Research on Optimization of Regional Comprehensive Transportation Network Structure Based on Multi-objective Planning

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Abstract: The paper, based on the practical problem of optimizing regional comprehensive transportation network structure, and referring to economics theory, uses multi-objective planning to propose an optimization model based on supply-demand equilibrium, minimizing generalized cost, and green sustainability. Due to more than two objective functions in the model, it is troublesome to convert the model into a single-objective programming problem. Therefore, the model is considered to be converted into a bi-level programming problem. Based on the genetic algorithm, the specific algorithm for solving the model is given and conducted a simulation calculation. The results shows that the proposed method in this paper is verified to solve practical problem.

1. Introduction

With the transformation of our nation's economic development mode and the adjustment of industrial structure, the relationship between transportation and the economic and social have gradually transferred into the construction adaptation from the total size adaptation. With the acceleration of the pace of transformation, the structural contradiction of the regional comprehensive transportation network has intensified, which has seriously affected the efficiency of transportation resources' allocation. Some scholars have noticed similar problems, for example, Basso, Leonardo J and Jara-Diaz, Sergio R analyzed the index of the transport structure from the economic point of view. It is considered that the density of the economy and the scope of the economy are the two basic indicators of transport structure [1]; Baiding Hu, Michael McAleer considered that the transportation industry should be incorporated into the industrial structure for research [2].

In recent years, around the optimization of the structure of the transportation system, some achievements have been made by the academic community based on relevant mathematical models and algorithms. About the specific issues in the structural aspects of transportation systems, Mark W. Homer, Morton E. O'Kelly studied on how to realize the optimization of space configuration of

service systems for container ports [3]; Illi Racunica, Laura Wynter, etc. did in-depth research on how to realize the optimization of transportation system structure and the effective allocation of transportation resources from the aspects of economies of scale, etc. [4]; In terms of model solution, in order to solve the problem about imbalance of Japanese specialized container hub structures, Akio Imai and Etsuko Nishimura, etc. revised the existing model of the berth structure of the port, and used the genetic algorithm technology to solve nonlinear problems [5].

The paper is based on the practical problem of optimizing regional comprehensive transportation network structure, and, referring to economics theory, uses multi-objective planning to propose an optimization model. Then, the model is considered to be converted into a bi-level programming problem. Based on the genetic algorithm, the specific algorithm for solving the model is given and conducted a simulation calculation. The results show that the proposed method in this paper is verified to solve practical problem.

2. Problem Description

In terms of Economics, the optimized configuration of the regional comprehensive transportation network structure must seek to the equilibrium of supply and demand, namely, to meet the needs of users choosing different modes of transportation to travel. It is also necessary to meet the objective of optimizing the system's efficiency, that is, to reduce the generalized expenses for users to travel in different modes of transportation as much as possible. At the same time, from the standpoint of sustainable development of the system, it is necessary to guide the growth of environmentally friendly, resource-saving modes of transportation and suppress excessive development of the high-consumption, high-pollution transportation. The paper attempts to achieve the goal that meets a stable demand for passenger and freight transportation, and at the same time plays a guiding role for the travel of passenger and freight, in a more sustainable way under limited resource input. Sustainable development strategy. Therefore, there is a need to establish a multi-objective optimization programming model of regional comprehensive transportation network structure, which is based on supply-demand equilibrium, minimizing generalized cost, and green sustainability.

3. Mathematical Model

3.1 Section Headings

For decision makers, the purpose of adjusting the structural configuration of the regional comprehensive transportation network is to invest limited funds in the mode of transportation with insufficient supply capacity so that the ratio of supply and demand for various modes of transport tends to be stable, that is, approaches l, to build a harmonious and stable comprehensive transportation system. The existing modes of transportation often includes both passenger and cargo transportation. For example, there are both passenger and freight transport on the road. Due to the differences in the technical and economic characteristics of various modes of transport and the differences between passengers and cargo itself, passenger and freight transport are often different. It is necessary to discuss separately. This requires that the investment in construction of transport infrastructure not only meet the passenger supply-demand equilibrium, but also meet the freight supply-demand equilibrium.

So the goal of function is to make the passenger transport capacity of various modes of transport infinitely close to the demand of passenger travel and the cargo transport capacity of various transport modes infinitely close to the freight transport demand, that is, the objective function is:

$$\min Z = w_1 Z_1 + w_2 Z_2 \tag{1}$$

Where w_1 and w_2 are parameters as the priority of Z_1 and Z_2, and

$$Z_1 = \sum_{i=1}^{n} \left| \frac{(Ir_i / b_i + Z_i)c_{i1}}{X_{i1}} - 1 \right| \tag{2}$$

Where n is the number of types of transportation, I is total investment in transport infrastructure within the regional comprehensive transport system, r_i is the proportion of investment in the i-th mode of transport, b_i is the average unit line construction cost for the i-th mode of transport, Z_i is the original traffic mileage of the i-th type of transportation before investment, c_{i1} is unit passenger capacity of the i-th mode of transport, and X_{i1} is passenger demand for the i-th mode of transport.

$$Z_2 = \sum_{i=1}^{n} \left| \frac{(Ir_i / b_i + Z_i)c_{i2}}{X_{i2}} - 1 \right| \tag{3}$$

Where c_{i2} is unit freight capacity of the i-th mode of transport, X_{i2} is cargo demand for the i-th mode of transport.

3.2 Objective Function Based on Minimizing Generalized Cost

The generalized cost of transportation is an important factor about transportation efficiency in the comprehensive evaluation system. It is a comprehensive reflection of transportation costs, transportation time, transit costs, transfer time and other factors. It shows the final currency value of each factor through a certain conversion relationship. Broadly used costs were initially used in road traffic network planning and are comprehensive evaluations of all the attributes of road service levels. The service level attributes generally include such factors as transportation distance, travel time, flow-speed relationship, safety and comfort, and other expenses (such as fuel costs, tolls, etc.).

So the goal of function is to reduce generalized cost for passenger travel and freight as much as possible, that is, the objective function is:

$$\min Q = \varphi_1 Q_1 + \varphi_2 Q_2 \tag{4}$$

Where φ_1 and φ_2 are parameters as the priority of Q_1 and Q_2, and

$$Q_1 = \sum_{i=1}^{n} C_i = \sum_{i=1}^{n} \left(E_i \bullet \left(Z_i + Ir_i / b_i \right) + F_i + N_i + M_i + S_i \right) \tag{5}$$

And

$$F_i = (T_{i1} + T_{i1}')V_1(T) \tag{6}$$

$$N_i = (W_i + Y_i)V_1(T) \tag{7}$$

Where C_i is the generalized passenger travel cost of the i-th mode of transport, E_i is unit passenger travel price for the i-th mode of transport, F_i is rapidity costs of the i-th mode of transportation, N_i is convenience costs of the i-th mode of transport, M_i is comfort costs for the i-th mode of transport, S_i is security costs for the i-th mode of transport, T_{i1} is travel time for the i-th mode of transport, T_{i1}' is the time required for the passengers to connect with the i-th transportation mode, $V_1(T)$ is time value of a passenger, W_i is ticket purchase time for the i-th transportation method, and Y_i is The average

turnaround time for the *i*-th mode of transport.

$$Q_2 = \sum_{i=1}^{n} C_{i2} = \sum_{i=1}^{n} \left(E_{i2} \bullet \left(Z_i + Ir_i / b_i \right) + S_{i2} + F_{i2} + L_{i2} \right) \tag{8}$$

And

$$F_{i2} = (T_{i2} + T_{i2}')V_2(T) \tag{9}$$

Where C_{i2} is generalized freight cost for the *i*-th mode of transport, E_{i2} is unit freight price for the *i*-th mode of transport, L_{i2} is cost for goods' stevedoring of the *i*-th transportation method at the pick-up point, F_{i2} is time cost of the *i*-th mode of transport (transportation time, stevedoring time), S_{i2} is the security cost of the *i*-th transportation method, T_{i2} is average transit time of the *i*-th mode of transport, T_{i2}' is time for goods' stevedoring of the *i*-th transportation method at the pick-up point, and $V_2(T)$ is time value of cargo transportation.

3.3 Objective Function Based on Green Sustainability

Due to the differences in the means of transportation, its energy consumption and the pollution to the environment are different when transporting the same weight goods. From the perspective of the entire transportation system, we should encourage the development of transportation modes with low energy consumption and less environmental pollution, and actively build the corresponding infrastructure which can undertake more transportation. This paper selects energy consumption objective function to reflect the sustainable development capacity of the comprehensive transport system. The function means that under a certain proportion of investment, the minimum energy is consumed when the new-build infrastructure complete the same transportation, that is, the objective function is:

$$\min G = \sum_{i=1}^{n} Ir_i / b_i \left(c_{i1} + c_{i2} \right) d_i \tag{10}$$

Where d_i is energy consumption of unit capacity of the *i*-th mode of transport.

Do the normalization of d_i, and the calculation formula is:

$$u_i = d_i / \sum_{i=1}^{n} d_i \tag{11}$$

Then do the normalization of the objective function, the calculation formula is:

$$\min G' = \frac{\sum_{i=1}^{n} Ir_i / b_i \left(c_{i1} + c_{i2} \right) u_i}{\sum_{i=1}^{n} Ir_i / b_i \left(c_{i1} + c_{i2} \right)} \tag{12}$$

3.4 Multi-objective Optimization Programming Model

All of the above objective functions have their constraints, and only the solutions that satisfy the constraints are the feasible solutions and the optimal solutions. There are two kinds of constraints.

First, there is system constraints, which refer that the sum of the investment ratios of various transport modes is l, as consideration of all transport modes within the transportation system, that is:

$$\sum_{i=1}^{n} r_i = 1 \tag{13}$$

Second, there is a scope constraint, which refers that the investment ratio of various modes of transport should be a number between 0 and 1, that is:

$$0<r_i<1 \quad i=0,1,2,...,n \tag{14}$$

$$0<I<N \tag{15}$$

Where N is number of the largest investment in the region.

Therefore, the form of multi-objective optimization programming model of regional comprehensive transportation network structure is as follows:

$$\min Z = w_1 \sum_{i=1}^{n} \left| \frac{(Ir_i / b_i + Z_i)c_{i1}}{X_{i1}} - 1 \right| + w_2 \sum_{i=1}^{n} \left| \frac{(Ir_i / b_i + Z_i)c_{i2}}{X_{i2}} - 1 \right| \tag{16}$$

$$\min Q = \varphi_1 \sum_{i=1}^{n} \left(E_i \bullet \left(Z_i + Ir_i / b_i \right) + (T_{i1} + T_{i1}' + W_i + Y)V_1(T) + M_i + S_i \right) + \varphi_2 \sum_{i=1}^{n} \left(E_{i2} \bullet \left(Z_i + Ir_i / b_i \right) + S_{i2} + (T_{i2} + T_{i2}')V_2(T) + L_{i2} \right) \tag{17}$$

$$\min G' = \frac{\sum_{i=1}^{n} Ir_i / b_i \left(c_{i1} + c_{i2} \right) u_i}{\sum_{i=1}^{n} Ir_i / b_i \left(c_{i1} + c_{i2} \right)} \tag{18}$$

The constraints is:

$$s.t. \begin{cases} \sum_{i=1}^{n} r_i = 1 \\ 0 < r_i < l \quad i = 0,1,2,...,n \\ 0 < I < N \end{cases} \tag{19}$$

4. Solution for the Model and Algorithm

4.1 Transformation of the Model

Due to more than two objective functions in the model, it is troublesome to convert the model into a single-objective programming problem. Therefore, the model is considered to be converted into a bi-level programming problem.

The model is divided into two layers: the upper layer is an objective function based on supply-demand equilibrium and minimizing generalized cost, and the lower layer is an objective function based on green sustainability, as follows.

The upper layer:

$$\min(Z, Q) \tag{20}$$

$$s.t.\begin{cases}\sum_{i=1}^{n} r_i = 1 \\ 0 < I < N\end{cases} \tag{21}$$

The lower layer:

$$\min G' \tag{22}$$

$$s.t.\begin{cases}0 < r_i < 1 \quad i = 0,1,2,...,n \\ 0 < I < N\end{cases} \tag{23}$$

4.2 Design of Algorithm

From the above, the basic form of the model is:

$$\begin{cases}\min\limits_{x \in X}(A_1(\mathrm{x},\mathrm{y}), A_2(\mathrm{x},\mathrm{y}), \cdots, A_m(\mathrm{x},\mathrm{y})) \\ S.T.\ \ G(\mathrm{x},\mathrm{y}) \le 0 \\ \min\limits_{y \in Y} a(\mathrm{x},\mathrm{y}) \\ S.T.\ \ \mathrm{g}(\mathrm{x},\mathrm{y}) \le 0\end{cases} \tag{24}$$

The following assumptions are made for the established model:

1) S is non-empty, guaranteeing the existence of solutions;

2) It is assumed that the lower optimal solution is unique for each upper variable. If the lower optimal solution is not unique, it is necessary to select a suitable lower optimal solution according to the preference of the upper decision maker for ease of calculation.

In view of the advantages of genetic algorithm in solving the problems based on complex bi-level programming, this paper designs a genetic algorithm program for solving the model [6].

Step 0: randomly select M points in X, $x_i = (x_i^1, x_i^2, \cdots, x_i^\alpha), i = 1,2,\cdots m$ and use the genetic algorithm to calculate the corresponding optimal solution of the lower layer, $y_i = (y_i^1, y_i^2, \cdots, y_i^\beta), i = 1,2,\cdots m$, to obtain the interpolation function $\varphi(x) = (\varphi^1(x), \varphi^2(x), \cdots, \varphi^\beta(x))$;

Step 1: Extract M_1 points from X, and bring these points into the interpolation function $\varphi(\mathrm{x})$ to get the initial population with population size N_1 [7]:

$$group(0) = \begin{pmatrix} x_1^1 & x_1^2 & \cdots & x_1^\alpha & \varphi^1(\mathrm{x}_1) & \varphi^2(\mathrm{x}_1) & \cdots & \varphi^\beta(\mathrm{x}_1) \\ x_2^1 & x_2^2 & \cdots & x_2^\alpha & \varphi^1(\mathrm{x}_2) & \varphi^2(\mathrm{x}_2) & \cdots & \varphi^\beta(\mathrm{x}_2) \\ \vdots & \vdots & \cdots & \vdots & \vdots & \vdots & \cdots & \vdots \\ x_m^1 & x_m^2 & \cdots & x_m^\alpha & \varphi^1(\mathrm{x}_m) & \varphi^2(\mathrm{x}_m) & \cdots & \varphi^\beta(\mathrm{x}_m) \end{pmatrix} \tag{25}$$

And let r=0;

Step 2: From the group(r), select the parents that participated in the cross. The probability of crossing is P_c, and the descendant set is G_1. Under the specific hybridization process, let X_1 and X_2 be parent individuals, where $\lambda \in (0,1)$;

Step 3: From the group(r), select the parents that participated in the mutation, the mutation

probability is P_s, and the offspring set is G_2. The mutation process is as follows: If $x=(x^1,x^2,\cdots,x^\alpha)$ are selected to participate in mutation, at first, give the interval where each component is located, $x^i \in \left[\sigma^i,\mu^i\right], i=1,2,\cdots,\alpha$. Randomly generate a random number according to the uniform distribution, $\theta_i \in [0,1], i=1,2,\cdots,\alpha$, then

$$x^{\mathrm{r}}=\begin{cases} Randomly\ generate\ \overline{x^{\mathrm{r}}} \in \left[\sigma^{\mathrm{i}},\ \mu^{\mathrm{i}}\right] if\ \theta_{\mathrm{r}} \le P_S \\ X^r \qquad\qquad\qquad\qquad\qquad if\ \theta_{\mathrm{r}} \ge P_S \end{cases} \tag{26}$$

The mutated offspring set are $\overline{x}=(\overline{x^1},\overline{x^2},\cdots,\overline{x^\alpha})$ [8].

Step 4: Carry out a fast non-dominant sort for each point in $H=\{group(r)\cup G_1\cup G_2\}$ and determine each individual's rank order value. Calculate the crowding degree for individuals with the same ordinal value. Then, each individual gets two attributes of *i*. Irank(i_{rank}) and crowding degree(i_d), which can deterne the individual's superiority and inferiority relation according to these two attributes, when satisfy $i_{rank} < j_{rank}$, or $i_{rank} = j_{rank}$, and $\mathrm{i_d} > j_d$, say $i \prec j$. With the method above, *M* individuals are selected from *H* as the next-generation population group (*r*+1) [9].

Step 5: Select the individuals with i_{rank}=1 (assuming there are *m*) from the descendant set, correct the lower optimal solutions of the *m* individuals, and update the interpolation function with these points as the new interpolation points. In order to reduce the amount of calculations in the correction process, a method for evaluating multiple criteria can be designed: First, for each point *x*, generate *t* points according to a Gaussian distribution. Then, obtain a population with $t \bullet m$ as the population size. In the process of evolution and selection, *m* fitness functions are generated by substituting *m* upper-level decision variables into the lower objective function. [10].

Step 6: If the algorithm reaches the maximum algebra, or if the results of the 20th generation are not improved, the algorithm stops; otherwise, let *r* = *r* + 1, and go to step 2.

5. Simulation

It is assumed that within a certain area *HB* , there are four modes of transportation, such as, railways, highways, inland river shipping, and aviation, and the technology level of transportation within a certain period of time remains unchanged, and the energy consumption level of each mode of transportation remains unchanged. Referring to reports on the government's work, statistical yearbooks, transportation-related planning and transportation-related data in the region, the model parameters can be determined. Some of the model parameters in the model are shown in Table 1.

What's more, for ease of calculation, consider the objective functions Z_1 and Z_2 as equally important, that is, $w_1=w_2=0.5$, and similarly, let $\varphi_1=\varphi_2=0.5$.

In the multi-objective genetic algorithm, the population size is 100, the largest generation population size is 2000, the crossover rate is 0.1, and the mutation rate is 0.3. According to the previous solution steps, the Parato frontiers of the multi-objective programming model can be obtained by programming calculation with MATLAB software, as shown in Figure 1. Finally, the results of optimization in this area are determined as shown in Table 2.

Table 1 Model Parameters Value

Parameter	Railway	Highway	Inland river shipping	Aviation
i	1	2	3	4
X_{i2}, million t	5231	4103	5012	900
E_i, ￥/km	0.15	0.2	0.08	1.05
T_{i1}', h	1.52	0.84	1.33	2.11
Y_i, h	0.51	0.17	0.83	1.01
E_{i2}, ￥/km	0.3	0.5	0.1	0.8
$V_1(T)$, ￥/h	18.5			
d_i,kg of standard coal /(thousand people▪ km)	1.6	20	8	500
u_i	0.111	0.555	0.056	0.278
N,million ￥	430			

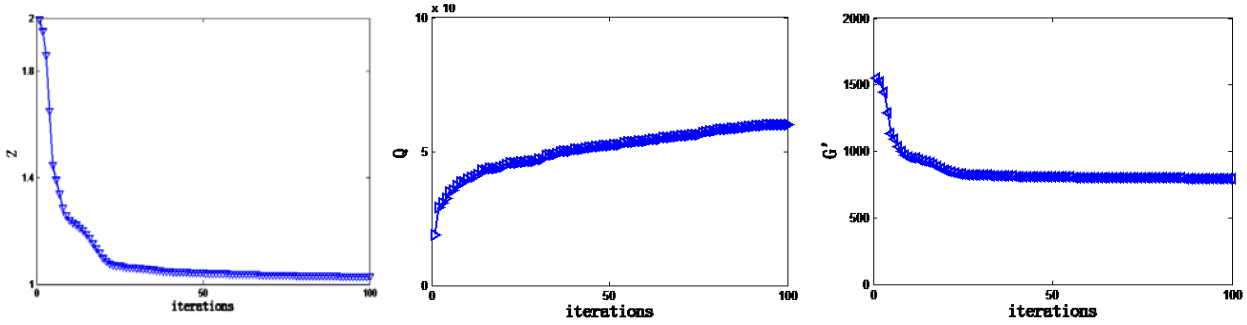

Fig. 1 the Parato frontiers of the multi-objective programming model

Table 2 the Results of Optimization

Optimum solution	Railway	Highway	Inland river shipping	Aviation
Investment ratio	17.88%	70.33%	3.61%	8.18%
Investment amount,million yuan	70.4472	277.1002	14.2234	32.2292
Total investment,million yuan	394			

6. Conclusions

The optimization of regional comprehensive transportation structure is a dynamic optimization process. The multi-objective programming model is used to abstract the problem of regional comprehensive transportation structure optimization into a mathematical problem, which is of certain scientificalness. This paper selects a multi-objective genetic algorithm to solve the model, and the example application of the algorithm can get a more uniform distribution of pareto frontiers, which converge faster and have better stability. So it is suitable for solving bi-level multi-objective programming problems.

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