

文章编号:1671-1637(2012)04-0059-08

## 容量限制与运输模式联合选择的综合 客运枢纽布局模型

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**摘 要:**分析了传统的综合客运枢纽布局优化模型,同时增加运输模式与中转能力的约束条件,提出了改进后的综合客运枢纽布局优化模型,并设计了改进的遗传算法对其求解。应用 LINGO 软件进行有效性检验,分别计算了 8 节点与 50 节点 Solomon 标准测试数据,并将改进模型与经典算法进行比较。计算结果表明:当应用 LINGO 软件计算 8 节点 Solomon 标准测试数据时,平均运算时间为 5 043 s,最优成本为 1 952 418 元,应用遗传算法与 MATLAB 软件计算的平均运算时间为 62 s,最优成本为 1 955 900 元;当应用遗传算法与 MATLAB 软件计算 50 节点 Solomon 标准测试数据时,平均运算时间为 574 s,最优成本为 8 500 600 元;当计算 25 节点的 AP 数据且枢纽节点数量为 3 时,平均运算时间为 612 s,最优成本为 155 148 元,比经典算法降低了 108 元。可见,改进模型有效。

**关键词:**交通规划;客运枢纽;布局规划;二阶段优化模型;容量限制;运输模式

**中图分类号:**U491.12

**文献标志码:**A

### Comprehensive passenger hub layout model of combined selection for capacity limitation and transportation mode

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**Abstract:** The traditional optimization model of comprehensive passenger hub layout was analyzed, and the constraints of transportation mode and transfer capability were considered simultaneously. The improved optimization model of comprehensive passenger hub layout was proposed, and the improved genetic algorithm was introduced to solve the model. LINGO software was used to test the effectiveness, Solomon standard test data with 8 and 50 nodes were calculated respectively, and the improved model was compared with the classical algorithm. Calculation result shows that while calculating Solomon standard test data with 8 nodes, the average running time is 5 043 s and the optimal cost is 1 952 418 yuan by using LINGO software, the average running time is 62 s and the optimal cost is 1 955 900 yuan by using genetic algorithm and MATLAB software. While calculating Solomon standard test data with 50 nodes, the average running time is 574 s and the optimal cost is 8 500 600 yuan by using genetic algorithm and MATLAB software. While calculating AP data set with 25 nodes and hub node number is 3, the average running time is 612 s and the optimal cost is 155 148 yuan, the optimal cost decreases 108 yuan

**Receipt** Date: 2012-02-06

**Research Projects:** National Key Technology R&D in the 11th Five-year Plan of China(2009BAG13A04); Transportation Technology Project of Inner Mongolia(NJ2003-004); Special Fund for Basic Scientific Research of Central Colleges(CHD2011JC002)

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compared with the classical algorithm. So the improved model is effective. 6 tabs, 6 figs, 20 refs.

**Key words:** traffic planning; passenger hub; layout planning; two-stage optimization model; capacity constraint; transportation mode

## 0 Introduction

As an important section of comprehensive transportation system, the comprehensive passenger hub is an essential area for passengers to jointly gather, disperse and transfer, and plays an important role on connecting urban traffic and city transportation. Compared with foreign cities, the comprehensive passenger hub construction in China is laggard. Due to transportation management system factors, the construction of hub is lack of unified planning. Therefore, the layout of traffic facility is unreasonable and leads to long passenger traveling distance, the cross interference of passenger flow and car flow, low transfer efficiency. With the development of passenger dedicated railway, national highway hub and airport hub, the planning of comprehensive passenger hub is not the only station planning of traffic mode. So it is an urgent problem to consider the demands of different transportation modes in hub planning, and to coordinate different transportation modes in comprehensive passenger hub.

O'Kelly studied airline network and put forward  $p$ -hub optimization model firstly, used US Civil Aeronautics Board (CAB) statistics data set to verify the model<sup>[1]</sup>. Marin et al found that CAB data and Australia Post (AP) data were used as normal test data in the field<sup>[2-4]</sup>. Jaillet et al built a capacitated airline network planning model and used heuristic algorithm to solve the model<sup>[5]</sup>. Yuan et al put forward two-stage comprehensive passenger hub planning model based on traffic demand generation mechanism<sup>[6]</sup>, but didn't design solution algorithm. Topcuoglu et al applied genetic algorithm to study the uncapacitated single-hub layout problem and used CAB data set to test the model, and found that the result was consistent and the calculation time was smaller<sup>[7]</sup>. Gelareh et al applied mixed integer programming model to solve hub location problem in public transportation planning and put forward accelerated Benders

decomposition algorithm and greedy neighborhood search algorithm<sup>[8]</sup>. Chen et al studied the layout problem of road-railway comprehensive freight hub and logistics center, set up a layout model based on service efficiency and designed large neighborhood search algorithm<sup>[9]</sup>. Liu et al proposed a bi-level programming model for regional comprehensive transportation hub layout, tested the efficiency of genetic algorithm by using Beijing-Tianjing-Hebei Regional Railway Network data<sup>[10]</sup>. Lin et al studied a hub-and-spoke network, proposed a general capacitated  $p$ -hub median model, and designed genetic algorithm to identify hub location<sup>[11]</sup>.

In summary, the  $p$ -hub layout optimization models were built, including transportation modes such as air, road and railway, and various heuristic algorithms were designed. However the constraints of transportation mode and route as well as hub capacity are not considered simultaneously. The two-stage model with the choosing constraints of hub capacity and transportation mode is built, and genetic algorithm is designed by using MATLAB, which makes the model more practical and scientific.

## 1 Two-stage optimization model of comprehensive passenger hub layout

In order to reflect the dynamic characteristic of regional transportation network, transportation planning theory and traffic flow theory are introduced into comprehensive passenger hub layout planning. At the same time, the four-stage method of traffic planning and the location model of logistics nodes are introduced to discuss comprehensive passenger hub layout model. The proposed comprehensive passenger hub layout model is divided into two steps.

The first step determines candidate hub location and number with the 4-stage method of traffic planning. The second step chooses final passenger hub from the candidate hubs. The

constraints include developing scale, construction fund, transportation network structure. By establishing optimization model and finding optimal solution, the passenger travel cost can be reduced and transportation network efficiency can be improved.

### 1.1 Related assumption

The hub planning area can be simplified to a directed weighed graph  $G, G=(N, A, L)$ .  $N, A, L$  are the set of city nodes for transportation network, the set of road sections among cities and the set of road physical characteristics respectively. There are  $n$  city nodes in the network and  $N=\{1, 2, \dots, n\}$ . Candidate hub set  $K$  is selected from the nodes in the first stage model. In the second stage model, the final  $p$  hubs are chosen from  $K$ , which are  $k_1, k_2, \dots, k_p$ .  $A=\{a_{ij}\}$ ,  $a_{ij}=f(i, j, l_{ij})$  is the directed arc from node  $i$  to node  $j$ .  $l_{ij}$  is the weight of  $a_{ij}$  and  $l_{ij} \geq 0$ .  $l_{ij}$  is a road physical characteristic parameter, such as distance, travel time or cost. Here  $l_{ij}$  refers to passenger travel distance and it is the arc length from  $i$  to  $j$ . Based on the forecasting result of passenger flow volume, OD matrix  $W$  is established, where the element of  $W$  is  $w_{ij}$  and  $w_{ij}$  is the passenger flow volume between every origin-destination node pair  $i$  and  $j$ .  $O_i$  is the generating volume of passenger flow from node  $i$  and  $D_j$  is the attracting volume of passenger flow for node  $j$ , which are shown in Eq. (1) and Fig. 1.

$$\begin{cases} O_i = \sum_j w_{ij} \\ D_j = \sum_i w_{ij} \end{cases} \quad (1)$$

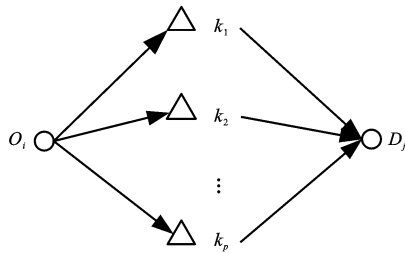


Fig. 1 Passenger flow volume

There are two kinds of nodes including common node and hub node. Hub node can not only gather and disperse passengers, but also generate or

attract passengers. Common node is non-hub node, can only generate or attract passengers<sup>[12]</sup>. Passengers can transfer at hub nodes, or travel between common nodes directly. So transportation modes in the network include direct transportation based on common nodes and transportation based on hub nodes.

For the hub-based transportation mode, passengers gather in hub node firstly and then travel to the target hub node. After arriving at the target hub node, passengers disperse, so passengers travel through two hubs<sup>[13]</sup>. In summary, there are three kinds of transportation routes. The first is that passengers are generated or attracted at common nodes, passengers transfer to the target hub node through 1 hub node or 2 hub nodes, The second is that passengers are generated at hub nodes and destination node is common node, they travel to destination node directly or through 1 hub node. The third is that passengers are generated at common nodes and are attracted at hub nodes, they travel to the target hub node directly or through 1 hub node.

The comprehensive transportation network and routes are shown in Fig. 2,  $i_n$  and  $j_n$  are nodes.

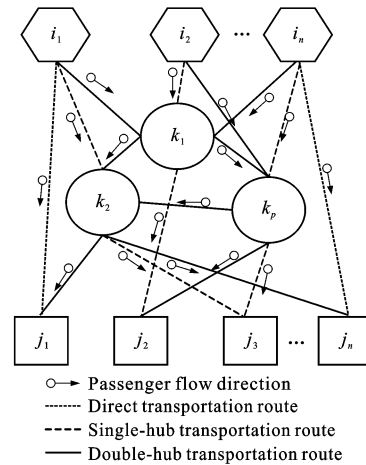


Fig. 2 Comprehensive transportation network

The proposed comprehensive transportation network has a broader meaning than the traditional supply-demand balance system. The traditional transportation network is based on single hub, the condition of passenger secondary transfer is not considered. The proposed network includes three

passenger transportation routes, which are direct transportation route, single-hub transportation route and double-hub transportation route.

## 1.2 Modeling process

### 1.2.1 Objective function

#### (1) Total hub operation cost

The total hub operation cost  $Z_1$  is

$$\min Z_1 = \sum_{k \in K} y_k (F_k + c_k x_k) \quad (2)$$

where  $y_k$  is decision variable and  $y_k$  is 0 or 1;  $F_k$  is the fixed construction cost of hub node  $k$ ;  $c_k$  is the unit transfer cost of gathering and dispersing passengers for hub node  $k$ ;  $x_k$  is the transfer volume of hub node  $k$ .

#### (2) Total cost of comprehensive transportation network

According to the different transportation modes, transportation cost is divided into hub-based cost and direct transportation cost.

$$\min Z_2 = \sum_{i \in N} \sum_{j \in N} \sum_{k \in K} \sum_{m \in K} (\alpha c_{ik} + \beta c_{km} + \alpha c_{mj}) \cdot X_{ijkm} B_{ijkm} + \sum_{i \in N} \sum_{j \in N} Q_{ij} \hat{c}_{ij} \hat{B}_{ij} \quad (3)$$

where  $Z_2$  is the total cost of comprehensive transportation network;  $\alpha$ ,  $\beta$  are conversion coefficients and  $\beta < \alpha < 1$ ;  $c_{ik}$  is the unit transportation cost from origin node  $i$  to initial hub node  $k$ ;  $c_{km}$  is the unit transportation cost between initial hub node  $k$  and destination node  $m$ ;  $c_{mj}$  is the unit transportation cost from target hub node  $m$  to destination node  $j$ ;  $B_{ijkm}$  is decision variable and is 0 or 1;  $X_{ijkm}$  is the transfer passenger flow volume through hub node for a certain OD pair;  $\hat{c}_{ij}$  is the unit transportation cost among nodes;  $\hat{B}_{ij}$  is decision variable and is 0 or 1;  $Q_{ij}$  is the direct transportation passenger flow volume for a certain OD pair.

So the objective function of optimization model is

$$\min Z = \sum_{k \in K} y_k (F_k + c_k x_k) + \sum_{i \in N} \sum_{j \in N} \sum_{k \in K} \sum_{m \in K} (\alpha c_{ik} + \beta c_{km} + \alpha c_{mj}) X_{ijkm} B_{ijkm} + \sum_{i \in N} \sum_{j \in N} Q_{ij} \hat{c}_{ij} \hat{B}_{ij} \quad (4)$$

where  $Z$  is the total cost.

### 1.2.2 Constraint condition

#### (1) Feasible region constraint

Based on the first stage model, candidate hub nodes are determined to enhance the efficiency of

optimal model, so there is

$$P = \sum_{k \in K} y_k \quad (5)$$

where  $P$  is hub node number which is need to be established.

#### (2) Transportation mode selection constraint

Assuming that  $B_{ik}$ ,  $B_{mj}$  and  $\hat{B}_{ij}$  are decision variables and are 0 or 1. For a certain OD pair, only one transportation mode can be selected. It is hub-based transportation or direct transportation. Moreover, hub-based transportation should be based on the condition of hub node construction. So the constraints are as follows

$$\sum_{k, m \in K} B_{ijkm} = 1 - \hat{B}_{ij} \quad (6)$$

$$B_{ijkm} \leq y_k \quad (7)$$

$$B_{ijkm} \leq y_m \quad (8)$$

$$B_{ijkm} = 0 \quad i = m \neq k \quad (9)$$

$$B_{ijkm}, \hat{B}_{ij} \in \{0, 1\} \quad (10)$$

#### (3) Supply-demand balance constraint

Comprehensive transportation system is a supply-demand balanced system, so for any city node, its supply and demand should be consistent with the passenger flow volume forecasting result, there are

$$Q_i = \sum_{j \in N} \sum_{k \in K} \sum_{m \in K} X_{ijkm} B_{ijkm} + \sum_{j \in N} Q_{ij} \hat{B}_{ij} \quad (11)$$

$$D_j = \sum_{i \in N} \sum_{k \in K} \sum_{m \in K} X_{ijkm} B_{ijkm} + \sum_{i \in N} Q_{ij} \hat{B}_{ij} \quad (12)$$

#### (4) Hub capacity constraint

Since the passengers gather and disperse at hub nodes, the transfer volume should be less than planned hub capacity, there are

$$x_k = \sum_{i \in N} \sum_{j \in N} \sum_{m \in K} X_{ijkm} B_{ijkm} \quad (13)$$

$$x_m = \sum_{i \in N} \sum_{j \in N} \sum_{k \in K} X_{ijkm} B_{ijkm} \quad (14)$$

$$x_k \leq C_{kk} \quad (15)$$

$$x_m \leq C_{mm} \quad (16)$$

where  $x_k$  is the transfer volume of hub node  $k$  and is the sum of all passenger volumes through hub  $k$ ;  $C_{kk}$ ,  $C_{mm}$  are planned passenger volumes when  $k$  or  $m$  is selected as hub node respectively.

## 2 Model validation

The model must be tested to prove the validity as

well as to provide reference for designing algorithm. Running LINGO software, based on international Solomon standard test data, 8 cities are selected as city nodes, and the model is tested

with stochastic passenger flow volumes between OD pairs. The distances and passenger flow volumes are shown in Tabs. 1 and 2.

The optimal solution can be obtained from the

**Tab. 1 Distances of 8 city nodes**

km

Node	1	2	3	4	5	6	7	8
1	0.00	35.36	15.00	33.54	35.36	51.48	55.23	60.42
2	35.36	0.00	36.40	32.02	42.43	41.23	64.03	50.99
3	15.00	36.40	0.00	21.21	20.62	39.05	40.31	47.17
4	33.54	32.02	21.21	0.00	11.18	18.03	32.02	26.93
5	35.36	42.43	20.62	11.18	0.00	22.36	22.36	28.28
6	51.48	41.23	39.05	18.03	22.36	0.00	31.62	10.00
7	55.23	64.03	40.31	32.02	22.36	31.62	0.00	30.00
8	60.42	50.99	47.17	26.93	28.28	10.00	30.00	0.00

**Tab. 2 Passenger flow volumes of 8 city nodes** 10<sup>4</sup> person

Node	1	2	3	4	5	6	7	8
1	0	100	100	100	100	100	100	10
2	150	0	80	18	80	120	100	20
3	150	130	0	18	80	12	100	100
4	150	10	110	0	80	120	100	100
5	150	130	15	15	0	120	80	90
6	150	130	15	15	110	0	80	60
7	150	130	110	80	110	110	0	50
8	15	15	110	110	110	110	110	0

**Tab. 3 Transportation routes by using LINGO software**

Node	1	2	3	4	5	6	7	8
1	—	1-5-2	direct	direct	direct	1-5-6	1-5-7	1-5-8
2	2-5-1	—	2-5-3	2-5-4	2-6-5	direct	2-6-7	2-6-8
3	direct	3-5-2	—	direct	direct	direct	3-6-7	3-6-8
4	4-6-1	4-6-5-2	4-5-3	—	direct	4-5-6	4-6-7	4-6-8
5	direct	5-6-2	direct	direct	—	5-4-6	direct	direct
6	direct	6-5-2	6-4-3	direct	direct	—	direct	direct
7	7-6-1	7-6-2	7-5-6-3	direct	direct	direct	—	7-5-8
8	8-6-1	8-6-2	8-4-3	8-5-4	direct	direct	8-5-4-7	—

nodes 1 and 2 must go through hub node 6. The routes from node 7 to node 3 must go through hub nodes 5 and 6. The routes from node 7 to node 8 must go through hub node 5. So there are three kinds of transportation modes including direct transportation route, single-hub transportation route and double-hub transportation route. From the optimization result, the choices of transportation modes and routes are more abundant.

model and the solution is consistent with reality value. So the objective function and the constraints of model are all reasonable, and the model is a nonlinear integer programming model. After calculating, the optimal cost is 1 952 418 yuan and nodes 4, 5 and 6 are chosen as hub nodes. The transportation routes are shown in Tab. 3.

Taking node 7 for example, the optimal transportation routes are shown in Fig. 3. The routes from node 7 to hub nodes 4, 5 and 6 are all direct transportation. The routes from node 7 to hub

The problems can be solved by general mathematical softwares such as LINGO, but these softwares can only solve small-scale problem. For large-scale problem, the calculating time will increase dramatically. So heuristic algorithm is recommended to solve the large-scale problem.

### 3 Calculation result analysis

To solve large-scale problem, genetic algorithm is

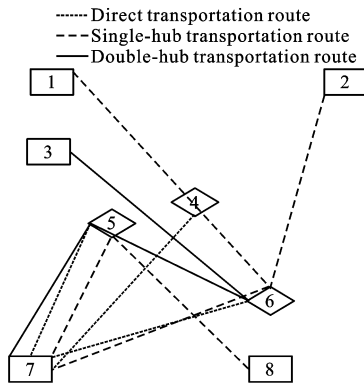


Fig. 3 Routes of node 7 as origin node

used. In the model, two basic problems of hub location and passenger flow distribution are considered, the basic idea is to generate an initial hub location randomly. Genetic algorithm is used to identify hub location and transportation mode. Assuming that when passenger flow is more than a certain value and a direct transportation mode is chosen. Moreover, every passenger will choose the nearest hub to transfer. When the termination condition is met, the optimal solution is output. The flow of genetic algorithm (GA) is shown in Fig. 4.

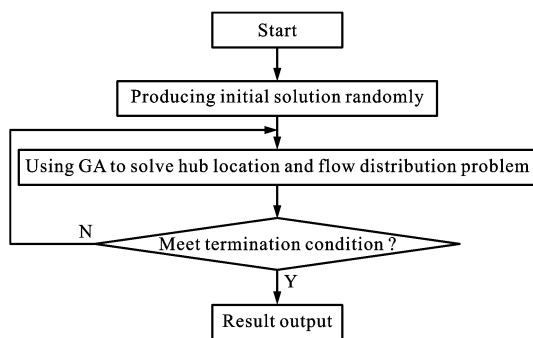


Fig. 4 Algorithm flow

#### (1) Coding

According to the feature of model solution, 0-1 string coding is chosen. Individual length is the number of candidate hub node. In string coding, 1 represents the city node is chosen as hub and 0 represents the node isn't chosen<sup>[14]</sup>.

#### (2) Population initialization

A 1-dimensional vector of initial population including 1 and 0 is generated randomly, when the number of 1 is  $p$ , there are  $p$  nodes chosen to build.

#### (3) Fitness function identification

It is easy and convenient to transfer objective function to fitness function directly. The fitness function relates to transportation mode choosing closely, so the complex calculation of fitness function is changed into some independent sub-problems.

#### (4) Genetic operator

Considering the feature and the convenience of model, single point crossover operation is selected. A certain mutation probability of chromosome is set in advance. If the probability is larger than a random generated value, the mutation of chromosome happens.

Because the model is a  $p$ -hub problem, not all the individuals of new population can meet the constraints of  $p$  hubs, the individuals which can't meet conditions should be deleted.

#### (5) Termination condition

The maximum iterations are set in advance. When iteration times reach the value, the algorithm stops. The method can control the solution accuracy and running time effectively.

To test algorithm accuracy, MATLAB is introduced to design genetic algorithm with 8 city nodes test data. The obtained routes among OD nodes are shown in Tab. 4.

The result is compared to the result of LINGO software, which is shown in Tab. 5.

By using genetic algorithm, the convergence rate is faster, but the optimal cost is slightly bigger. The differences of transportation routes and cost are mainly due to different traffic flow distribution rules of LINGO software and genetic algorithm. By using LINGO software, the distance of traffic flow is simply considered. By using genetic algorithm, the direct transportation is chosen when traffic volumes among nodes are enough, however transportation based on hub node is recommended. Moreover, passengers select the nearest hub to transfer. So genetic algorithm based on MATLAB is more real.

To test the reliability of genetic algorithm, Solomon standard test data are used. There are 50 nodes, 20 nodes are candidate hubs. Assuming

**Tab. 4 Transportation routes by using genetic algorithm**

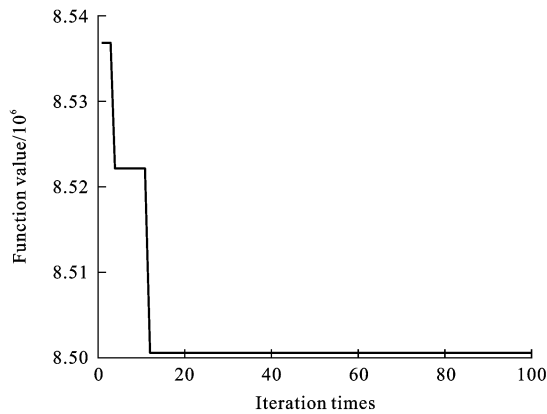
Node	1	2	3	4	5	6	7	8
1	—	1-3-2	direct	1-3-4	1-3-5	1-3-6	1-3-5-7	1-3-6-8
2	2-3-1	—	direct	2-3-4	2-3-5	2-3-6	2-3-7	2-3-8
3	direct	direct	—	3-5-4	direct	direct	direct	direct
4	4-5-1	4-5-2	4-5-3	—	direct	4-5-6	4-5-7	4-5-8
5	direct	direct	direct	direct	—	direct	direct	direct
6	direct	direct	direct	6-5-4	direct	—	direct	direct
7	7-5-1	7-5-2	7-5-3	7-5-3	direct	7-5-6	—	7-5-8
8	8-6-1	8-6-2	8-6-3	8-6-4	8-6-5	direct	8-6-7	—

**Tab. 5 Result comparison**

Method	Average running time/s	Optimal cost/yuan
LINGO software	5 043	1 952 418
Genetic algorithm	62	1 955 900

that passenger volume is set randomly, 10 hub nodes are selected finally.

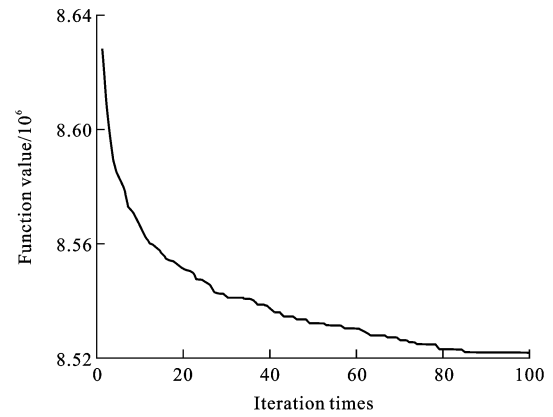
The population size is 50, iteration times are 100 and mutation rate is 0.08. After repeating independent calculation, stable calculation result is obtained. The average running time is 570 s. Nodes 1, 3, 5, 6, 7, 10, 14, 17, 19 and 20 are selected as hub nodes. The convergence curve of optimal fitness function is shown in Fig. 5, and the objective function is smallest at the 10th iteration. The convergence curve of average fitness function is shown in Fig. 6, and the objective function is smallest at the 90th iteration.



**Fig. 5** Convergence curve of optimal fitness function

## 4 Calculation result comparison

Kratika et al used improved genetic algorithm to solve uncapacitated  $p$ -hub problem<sup>[15-20]</sup>. It is



**Fig. 6** Convergence curve of average fitness function

similar to the proposed problem in this paper, and its model constraints are simpler. Compared with the proposed model, Kratika et al could not consider hub capacity and only used a single mode of origin-hub-destination. Compared with the calculation results of two models, the AP data set of 25 nodes are used and  $p$  is 3. At the 20th calculation point, the results between this paper (method 1) and reference [15] (method 2) are shown in Tab. 6.

**Tab. 6 Comparison of results for two methods**

Method	Average running time/s	Optimal cost/yuan
Method 1	612.000	155 148
Method 2	0.185	155 256

The optimal cost of method 1 decreases 108 yuan. By using method 1, the solution can be found with less cost because method 2 only allows origin-hub-destination transportation mode, while method 1 considers more modes including direct transportation, transportation based on 1 hub node and 2 hub nodes. When direct transportation cost is less, transportation based on hub node is

unnecessary.

## 5 Conclusions

The layout optimization model of traditional comprehensive transportation hub is improved, hub transfer capacity and transportation mode selection constraints are considered, which makes the model more realistic and guarantees solution is more scientific. The model type is identified by LINGO software, MATLAB is introduced to design genetic algorithm, and the algorithm is tested. Research shows that capacitated  $p$ -hub problem with less cost solution is solved by using the improved model.

The  $p$ -hub layout optimization model with capacity and passenger transportation mode selection is built. Genetic algorithm and AP data set are used to test model validation. Other algorithms aren't utilized to find the solution, such as tabu search algorithm. On the same time, the model and algorithm are not applied in practical hub planning, which should be studied deeply in the future.

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