Air Route Network Generation Based on Traffic Assignment

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Abstract: Air route network is the carrier of air traffic flow, and traffic assignment is a method to verify the rationality of air route network structure. Therefore, air route network generation based on traffic assignment has been becoming the research focus of airspace programming technology. Based on link prediction technology and optimization theory, a bi-level programming model is established in the paper. The model includes an upper level of air route network generation model and a lower level of traffic assignment model. The air route network structure generation incorporates network topology generation algorithm based on link prediction technology and optimal path search algorithm based on preference, and the traffic assignment adopts NSGA-III algorithm. Based on the Python platform NetworkX complex network analysis library, a network of 57 airports, 383 nodes, and 635 segments within China Airspace Beijing and Shanghai Flight Information Regions and 187 975 sorties of traffic are used to simulate the bi-level model. Compared with the existing air route network, the proposed air route network can decrease the cost by 50.624%, lower the flight conflict coefficient by 33.564%, and reduce dynamic non-linear coefficient by 7.830%.

Key words: air route network; link prediction; traffic assignment; bi-level programming; NSGA-III algorithm

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0 Introduction

With the rapid increase of air traffic in China, the defects of air route network structures are gradually exposed, imposing bumps to the rapid development of China's civil aviation transportation industry. Air route networks are crucial to realizing effective air traffic transportation and the transportation situation can in turn act as an important basis for examining the structures of air route networks. Therefore, the generation of air route networks based on traffic assignment has become an urgent research topic in the field of airspace programming . Most research on air route network generation has focused on air route networks themselves and optimization of existing air route networks. Kotegawa et al. put forward three different algorithms based on existing historical data, logistic regression, fitness function method and artificial neural network algorithm, to predict future airport pairs route connection probability in the United States[1]. Zhang et al. explored the impact of output value of the tertiary industry, airport degree and inter-airport distance on the airline connection, and established an airline connection probability model[2]. Du et al. used K-core algorithm to evaluate China's air route networks and to divide China's air route networks into three levels, a core level, a connection level and an edge level, and analyzed the structural characteristics of different levels of air route networks[3]. These studies have provided references for the generation of air route networks. In terms of air route network optimization, Wang et al. introduced the cellular automaton model under the "three zones" evasion condition and conducted the air route network structure optimization using the data from the no-flow Beijing Flight Information Region. They also used their model to analyze the traffic capacity limitation of the Chinese mainland airspace. Their approach reduced the cost of air route network operation, the probability of

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flight conflict risk, and the non-linear coefficient[4-5]. Li et al. proposed an algorithm of CoM-ARN that considered both the optimization of waypoint location and adjacency relation in order to optimize the operational cost of air route networks and airspace security, and verified it with the actual airspace data in China[6].

However, current studies are all about network structures under the existing traffic assignment. With regard to traffic assignment, Tian et al. proposed a multi-objective nonlinear air traffic assignment optimization model, which not only optimized the flight departure time and air route selection in traffic assignment, but also reduced the workload of controllers[7]. Cai et al. developed a route and time assignment algorithm (RTA) to solve the optimization problem of multi-target air networks with traffic assignment[8]. Xiao et al. proposed an effective hybrid direct and indirect coding genetic algorithm (HybrlD-GA) for multi-objective nonlinear air traffic assignment optimization[9]. Wu et al. proposed a multi-objective optimization model for airspace spatial sector networks to solve the global traffic flow collaborative optimization of spatial sector networks[10].

Although a large number of scholars have devoted to air route network generation and traffic assignment, the research on the integration of both has been rarely reported. This paper proposes a model that generates air route networks based on traffic assignment . This bi-level model incorporates the upper level of system programming decision maker, and the lower level of system that uses the decision maker. First, the upper level generates an air route network, and transmits the air route network to the lower level. Then the lower level selects the route for the planned air route network, and uploads the traffic assignment result to the upper level, until air traffic network structure based on traffic assignment reaches the optimization.

1 Air Route Network Related Theory

1.1 Air route network and complex network

An air route network can be abstracted as a graph $G=(V, E, W)$ by mathematical description, where V represents the set of nodes in the network; E represents the set of connected segments between nodes, which are used to describe some relationship between nodes; W represents the set of segment weights between nodes. As shown in Fig.1, the node set V in an air route network is divided into two airport points and one node, and the side set E is composed of the segment, and the weight W between two nodes is represented by the flow between them.

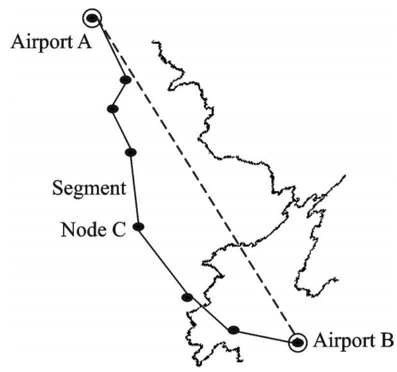

Fig.1 Air route network

If a network is formed by a mass number of nodes with complicated relationships, the network can be called a complex network. Ref.[11] analyzed the structure of China's mainland air route network from the perspective of complex network, and concluded that China's air route network is a scale-free network, and node v_i is subject to the power law distribution. Its average route length L is 13.19, that is, the route of any two nodes (v_i, v_j) are connected by 13 nodes. Most of the node interfaces B_i are small, and only a few of node interfaces are large, thus the overall distribution is uniform. The convergence coefficient C of the China's air route network is 0.119, and the connections between nodes are not close.

1.2 Link prediction

Link prediction aims to infer the relationship between the existing information route points in a network, and to predict the possible segments based on the network structure, node attributes, etc.

According to the link prediction index NSIA[12], this paper introduces the weighted traffic flow between airport pairs of an air route network, and proposes the weighted neighbor set information traffic assignment index (WNSIA). The formula of the link prediction on the node pair similarity scores for WNSIA is as follows

$$S_{xy}^{\Omega}=-W_{xy}I(L_{xy}^{1}|\Omega)=\sum_{i=1}^{2}\sum_{j=1}^{m_i}W_{xy}\mu_{ij}\left[I(L_{xy}^{1})-I(L_{xy}^{1}|\omega_{ij})\right]-I(L_{xy}^{1}) \tag{1}$$

where W_{xy} is the airport pairs traffic flow; $I(L_{xy}^{1}|\Omega)$ the conditional self-information of the connected segment between a node pair (x, y) under the known condition common neighbor set Ω.

1.3 Bi-level programming

Bi-level programming is to optimize the network by introducing decision-makers at different levels. Decision-makers at different levels have different demands for network programming, and form the optimal result of network programming through cooperation among different decision-makers.

Compared with regarding the route network problem as a single-level programming, the bi-level programming method has the following advantages:

(1) In the bi-level programming, the two hierarchical structures are neither isolated, nor simply joined. They influence and interact with each other.

(2) Bi-level programming has more hierarchical structures, more perspectives of decision-making and more potentials in practice.

(3) Bi-level programming can analyze two different decision-making angles from two hierarchical structures, both of which have their own objective functions and constraints, and even the objective functions of the two decision-makers are contradictory.

2 Model Establishment

The upper model is the air route network generation model, which reconstructs the air route network structure with the objective of network similarity. The lower model is the traffic assignment model, and the traffic demand is allocated to the air route network with the objectives of air route network operating cost, flight conflict coefficient and dynamic non-linear coefficient. Fig.2 shows the flow chart of the air route network generation based on traffic assignment.

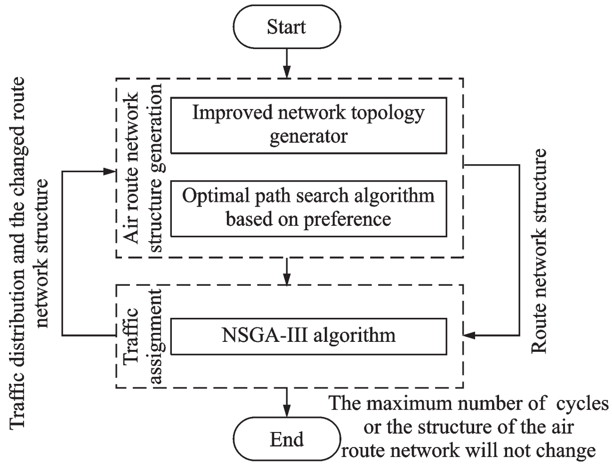

Fig.2 Air route network generation based on traffic assignment flowchart

Some assumptions are listed as follows:

(1) Aircraft that fly on the air route network are regarded as a mass point;

(2) All aircraft in the air route network are located at the same level, regardless of those rising or landing;

(3) The flying speed of the aircraft is 800 km/h, and the range of the node movement is plus or minus 50 km;

(4) Flight conflicts in the airport terminal area are not considered.

2.1 Establishment of air route network generation model

Air route network generation aims to analyze the structural characteristics and traffic characteristics of the air route network, and generate the initial air route network structure.

2.1.1 Objective function

Air route network node pair similarity refers to the score of the connection probability between node pairs in the air route network calculated by the link prediction algorithm, considering air route network structure characteristics and flow characteristics comprehensively, and the formula is given as

$$\max\sum_{i=1}^{m+n}\sum_{j=1}^{m+n}S_{ij}x_{ij} \tag{2}$$

where S_{ij} is the similarity between the nodes pair ij, and x_{ij} a binary variable, and

$$x_{ij}=\begin{cases}1 & \text{Node } i \text{ and node } j \text{ have connections}\\ 0 & \text{Node } i \text{ and node } j \text{ do not have any connections}\end{cases}$$
$$(i,j)\in N$$

2.1.2 Bound for objective function

In the process of generating air route network, the distance of the generated segment should be within a certain range, and all airports should be connected to the air route network.

(1) Segment distance constraint

$$d_{\min}\leqslant d_{ij}x_{ij}\leqslant d_{\max}\quad i,j\in[1,m+n] \tag{3}$$

where d_{ij} is the distance of the segment ij.

(2) Airport non-isolated constraint

$$b_i\geqslant 1\quad i\in[1,m] \tag{4}$$

where b_i is the number of sides of the airport i.

2.2 Establishment of traffic assignment model

Traffic assignment aims to distribute traffic flow of airport pairs to air route network.

2.2.1 Objective function

In the process of traffic assignment, the economics, safety and feasibility of the air route network are comprehensively considered. The air route network operating cost, flight conflict coefficient and dynamic non-linear coefficient are used as the objective function for traffic assignment.

(1) Air route network operating cost

$$\min\sum_{i=1}^{m+n}\sum_{j=1}^{m+n}f_{ij}d_{ij}x_{ij} \tag{5}$$

where f_{ij} is the flow of the segment ij.

(2) Flight conflict coefficient

$$\min\sum_{i=1}^{m+n}\sum_{j=1}^{m+n}\sum_{k=1}^{m+n}[(2f_{ji}f_{ki}/V)\cdot Y\cdot \arccos((\theta_{ij}^{k}/2)/(f_{ji}+f_{ki}))] \tag{6}$$

where f_{ji}, f_{ki} are the flows of the segment ji and the segment ki, respectively; V is the flying speed of the aircraft; Y the horizontal safety interval; and θ_{ij}^{k} the angle between the segment ik and the segment jk.

(3) Dynamic non-linear coefficient

$$\min\sum_{i=1}^{m}\sum_{j=1}^{m}I_{ij}\overline{f_{ij}}x_{ij}/\sum_{i=1}^{m}\sum_{j=1}^{m}\overline{f_{ij}} \tag{7}$$

where I_{ij} is the non-linear coefficient between airport i and airport j, and f_{ij} the flow of segment ij.

2.2.2 Bound for objective function

(1) Segment capacity constraint

$$f_{ij}x_{ij}\leqslant C_{ij}\quad i,j\in[m+1,m+n] \tag{8}$$

where C_{ij} is the capacity of the segment ij.

(2) Node flow conservation constraint

$$f_i^{\text{in}}=f_i^{\text{out}}\quad i\in[m+1,m+n] \tag{9}$$

where f_i^{in} is the flow of entering the node i and f_i^{out} the flow of going out from the node i.

(3) The number of airlines between an airport pair

$$n_{st}=1\quad s,t\in[1,m] \tag{10}$$

where n_{st} is the number of airlines between the airport pair st.

3 Algorithms

3.1 Improved network topology generator

According to the analysis of Ref.[11], air route network has a scale-free network structure, so this paper designs the initial topology structure of an air route network based on the traditional BA model.

According to the BA model, the newly added node j and the existing node i are independent of the great circle distance between this two nodes, and the probability of connection is $P_{ij}=D_i\big/\sum D_i$. Based on Ref.[13] and link prediction similarity, the traditional BA model is improved in this paper. It is assumed that the connection probability of the newly added node j and the existing node i satisfies the Eq.(11)

$$P_{ij}=\frac{S_{ij}^{\Omega}}{\sum_{i=1}^{N}S_{ij}^{\Omega}} \tag{11}$$

The initial topology generation process of air route network is listed as follows.

Step 1 Sort the nodes of the air route network according to importance values.

Step 2 Add the nodes into the initial structure of the air route network according to the order of the nodes, and calculate the connection probabilities between the newly added nodes and the existing nodes according to Eq.(11).

Step 3 Sort the connection probabilities, and connect the new nodes to the existing node of the first ranking.

Step 4 Repeat Step 2 to Step 3 until all nodes in the air route network are added to the initial structure of the air route network.

3.2 Optimal path search algorithm based on preference

According to Ref.[14], the optimal path search algorithm based on preference is a path search algorithm combining K shortest path search algorithm and the idea of link prediction similarity index.

(1) Algorithm principle

The optimal path search algorithm based on preference searches paths on the air route network generated by the improved network topology generator, which is a component of the air route network generation.

(2) Algorithm process

Step 1 Select an origin-destination (OD) airport pair with traffic demand in the air route network, and use the similarity-based Dijkstra algorithm to obtain a path of this OD pair;

Step 2 Convert the path from the start point to the end point into a flight segment set, extract the segment from segment set continuously and set it to the off state. Then use the Dijkstra algorithm to search the path based on similarity;

Step 3 Repeat Step 2 until searching K paths for OD airport pair are found;

Step 4 Select the least number of segments in the K path set as the final path selection of the OD airport pair;

Step 5 Repeat Step 1 to Step 4 until the final results are determined for all OD airport pairs.

3.3 NSGA-III algorithm

The NSGA-III algorithm is essentially a non-dominated genetic algorithm, which is a third-generation multi-objective programming algorithm based on Deb[15]. It inherits the non-dominated sorting of NSGA-II algorithm, in order to overcome the shortcomings of premature convergence of the NSGA-II algorithm. The reference distance are deduced with the method of correlation operation instead of crowded degree operator, thus improving the diversity of algorithm population. Especially when the programming model catains more than three objective functions, the programming effect of the NSGA-III algorithm is significantly better than the NSGA-II and NSGA-I algorithms[16-17]. The specific steps are as shown in Fig.3.

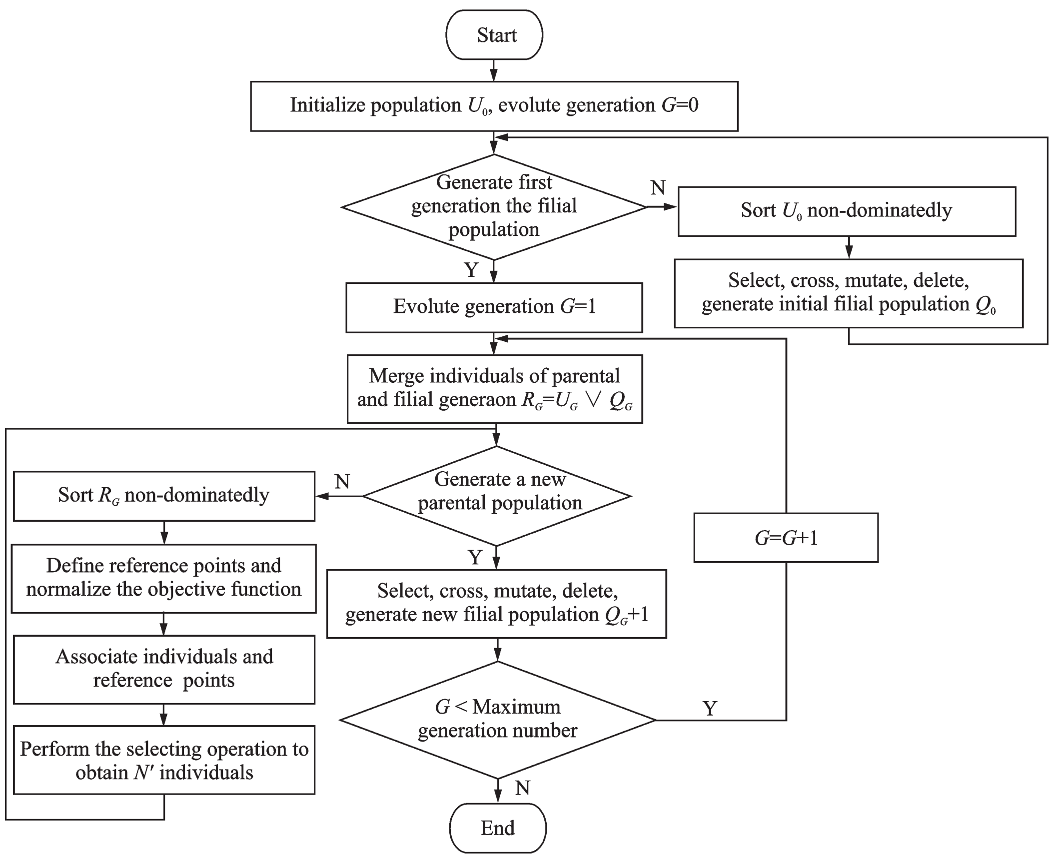

Fig.3 NSGA-III algorithm flowchart

4 Simulation

Based on the Python platform NetworkX of complex network analysis library, a simulation scenario is conducted for China Airspace Beijing and Shanghai Flight Information Regions. First, based on the improved network topology generator, the air route network topology is generated for these areas. Then, based on the optimal path search algorithm based on preference, the path search is performed on the generated air route network topology structure, and the initial air route network is generated for these areas. Finally, traffic assignment is carried out based on NSGA-III algorithm.

Step 1 Generate air route network topology based on the improved network topology generator.

After using the improved network topology generator to generate air route network topology, we obtain 383 nodes and 436 segments. The topology diagram of air route network is given in Fig. 4. The specific segment data and its similarity data are shown in Table 1.

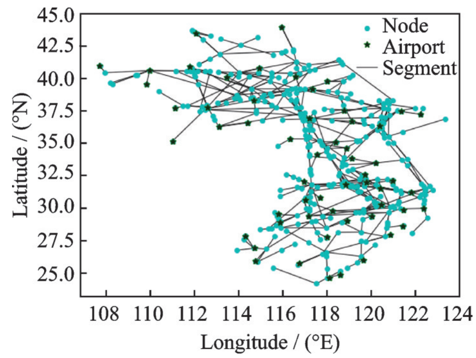

Fig.4 Initial topology of the air route network

Table 1 Partial segments and its similarity data of initial air route network

Number	Segment		Similarity	Number	Segment		Similarity	Number	Segment		Similarity
1	P318	P264	5.220	16	TEBON	P147	6 867.552	31	P323	MUPIK	5.583
2	P255	P254	3 365.182	17	P132	DST	70 901.740	32	NINAS	MLJ	5.220
3	P47	P252	61 005.061	18	P10	BAV	44 546.780	33	SELGO	MEGUS	31 376.011
4	P263	P251	192 004.988	19	SJW	OLRAP	68 444.303	34	P318	LEGIV	5.542
5	TOS	P240	59 628.026	20	P132	OKTUG	5.220	35	KM	HUR	33 743.202
6	P231	P206	304 547.711	21	ODULO	GORPI	98 046.851	36	KAGVO	ATVIM	6.672
7	PA	P230	9 809.289	22	NXD	KAKIS	88 602.492	37	KAGIP	FZ	7 411.997
8	SHZ	P23	6.552	23	P07	NOKAK	18 677.228	38	JYC	JGS	6.672
9	P308	P218	51 570.188	24	NOBOB	LATUX	1 599.554	39	UBLAT	ISGOD	140 251.324
10	P214	BZ	51 616.517	25	TMR	NIXUR	6.672	40	TODAM	ISBAM	6.672
11	P198	AR	90 444.625	26	TAPEN	NIVIK	45 652.857	41	REPEP	IRVAG	6.188
12	P292	P197	22 196.141	27	NIPES	AVNIX	6.672	42	PONAB	IPRAG	6.188
13	TOS	P181	76 628.026	28	PINOT	NINAS	52 295.473	43	P57	INTIK	6.518
14	P214	P176	5.220	29	NIPES	NIKIT	5.220	44	RANGA	IGRAT	106 447.059
15	P169	FQG	184 988.640	30	P120	NF	100 491.880	45	NIXUR	IGPAS	94 428.843

Step 2 Use the optimal path search algorithm based on preference to conduct path search on the generated route network topology. If no path is found, the path search is conducted on the full connected network to generate the initial route network.

The optimal path search algorithm based on preference is used to search the path of 226 airport pairs on the air route network topology. The initial route network structure generates 325 nodes and 433 segments. Fig.5 shows the initial generation diagram of the air route network. The specific airport pairs path search data is shown in Table 2.

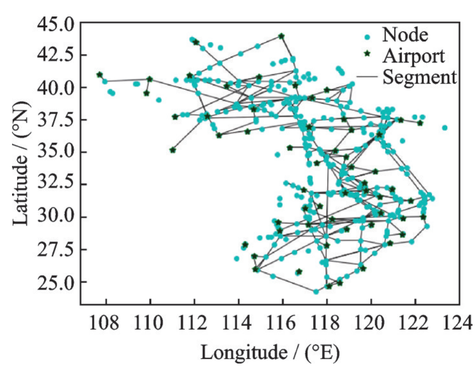

Fig.5 Air route network generation

Table 2 Partial airline data

Number	Airport pair		Airline
1	ZSOF	ZSCN	ZSOF BIPIM PEDNU HFE SHR KHN NCH ZSCN
2	ZSFZ	ZBTJ	ZSFZ FQG LJG DO MEXUP PIX WFG KALBA LADIX JB CG ZBTJ
3	ZSGS	ZSAM	ZSGS JGS PLT P147 TEBON XLN ZSAM
4	ZSWH	ZSNJ	ZSWH WEH FZ FD OF ZSNJ
5	ZBSN	ZBSJ	ZBSN LUX P290 P75 CG JB SAKOD ZBSJ
6	ZSGZ	ZSAM	ZSGZ P119 PLT P147 TEBON XLN ZSAM
7	ZSPD	ZSJN	ZSPD VMB ZJ OF FD YQG ZSJN
8	ZSXZ	ZSFZ	ZSXZ PIX MEXUP DO LJG FQG ZSFZ
9	ZBSJ	ZBDS	ZBSJ SAKOD UBTAB KR NONIT BAV HDS ZBDS
10	ZSNB	ZSCN	ZSNB BK SHZ JDZ P34 NCH ZSCN

Step 3 Conduct traffic assignment based on NSGA-III algorithm, and transfer the resulted assignment and changed route network structure to Step 2.

The NSGA-III algorithm is used to search the path on the optimized route network. In the air route network structure after traffic assignment, 338 nodes and 521 segments are shown. Fig.6 shows the network diagram after traffic assignment. Airport pairs assignment data are shown in Table 3.

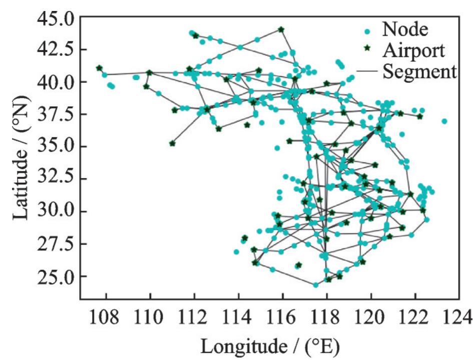

Fig.6 Air route network traffic

Table 3 Partial traffic result data for airports

Number	Airport pair		Airline
1	ZSNJ	ZSFZ	ZSNJ RANGA IGRAT CJ TOL UGAGO P30 BZ DAGMO LJG ZSFZ
2	ZSJU	ZSAM	ZSJU SHR P215 P48 DO P84 P21 JNJ XLN ZSAM
3	ZSYT	ZBTJ	ZSYT FZ P323 FD TEKAM HCH P07 NOKAK P254 CG ZBTJ
4	ZSQD	ZSJN	ZSQD VEPGI TAO P65 YO WFG P291 YQG ZSJN
5	ZBTJ	ZBCZ	ZBTJ CG JB SAKOD ZBSJ SJW OLRAP P346 SQ ZBCZ
6	ZSWZ	ZSPD	ZSWZ DST P22 P23 REMIM SHZ VEXEX BK ZSPD
7	ZBYC	ZBDT	ZBYC YCE P130 TYN GODON EKETA EXUMI TEDIB NONIT BJZ ZBDT
8	ZSPD	ZSCN	ZSPD NXD KAKIS TOL ELNEX ABVIL TXN P33 JDZ P34 NCH ZSCN
9	ZSYT	ZSJN	ZSYT FZ TEKAM HCH REPOL DYN BASOV ZSJN
10	ZSJN	ZBSJ	ZSJN YQG TUMLO P148 HG P331 P66 FL SJW ZBSJ

5 Discussion

Air route network evaluation is divided into the static structure evaluation and the dynamic operation index evaluation. The static structure index is to evaluate the internal structure of the air route network. The dynamic operation index is to evaluate the operational data of the air route network after the demand traffic flow of OD airport pairs are assigned to the air route network.

Air route network structure evaluation includes the number of nodes, the number of segments and the nodes, as shown in Table 4.

The evaluation on the air route network evalu-

Table 4 Air route network static structure evaluation index

Parameter	Initial air route network topology	Air route network structure generation	Traffic assignment
Node	383	325	338
Segment	436	433	521

ates the existing the generated air route network and air route network based on traffic assignment with air route network operating cost, flight conflict coefficient and dynamic non-linear coefficient.

Table 5 shows that compared with the existing air route network, the gererated network decreases the operating cost by 50.624%, decreases the flight conflict coefficient by 33.564%, and decreases the dynamic non-linear coefficient by 7.830%.

Table 5 Air route network dynamic operation evaluation index

Parameter	Existing network	Optimized network	Change/%
Air route network operating cost/ (fight•km)	469 241 610	231 692 237	−50.624
Flight conflict coefficient	0.028 9	0.019 2	−33.564
Dynamic non-linear coefficient	1.226	1.130	−7.830

6 Conclusions

Based on the complex network theory and the optimization theory, this paper proposes a scheme of air route network generation based on traffic assignment, and introduces a bi-level programming model that includes an upper level of air route network programming, and a lower level of an air route network system. The upper level first generates an air route network, and then transmits its structure to the lower level. The lower level chooses routes on the programmed air route network and uploads the traffic assignment to the upper level. The proposed approach regards the two levels as two decision makers to target two respect issues, which is more approaching practical scenarios. In the bi-level model, the upper level considers the similarity during air route network generation, and the lower level considers the air route network operating cost, flight conflict coefficient and dynamic non-linear coefficient of traffic assignment. Network topology generation algorithm based on link prediction and optimal path search algorithm based on preference are used to generate air route networks. NSGA-III algorithm is used for traffic assignment. Then, the flight network composed of 57 airports, 383 nodes and 635 segments of the Beijing and Shanghai Flight Information Regions in China's mainland airspace and 187 975 airport traffic flows are used for simulation. After using the improved network topology generator a to generate an air route network topology, 383 nodes and 436 segments are obtained. The optimal route search algorithm based on preference is used to search 226 airport pairs on the air route network topology, and there are 325 nodes and 433 segments in the network structure. The NSGA-III algorithm is used to search the route on the optimized air route network. After traffic assignment, there are 338 nodes and 521 segments. Finally, compared with the dynamic operation index of the generated air route network and the existing air route network, it is found that the air route network operating cost is decreased by 50.624%, the flight conflict coefficient by 33.564%, and the dynamic non-linear coefficient is 7.830%. However, due to the limitation of "three-zone" in practice, some adjustments need to be made in future work.

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Author contributions Dr. **WANG Shijin** designed the study, conducted the analysis. Ms. **LIN Jingjing** wrote the manuscript, interpreted the results. Mr. **HAN Yunxuan** complied the model, studied the background of the study.

Competing interests The authors declare no competing interest

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基于交通分配的航路网络生成

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摘要：航路网络是空中交通分配的载体，而交通分配是检验航路网络的依据，如何构建基于交通分配的航路网络生成便成了当前空域规划技术中的研究方向。论文基于链路预测理论、优化理论，建立了上层为航路网络生成，下层为交通分配的双层规划模型，采用基于链路预测的网络拓扑生成器和基于偏好的最优路径搜索算法进行航路网络生成，采用NSGA-III算法进行交通分配。论文基于Python平台NetworkX复杂网络分析库，采用中国大陆空域北京和上海飞行情报区57个机场、383个航路点、635条航段组成的航路网络和187 975架次机场对交通流量进行案例仿真。通过与现有航路网络对比，交通分配运行成本下降50.624%，飞行冲突系数下降33.564%，动态非直线系数下降7.830%。

关键词：航路网络；链路预测；交通分配；双层规划；NSGA-III算法