. Known from the knowledge of probability theory, the formula $\Pr_i\{K_i \ge \varepsilon_i\} = \emptyset_i(K_i), i = 1, 2, \cdots, a$ is always established. It can be concluded that $K_i = \emptyset_i^{-1}(\alpha_i), i = 1, 2, \cdots, a$ is always established, where $\emptyset_i^{-1}(\cdot)$ is the inverse of $\emptyset_i(\cdot)$. Since there is more than one solution of the formula $\Pr_i\{K_i \ge \varepsilon_i\} \ge \alpha_i, i = 1, 2, \cdots, a,$ the corresponding $\emptyset_i^{-1}(\alpha_i)$ is not unique. For this situation, the boundary value $K_i = inf\{\emptyset_i^{-1}(\alpha_i)\}, i = 1,2, \cdots, a$ is taken as the solution.

(2) Genetic simulated annealing algorithm
The uncertainty of the bi-level programming model is very high, and the difficulty of solving is very high. Currently, the solution of bi-level programming is mainly embodied in the following aspects: For the linear bi-level programming, Zhao and Gao proposed penalty function method to solve the problem of bi-level programming [21]. Wan, Ji and Wang use a dual approximation algorithm to solve the problem of bi-level programming [22]. For the nonlinear bi-level programming, Sun and Gao proposed a heuristic algorithm based on sensitivity analysis [23].

In recent years, some intelligent algorithms are widely used to solve the problem of transportation bi-level planning model, such as genetic algorithm and cloud adaptive genetic algorithm, etc. Although the genetic algorithm can solve the model directly under the uncertain rules through a global search of feasible solutions, but its search speed is slow, easily to fall into the local optimal solution and do not converge. Obviously, the transport routes and transport modes for the uncertainty cannot be accurately described.

The simulated annealing algorithm (SA) has high quality and robust initial experimental performance. Some scholars have studied the probability of using the simulated annealing algorithm to solve the global minimum point, and found that the obtained probability value is very close to 1. Therefore, the simulated annealing algorithm will not fall into the local optimal solution until it finds the global minimum point, but this optimization process is often longer. Combining genetic algorithm with simulated annealing algorithm to obtain a hybrid optimization algorithm-genetic simulated annealing algorithm (GASA), which makes the two algorithms make up for each other and the defects are well compensated. Therefore, this paper uses genetic simulated annealing algorithm to solve the transport routes and transport modes selection of bi-level programming model.

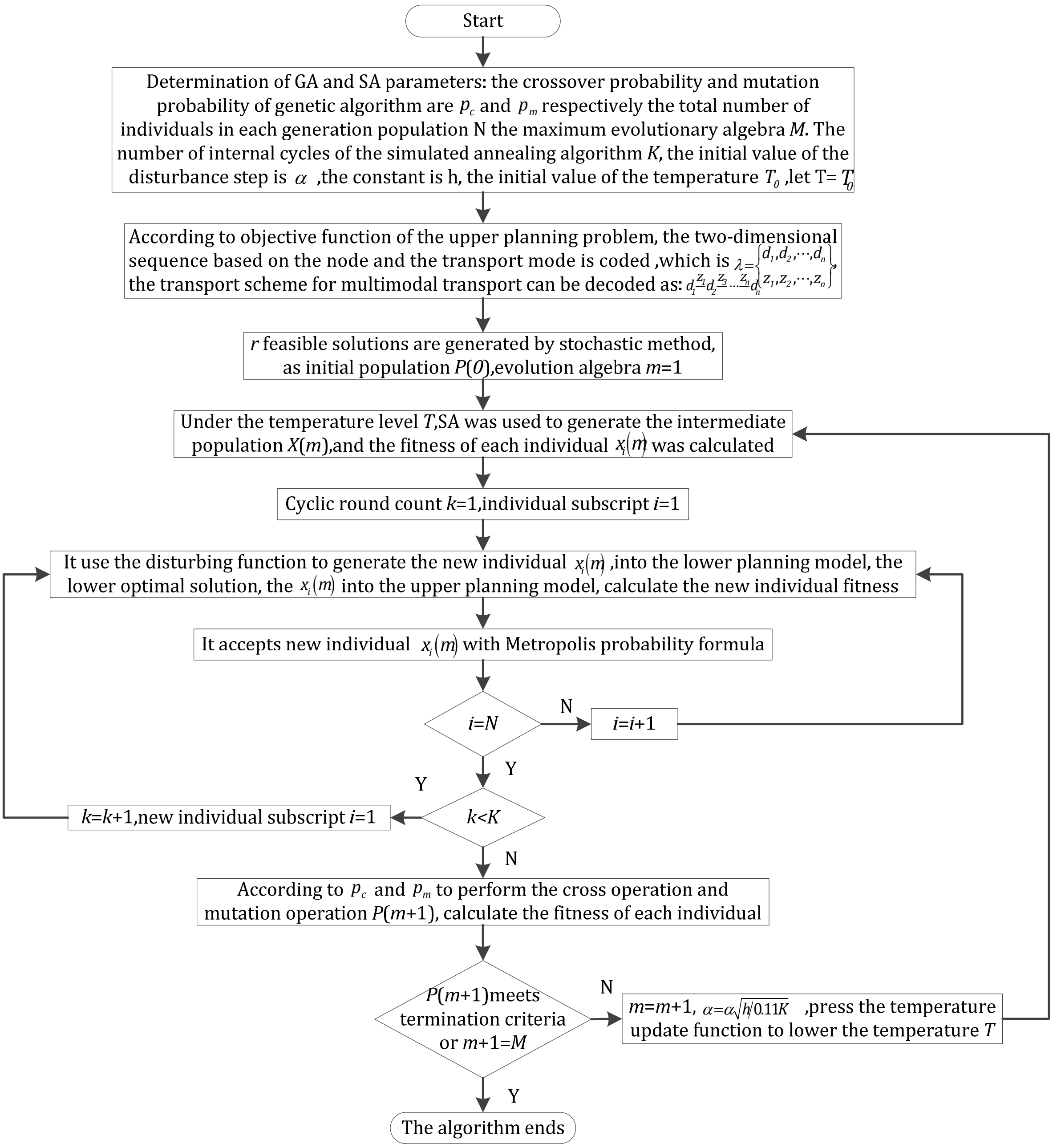

Fig. 2 Algorithm flow chart

First, according to the decision-making scheme of the inland container transit station obtained from the upper model, the transportation route and transportation mode of the lower model are selected and optimized; secondly, the upper cargo transportation plan is adjusted through the optimization of transportation methods and routes. Followed by the optimization of the transport routes and transport methods back to the upper model to re-distribution of goods; finally it is expected to converge to the near-optimal solution of bi-level programming through several iterations, the algorithm flow is shown in Fig. 2.

4. Results and discussion

4.1 Data sources

The example selects one hinterland city, three locations where inland container transit stations can be built and two ports form an inland collection and distribution network. The optimization problem of transportation demand satisfying the confidence level of 90 % was studied, the relevant data is shown in Tables 2-14. Due to different modes of transport, there are differences in capacity limits. The means of transport for railway transport are container regular trains, the unit load is 140 TEU, road transport is a container truck with a unit carrying capacity of 2 TEU.

Table 2 The number of cars available from city to port

Node	Port 1	Port 2
City	13205	52823

Table 3 The number of cars available from city to transit station

Node	Transfer station 1	Transfer station 2	Transfer station 3
City	1758	4746	8575

Table 4 The number of cars available from transit station to port

Node	Transfer station 1	Transfer station 2	Transfer station 3
Port 1	8167	11398	24374
Port 2	15818	38954	85275

Table 5 The number of trains available from transit station to port

Node	Transfer station 1	Transfer station 2	Transfer station 3
Port 1	122	156	261
Port 2	100	100	200

Table 6 The number of trains available from city to transit station

Node	Transfer station 1	Transfer station 2	Transfer station 3
City	100	50	0

Table 7 The unit freight rates of road from city to port (Yuan/TEU)

Node	Port 1	Port 2
City	4242	2126

Table 8 The unit freight rates of road from the city to the transit station (Yuan/TEU)

Node	Transfer station 1	Transfer station 2	Transfer station 3
City	834	3968	5092

Table 9 The unit freight rates of road from the transit station to the port (Yuan/TEU)

Node	Transfer station 1	Transfer station 2	Transfer station 3
Port 1	1063	1913	2563
Port 2	1175	2192	2750

Table 10 The unit freight rates of railway from the transit station to the port (Yuan/TEU)

Node	Transfer station 1	Transfer station 2	Transfer station 3
Port 1	965	1436	1871
Port 2	1190	1687	2122

Table 11 The unit freight rates of railway from the city to the transit station (Yuan/TEU)

Node	Transfer station 1	Transfer station 2	Transfer station 3
City	1398	2714	0

Table 12 The distance between city and port (Km)

Node	City
Transfer station 1	425
Transfer station 2	405
Transfer station 3	356
Port 1	1100
Port 2	945

Table 13 The distance between transit station and port (Km)

Node	Port 1	Port 2
Transfer station 1	424	445
Transfer station 2	556	356
Transfer station 3	439	357

Table 14 Transfer station and port operating capacity and unit service fee

Node	Operational capability (TEU / year)	Unit service charge (Yuan / TEU)
Transfer station 1	140000	220
Transfer station 2	100000	240
Transfer station 3	140000	200
Port 1	500000	350
Port 2	140000	340

4.2 Demand calculation

Through investigation and statistics of the city's 52-week demand for transportation within a year, it is found that transport demand is not uniform, as shown in Fig. 3.

(1) Mathematical expectation. Using Eviews software to analyze the above-mentioned 52-week transportation demand, the demand for transportation within one year obeys the normal distribution. The expected value is 2034 and the standard deviation is 110. Since random variables are additive, the transport demand for this year follows a normal distribution, which is $\varepsilon_i \sim N(105768, 735^2)$. The expected value is 105768 TEU and the standard deviation is 735 TEU.

(2) Maximum shipping value. Assuming that the port needs to meet 90 % of the city's transportation, which means $\alpha_i = 0.9$. According to the standard normal distribution table, there is $\emptyset(1.28) = 0.9$. So, the maximum freight (K) obtained to meet the stochastic demand with 90 % confidence level is $K_1 = \varepsilon_1 = min\{105768 + 735 \times 1.28, 105768 + 735 \times 1.29\} = 106709(\text{TEU})$.

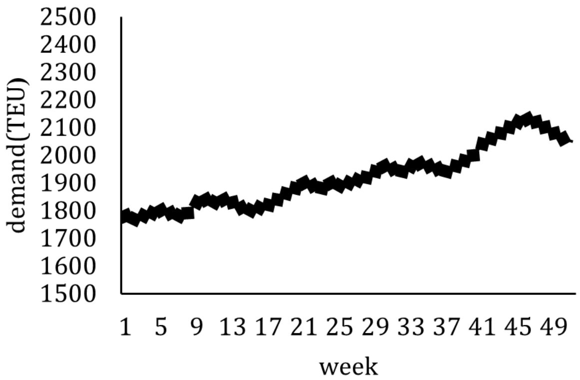

Fig. 3 The demand for container transportation generated every week within a year (Unit: TEU)

4.3 Numerical result

According to the example, we can see that a = 1, b = 3, c = 2. Number 1 stands for the city, and number 2-4 is three container terminals, and number 5, 6 is respectively for the two ports. The population size of genetic algorithm N = 100 and the number of evolutionary M = 100; the number of internal cycles in simulated annealing K is 20 and the constant h is 50; the initial value of step α is 0.1 and the initial temperature T_0 is 2000. Temperature reduction scheme: For the first 20 generations, T is subtracted by 20 % of the current value, after each generation T minus 50 % of the current value. The weight vector of cost of collecting and dispatching and path travel time is ω= (0.4, 0.6). Suppose the railway transport speed is 80km/h, the highway transportation speed is 100km/h, and the service time agreed by the customer is [9, 11]. Genetic simulated annealing algorithm is used to solve the problem of inland collecting and dispatching system optimization under the change of freight demand, the result is shown in Table 15.

Genetic simulated annealing algorithm and genetic algorithm were used to solve the optimization problem of inland collection and distribution system, the results are shown in Table 16-17 and Figs. 4-5. According to the calculation results, the optimal value of the model calculated by genetic simulated annealing algorithm is better than that of the traditional genetic algorithm in the same evolutionary algebra. The success rate of the search is higher than that of the genetic algorithm, the ability of the algorithm to search the global optimal solution is optimized. The convergence precision and the robustness are improved, and the global convergence speed is improved effectively. It can be seen that the genetic simulated annealing algorithm can effectively and quickly solve the bi-level programming model. It can improve customer satisfaction and reduce the cost of collection and distribution by choosing the rationalization of transport modes and transport routes in the process of making the cargo flow distribution plan.

Table 15 Calculation results of genetic simulation annealing algorithm

Project	Minimum value	Maximum value	Optimum solution
Time/d	9.00	12.00	9.55
Cost / million	245910.61	418469.45	248120.96

Table 16 Calculation results of genetic algorithm

Project	Minimum value	Maximum value	Optimum solution
Time/d	9.45	11.00	10.61
Cost / million	248378.12	414468.33	255020.98

Table 17 Comparison of Genetic simulation annealing algorithm and genetic algorithm

Method type	Best transport plan	Optimization degree, %
GASA	$1\overset{2}{-}2\overset{1}{-}5,1\overset{2}{-}6$	58.2
GA	$1\overset{1}{-}2\overset{1}{-}5,1\overset{2}{-}6$	46.3

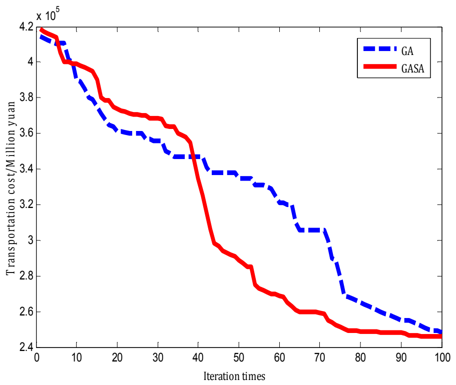

Fig. 4 Transport cost comparison chart

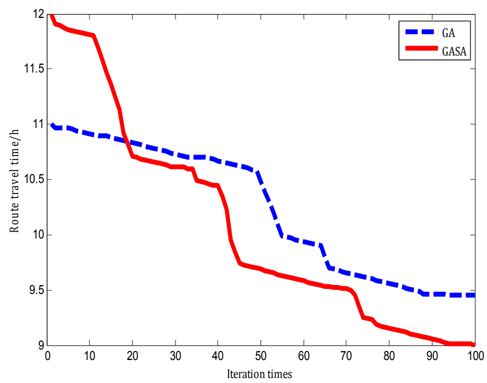

Fig. 5 Route travel time comparison chart

5. Conclusion

Considering the uncertainty of freight demand, the bi-level programming model for the selection of transportation routes and transportation modes was established from the perspective of lowering transportation costs and improving customer satisfaction. The genetic simulated annealing algorithm is used to solve the model and the optimal scheme is obtained. Finally, the validity and feasibility of the model and algorithm are verified by simulation experiments. On the container inland collection and distribution system optimization problem, the combination of the bi-level programming model and the genetic simulated annealing algorithm provides a balanced language model and solution for the port. It has certain practical value for improving customer satisfaction and reducing the cost of collecting and transporting.

The optimization of inland collection and distribution system is a very complicated problem. In terms of transportation, this article only considers the two ways of railways and highways. In the study of specific issues, the transportation of inland river should also be considered in light of actual conditions.

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