Multi-temporal Operational Efficiency Evaluation of Approach Control System Based on VIKOR

Zhaoning Zhang
College of Air Traffic Management, Civil Aviation University of China
Tianjin 300300, China
+86 133 8901 1559
zzhaoning@263.net

Yuying Fan
College of Air Traffic Management, Civil Aviation University of China
Tianjin 300300, China
+86 133 2404 2416
302868934@qq.com

Jimin Liu
Strategic Development Department, East China Regional Air Traffic Management Bureau of CAAC,
Shanghai 200335, China
+86 136 8183 0403
13681830403@163.com

Abstract. The efficient operation of approach control system is one of its main tasks. The operational efficiency of the approach control system needs to be evaluated. Firstly, based on the analysis of the operational process of the approach control system, the influencing factors of the operational efficiency are considered from three aspects, namely, controllers' workload, airspace utilization rate and degree of flight delay. Using the fishbone diagram analysis method, the main efficiency influencing factors are concluded from the aspect of man-machine-environment-management. Then, the evaluation index system of the operational efficiency of the approach control system is designed. On this basis, a multi-period operational efficiency evaluation model of the approach control system is established based on VIKOR. Finally, the operational efficiency of the Xiamen Air Traffic Control Station operational system is evaluated as an example which validate the feasibility of the model.

Introduction

The operational efficiency of the approach control system is crucial to the entire air traffic control system. An efficient control system can improve flight punctuality and reduce flight delays, improve airspace utilization and increase economic benefits, reduce fuel consumption and environmental pollution, thus promoting the sustainable development of the aviation industry.

At present, scholars around the world have gradually carried out studies related to the operational of air traffic control system. At abroad, in 1999 Almira Williams et al [1] investigated how to improve the efficiency of the air traffic control system under the condition of limited control resources through the MSP method. In 2006, Harris [2] used social techniques to systematically analyze the impact of airport ramp efficiency on air traffic control operational efficiency, which highlights the importance of integrating various operational aspects. In 2007, Abdel-Aty M et al [3] used mathematical frequency analysis methods and statistical analysis techniques to make measurements of air traffic control operational efficiency, offering a quantitative foundation that supports our methodological framework. In 2007, C. Edward Huang et al [4] conducted a cost and efficiency analysis of 20 air traffic control centers in US, concluding that the efficiency of ATC (Air Traffic Control) operation is related to the number of sectors. This finding informs our consideration of efficiency metrics. In 2016, Blucher et al [5] suggested that implementing changes to the AFD (Aerodrome Flight Data) rules in controlled airspace at high altitudes could increase the capacity of the flight paths and thus improve the operational efficiency of the air traffic control system, providing a basis for examining regulatory impacts in our study. In 2016, Baier et al [6] proposed an experimental working model for air traffic control in three dimensions and verified that the model can reduce the psychological load of controllers and improve the operational efficiency of the air traffic control system, which underlines the importance of human factors. In 2017, Aricò et al [7] used neurometrics to analyze human factors in the air traffic network and further explored effective measures to improve the efficiency of air traffic control services through neural network models.

In China, in 2012 Luo Guanzhong [8] explored factors affecting ATC operational efficiency based on man-machine-environment system engineering, establishing an index system for efficiency assessment. In 2014, Lv Zongping, Li Xintong, Zhang Zhaoning[9] established an ATC system quality evaluation index system from the dynamic operation process, using Fuzzy Analytic Network Process and improved grey comprehensive evaluation methods, which support our method's foundation. In 2015, Zhang Zhaoning et al [10] utilized the two-stage BCC (Banker, Charnes, and Cooper) model in data envelopment analysis to assess the airport control system's operational efficiency, informing our use of efficiency evaluation techniques. In 2015, Hu Yuqin et al. [11] used the fishbone diagram analysis method, identified the influencing factors that triggered the petroleum electrostatic accidents, and determined the evaluation index system. In 2017, Wang Mengli [12] used the idea of classification evaluation to establish an operational efficiency assessment model for approach control system based on the combination of system clustering and K-mean clustering. In 2020, Pan Weijun et al [13] screened main influencing factors using principal component analysis and applied Q-cluster analysis to assess ATC quality, guiding our variable selection process. In 2021, Zhang Zhaoning et al [14] proposed a comprehensive assessment model for terminal area control operational efficiency, combining improved principal component analysis and entropy value method. These studies provide a foundation for the evaluation of operational efficiency in air traffic control systems.

Due to the fact that international research on the performance indicator system for the operational efficiency of approach control is not yet perfect and at the same time, there are few studies on the assessment of the operational efficiency of the approach control system. This paper adopts the fishbone diagram analysis method and proposes the influencing factors of controllers' workload, airspace utilization rate and degree of flight delay based on the operation process of the approach control system. Then the evaluation index system of approach control system operation efficiency is designed. A multi-period operation efficiency evaluation model of the approach control system based on the VIKOR is established.

1 Influencing factors of the operational efficiency

Starting from the aspect of man-machine-environment-management, the influencing factors of the operational efficiency of the approach control system are considered from three aspects according to the operational process of the approach control system. They are controllers' workload, airspace utilization rate and degree of flight delay. [14], [15], [16]

Controllers' workload includes the frequency of unit land and air airtime control command, approaching hourly workloads in each sector, conflict relief review, the frequency of instructions issued by controllers and the saturation of approach control calls. Airspace utilization rate includes the sector on/off frequency, the flight altitude tier usage rate, flight traffic in terminal area, inbound flight flow and departure flight flow. The degree of flight delay includes the rate of flights in the terminal area delayed for control reasons, the rate of delay of incoming flights in the terminal area for control reasons, the rates of delayed departing flights in the terminal area for control reasons, the cumulative delay of flight hours in the terminal area due to control delays and the additional flight time for terminal area approach flights.

The Fishbone Diagram method of analysis, also known as Cause and Effect Diagram, is a graphical tool used to identify the causes of problems. The Fishbone Diagram method is ideally suited for analysing key factors affecting the efficiency of a system due to its comprehensive, structured and visual nature. Fishbone diagram analysis is used to identify the main influencing factors of the operational efficiency for the approach control system, as shown in Figure 1.

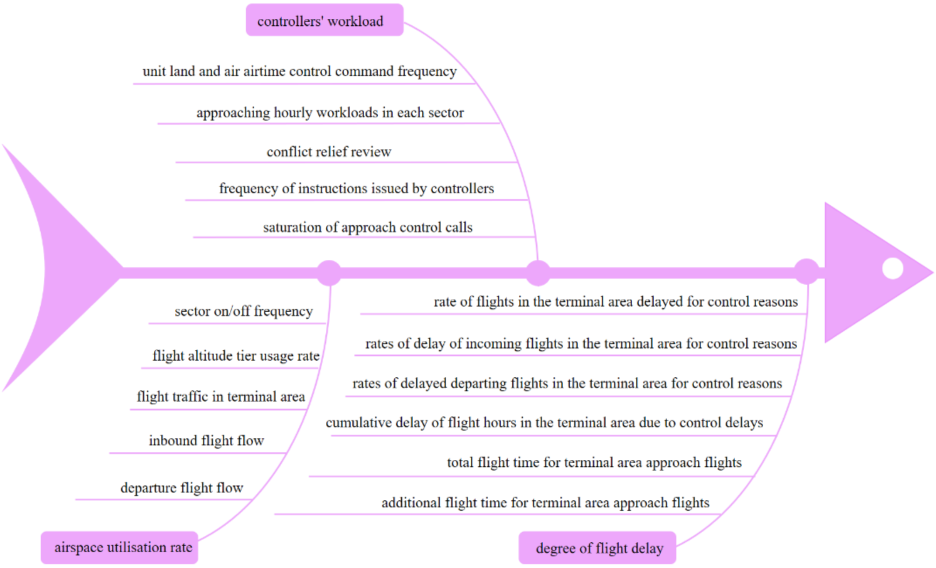

Figure 1. Fishbone diagram of influencing factors

2 Evaluation index system of the operational efficiency

According to the influencing factors of the operational efficiency of the approach control system, the evaluation index system of the operational efficiency of the approach control system is established from the three aspects of the controllers ' workload, airspace utilization rate and the degree of flight delay, as shown in Table 1.

Table 1: Evaluation index system of operational efficiency of the approach control system

Primary Indicators	V_i Secondary Indicators	Unit
A Controllers' workload	V_1 Unit land-air airtime control command sorties	sorties/ hour
	V_2 Approaching hourly workloads in each sector	
	V_3 Number of conflict releases	times/hour
	V_4 Number of instructions given by controllers	times/hour
	V_5 Saturation of approach control calls	
B Airspace utilization rate	V_6 Sector on/off frequency	
	V_7 Flight altitude tier usage rate	
	V_8 Flight traffic in terminal area	sorties/ hour
	V_9 Inbound flight flow	sorties/ hour
	V_{10} Departure flight flow	sorties/ hour
C Degree of flight delay	V_{11} Rate of flights in the terminal area delayed for control reasons	
	V_{12} Rates of delay of incoming flights in the terminal area for control reasons	
	V_{13} Rates of delayed departing flights in the terminal area for control reasons	
	V_{14} Cumulative delay of flight hours in the terminal area due to control delays	minutes
	V_{15} Total flight time for terminal area approach flights	minutes
	V_{16} Additional flight time for terminal area approach flights	minutes

The first-level evaluation indicators of the operational efficiency of the approach control system are defined as A controllers' workload, B airspace utilization rate, C degree of flight delay. V_i is used to denote the i-th secondary indicator ($i = 1,2,3,\cdots,16$), and each secondary indicator is defined as: V_1 unit land-air airtime control command sorties, V_2 approaching hourly workloads in each sector, V_3 number of conflict releases, V_4 number of instructions given by controllers, V_5 saturation of approach control calls, V_6 sector on/off frequency, V_7 flight altitude tier usage rate, V_8 flight traffic in terminal area, V_9 inbound flight flow, V_{10} departure flight flow, V_{11} rate of flights in the terminal area delayed for control reasons, V_{12} rates of delay of incoming flights in the terminal area for control reasons, V_{13} rates of delayed departing flights in the terminal area for control reasons, V_{14} cumulative delay of flight hours in the terminal area due to control delays, V_{15} total flight time for terminal area approach flights, and V_{16} additional flight time for terminal area approach flights.

3 Model of approach control system efficiency evaluation

The VIKOR method (VlseKriterijumska Optimizacija I Kompromisno Resenje) is an effective method for decision-making evaluation under multiple indicators, which provides an objective and comprehensive evaluation of alternatives by minimizing individual regrets and maximizing group benefits. It is suitable for solving the decision-making evaluation problems in situations where the decision maker's preferences are difficult to be accurately expressed or where there are conflicting indicators that cannot be metricized [17]. The VIKOR method was selected for evaluating the operational efficiency of approach control systems because it effectively handles decision-making scenarios with conflicting and non-commensurable criteria. Compared to Data Envelopment Analysis (DEA) and other multi-criteria decision-making methods such as AHP (Analytic Hierarchy Processor) or MAUT (Multi-Attribute Utility Theory), VIKOR is less data-intensive and avoids complex pairwise comparisons, making it particularly suitable for the dynamic and complex environment of air traffic control. It provides a straightforward analysis of multiple indices, offering clear directions for operational optimization.

The basic steps of the VIKOR method include:

1. Determining Evaluation Criteria: Select several evaluation criteria based on the specific needs of the system. In this study, the chosen evaluation criteria include controller workload, airspace utilization rate, and flight delay degree.

2. Establishing a Decision Matrix: Collect data on each evaluation object across different evaluation criteria to form a decision matrix.

3. Determining Ideal and Negative-Ideal Solutions: For each evaluation criterion, determine the ideal solution (best value) and the negative-ideal solution (worst value).

4. Calculating Evaluation Values for Each Object: Calculate the evaluation values for each object based on their distances to the ideal and negative-ideal solutions.

5. Comprehensive Evaluation and Ranking: Perform a comprehensive evaluation and ranking of the objects based on their evaluation values to determine the optimal solution.

3.1 Determination of positive and negative indicators. In the evaluation of the operational efficiency of the approach control system, V_1 of the controllers' workload, V_7, V_8, V_9 and V_{10} of the airspace utilization rate are taken as positive indicators, which means that the larger the indicator is, the better it is, and V_2, V_3, V_4, V_5 of the controller's workload, V_6 of the airspace utilization rate, and the degree of flight delays, $V_{11}, V_{12}, V_{13}, V_{14}, V_{15}$ and V_{16} are taken as negative indicators, which means that the smaller the indicator is, the better it is.

3.2 Positive and Negative Indicator.

Positive Indicator Calculation Formula:

$$\mathrm{d}_{\mathrm{ij}}^{+} = \frac{\mathrm{V_{ij}} - \min\limits_{\mathrm{j}} \mathrm{V_{ij}}}{\max\limits_{\mathrm{j}} \mathrm{V_{ij}} - \min\limits_{\mathrm{j}} \mathrm{V_{ij}}} \tag{1}$$

Negative Indicator Calculation Formula:

$$d_{ij}^{-} = \frac{\min\limits_{j} V_{ij} - V_{ij}}{\max\limits_{j} V_{ij} - \min\limits_{j} V_{ij}} \tag{2}$$

3.3 Normalized matrix of positive-negative indicators D. All positive and negative indicators were standardized; m is the number of evaluation indicators and n is the number of time periods to be evaluated (m=16, n=14), resulting in a standardized matrix D of positive and negative indicators:

$$D = [d_{ij}]_{m\times n} = \begin{pmatrix} d_{11} & d_{12} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \vdots & \vdots & & \vdots \\ d_{m1} & d_{m2} & \cdots & d_{mn} \end{pmatrix} \tag{3}$$

3.4 Positive and negative ideal solutions: $\mathrm{f}_{\mathrm{j}}^{+}$ and $\mathrm{f}_{\mathrm{j}}^{-}$. Calculate the positive ideal solution $\mathrm{f}_{\mathrm{j}}^{+}$ and the negative ideal solution $\mathrm{f}_{\mathrm{j}}^{-}$ based on the positive-negative indicator normalization matrix D. The calculation formulas are shown below:

$$f_j^{+} = \left[\left(\max_i d_{ij} \,\middle|\, j \in \Omega_e\right), \left(\min_i d_{ij} \,\middle|\, j \in \Omega_c\right)\right] \tag{4}$$

$$f_j^{-} = \left[\left(\min_i d_{ij} \,\middle|\, j \in \Omega_e\right), \left(\max_i d_{ij} \,\middle|\, j \in \Omega_c\right)\right] \tag{5}$$

In the formula, Ω_e is the efficiency indicator and contains the secondary indicators under the primary indicators of airspace utilization ($V_6, V_7, V_8, V_9, V_{10}$); And Ω_c is a cost-based indicator that includes all secondary indicators under the primary indicator except airspace utilization ($V_1, V_2, V_3, V_4, V_5, V_{11}, V_{12}, V_{13}, V_{14}, V_{15}, V_{16}$).

3.5 Group utility value S_i and individual regret value R_i for each evaluation subject. The group benefit is expressed as the weighted distance from the i-th evaluation object to the positive ideal solution. The smaller S_i is indicates that the benefit of the group is better, which means that the object being evaluated is more excellent. Similarly, the maximum regret value is expressed as the smaller S_i the smaller the individual regret value of the object, indicating that the object being evaluated is more excellent. Define ω_s expressed as the weight of the s-th indicator of the operational efficiency of the approach control system. The calculation formula is shown below:

$$S_i = \sum_{j=1}^{n} \frac{\omega_s\left(f_j^{+} - f_{ij}\right)}{f_j^{+} - f_j^{-}} \tag{6}$$

$$R_i = max\left[\omega_s \frac{f_j^{+} - f_{ij}}{f_j^{+} - f_j^{-}}\right] \tag{7}$$

6 Compromise feasible solution for operational efficiency of approach control system $\boldsymbol{Q_i}$.

$$Q_i = \nu \frac{S_i - S^{-}}{S^{+} - S^{-}} + (1-\nu)\frac{R_i - R^{-}}{R^{+} - R^{-}} \tag{8}$$

$$S^{-} = \min_i S_i \tag{9}$$

$$S^{+} = \max_i S_i \tag{10}$$

$$R^- = \min_i R_i \tag{11}$$

$$R^+ = \max_i R_i \tag{12}$$

In the above equation, the compromise feasible solution Q_i is the distance between the solution to be evaluated and the ideal solution, which has a value domain between [0,1]. The smaller the value of Q_i, the more efficient it is. ν is the coefficient of the decision-making mechanism, which is adopted as $\nu = 0.5$. ν denotes the use of a compromise method to ensure the maximization of group benefits as well as the minimization of negative impacts. A weighting of 0.5 means that equal importance is given to each objective, which balances the effects of multiple factors and makes the evaluation results more objective.

3.7 Operational efficiency of the approach control system. In order to make the evaluation value of the operational efficiency of the approach control system more consistent with the actual formulation, the value of the operational efficiency of the approach control system is defined as E_p by taking the value of the compromise feasible solution in reverse. The calculation formula is shown as follows:

$$E_p = 1 - Q_p \tag{13}$$

In the above equation, the ordering is based on the size of E_p. The operational efficiency of the approach control system is compared for different time periods. The larger E_p is, the more efficient the operation is.

3.8 Weighted average operational efficiency of daily flight movements. Since the operation of the approach control system takes one day as a cycle, the time range of the secondary indicator is one day. In order to illustrate the changes in the operational efficiency of the approach control system in a more obvious way, the time from 08:00 to 22:00 in a day is divided into time periods, taking into account the idle and busy periods of operation. Each hour is a time period, and the values of the secondary indicators are taken in each time period, so that the efficiency of each day can be evaluated.

Firstly, for each hourly segment, an efficiency evaluation is made according to the above formula. Then the efficiency evaluation value of the approach control system for one day, that is, the weighted average safety value of daily flight sorties, is given. The weighted average operational efficiency value of daily flights is defined as E_q. The formula is shown as follows: hourly flight traffic multiplied by the ratio of the corresponding operational efficiency value to the total flight traffic.

$$E_q = \frac{F_k * E_k}{\sum F_k} \tag{14}$$

In the above equation, F_k denotes the average hourly flow rate corresponding to the k-th time period, and E_q denotes the operational efficiency value corresponding to the kth time period calculated according to Eq. 14.

4 Example analysis

Taking the approach control system of Xiamen Air Traffic Control Station as an example, relevant data on the control process of the unit were collected. Through the actual operation of the approach control system, the weights of the evaluation indexes of the operational efficiency of the Xiamen approach control system are determined according to the expert evaluation method. The operational efficiency of Xiamen approach control system is evaluated.

4. 1 Determination of the system of indicators for evaluating the efficiency of the approach control system. According to the approach control system operation efficiency evaluation model, the operation efficiency value of Xiamen approach control system from 8:00 to 22:00 on a typical day is calculated. As shown in Table 2.

Table 2: Evaluation of the operational efficiency of the approach control system

Time period	Indicators for evaluating the operational efficiency of approach control																Effici-ency value	Ran-king
	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}	V_{12}	V_{13}	V_{14}	V_{15}	V_{16}		
8:00-9:00	0.64	0.49	7	54	0.77	0.27	0.69	48	25	23	0.13	0.20	0.13	68.3	125.3	0.513	0.3317	5
9:00-10:00	0.73	0.58	1	200	0.73	0.27	0.66	35	27	19	0.23	0.22	0.11	78.5	135.1	0.425	0.1274	13
10:00-11:00	0.63	0.49	2	80	0.77	0.26	0.69	45	25	23	0.04	0.04	0.04	85.5	125.2	0.453	0.5000	2
11:00-12:00	0.81	0.54	5	81	0.72	0.28	0.67	55	22	17	0.15	0.36	0.12	55	110.7	0.622	0.2878	7
12:00-13:00	0.69	0.62	7	59	0.7	0.34	0.66	47	22	21	0.11	0.23	0.05	86.3	110.6	0.509	0.1784	10
13:00-14:00	0.51	0.63	1	130	0.7	0.31	0.68	49	29	18	0.08	0.10	0.06	67.8	145.3	0.472	0.3477	4
14:00-15:00	0.62	0.61	1	70	0.74	0.29	0.66	43	28	24	0.05	0.07	0.04	78.1	140.1	0.668	0.3066	6
15:00-16:00	0.58	0.49	8	78	0.73	0.3	0.69	43	27	17	0.14	0.19	0.24	72.5	135.4	0.468	0.1492	12
16:00-17:00	0.59	0.65	5	45	0.69	0.25	0.68	41	21	18	0.10	0.14	0.11	68.6	105.3	0.576	0.7969	1
17:00-18:00	0.62	0.57	6	36	0.77	0.35	0.67	41	30	19	0.15	0.10	0.16	77.9	150.4	0.663	0.1168	14
18:00-19:00	0.71	0.56	4	36	0.77	0.32	0.7	47	20	22	0.15	0.20	0.14	81.2	100.8	0.541	0.2634	8
19:00-20:00	0.63	0.71	5	76	0.69	0.31	0.69	55	23	15	0.09	0.13	0.13	79.6	115.5	0.561	0.2312	9
20:00-21:00	0.56	0.69	1	50	0.77	0.35	0.69	35	20	18	0.11	0.10	0.06	78.2	100.7	0.466	0.1566	11
21:00-22:00	0.71	0.71	1	49	0.71	0.25	0.7	54	24	19	0.13	0.21	0.05	69.6	120.3	0.606	0.4500	3

4.2 Determination of indicator weights at each level. According to the expert evaluation method, the weights of the evaluation indicators of the operational efficiency of the Xiamen approach control system are determined. As shown in Table 3.

Table 3: Weight of indicators

Indicators	A			B		C		
weight	0.5099			0.2276		0.2625		
Indicators	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8
weight	0.0784	0.1322	0.1267	0.0973	0.0753	0.0435	0.0471	0.0528
Indicators	V_9	V_{10}	V_{11}	V_{12}	V_{13}	V_{14}	V_{15}	V_{16}
weight	0.0484	0.0358	0.0397	0.0415	0.0428	0.0431	0.0526	0.0428

4.3 Calculation results. According to the approach control system operation efficiency evaluation model, the average values of the primary indicators (controllers' workload, airspace utilization rate and degree of flight delay) and the operation efficiency values of the Xiamen Approach Control System for each time slot from 8:00 to 22:00 on a typical day are calculated, as shown in Table 4.

Table 4: Multi-time efficiency evaluation value of Xiamen approach control system operation

Time period	Indicators for evaluating the operational efficiency of approach control			
	Controllers' workload	Airspace utilization rate	Degree of flight delay	Efficiency value
8:00-9:00	66%	69.27%	30%	76.53%
9:00-10:00	70%	66.59%	28%	72.48%
10:00-11:00	61%	73.53%	29%	77.86%
11:00-12:00	67%	67.99%	31%	75.38%
12:00-13:00	76%	67.76%	31%	73.96%
13:00-14:00	78%	72.44%	28%	77.39%
14:00-15:00	78%	71.39%	12%	76.19%
15:00-16:00	66%	72.87%	31%	72.98%
16:00-17:00	74%	71.93%	24%	78.25%
17:00-18:00	69%	74.25%	32%	71.13%
18:00-19:00	77%	67.23%	27%	75.37%
19:00-20:00	80%	65.66%	23%	74.52%
20:00-21:00	75%	75.13%	13%	73.53%
21:00-22:00	74%	65.61%	27%	77.48%

Based on the approach control system operational efficiency evaluation model, the operational efficiency of the Xiamen approach control system from 8:00 to 22:00 on a typical day and the weighted average operational efficiency value of daily flights were calculated. The results show that, comparing the efficiency values for each time period, the highest value for the operational efficiency of the approach control system is 78.25%, and the weighted average operational efficiency of the approach control system according to daily flight movements is 75.22%. The results of the study can help airport management to identify specific shortcomings in the operational efficiency of the approach control system and drive the implementation of targeted improvement measures.

5 Conclusion

Based on the fishbone diagram analysis method, the three main influencing factors of controller workload, airspace utilization rate and flight delay were proposed. A system of evaluation indexes for the operational efficiency of the approach control system was established. Based on the compromise ranking method, an evaluation model of the approach control system's multi-time operation efficiency is established. Taking Xiamen Air Traffic Control Station as an example, the multi-time operation efficiency of the approach control system is calculated. It is verified that this method is an effective and feasible evaluation method, which is of positive significance for the optimization of the operational efficiency of the approach control system.

In conclusion, the application of our evaluation model to the Xiamen Air Traffic Control Station has demonstrated not only its feasibility but also its robustness in accurately assessing the operational efficiency of approach control systems. The model’s ability to integrate and analyze multiple key performance indicators provides a comprehensive tool for operational optimization. Our findings suggest significant potential for enhancing decision-making processes and resource allocation, highlighting the model's practical implications beyond theoretical applications. Future work will focus on extending this model’s application to other control stations and exploring its scalability and adaptability to different operational contexts.

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Biography

Zhaoning Zhang. Professor of Civil Aviation University of China, doctoral supervisor, has been engaged in teaching and researching air traffic planning and management for a long time, presided over the projects of National 863 High-Tech Programme, National Natural Science Foundation of China, National Air Traffic Control Commission, etc. He has published five academic books in Science Press and Civil Aviation Press of China. He has published more than 260 academic papers in Chinese and world academic journals and conferences.

Yuying Fan. Master student at Civil Aviation University of China, focusing on air traffic planning and management.

Jimin Liu. Senior engineer of Strategic Development Department, East China Regional Air Traffic Management Bureau of CAAC, mainly focusing on research in the planning and management of air transportation. He holds four air traffic control licenses, including airport control, aviation information services, and radar control, and has extensive experience in air traffic control. He has participated in several provincial and ministerial-level research projects and has published more than 20 high-level professional academic papers.