A Sector Capacity Assessment Method Based on Airspace Utilization Efficiency

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Abstract. Sector capacity is one of the core factors affecting the safety and the efficiency of the air traffic system. Most of previous sector capacity assessment methods only considered the air traffic controller’s (ATCO’s) workload. These methods are not only limited which only concern about the safety, but also not accurate enough. In this paper, we employ the integrated quantitative index system proposed in one of our previous literatures. We use the principal component analysis (PCA) to find out the principal indicators among the indicators so as to calculate the airspace utilization efficiency. In addition, we use a series of fitting functions to test and define the correlation between the dense of air traffic flow and the airspace utilization efficiency. The sector capacity is then decided as the value of the dense of air traffic flow corresponding to the maximum airspace utilization efficiency. We also use the same series of fitting functions to test the correlation between the dense of air traffic flow and the ATCOs’ workload. We examine our method with a large amount of empirical operating data of Chengdu Controlling Center and obtain a reliable sector capacity value. Experiment results also show superiority of our method against those only consider the ATCO’s workload in terms of better correlation between the airspace utilization efficiency and the dense of air traffic flow.

1. Introduction

Air traffic flow management (ATFM) is a service established with the objective of contributing to a safe, orderly and expeditious flow of air traffic by ensuring that air traffic control (ATC) capacity is utilized to the maximum extent possible \([1]\). Therefore, ATC sector capacity assessment should be the precondition and basis for implementing ATFM.

In last decades, studies on ATC sector capacity assessment have been mostly dedicated to examine the relationship between the capacity and the workload of air traffic controllers \([2-5]\). Although ATCO’s workload can be used to evaluate ATC sector capacity in terms of either the number of simultaneously present aircraft or the number of aircraft traversing the sector per unit of time, the sector capacity is also affected by some other factors. Ball et al. pointed out that the capacity of a sector presents variability and unpredictability. He summarized the factors into three categories, which were airspace physical structure, air traffic situation, and operational constraints \([6]\). In fact, estimating
the sector capacity by ATCO’s workload mainly concerns about the safety. However, as stated in the first paragraph, the sector capacity has significant impact on the ATFM, which aims at utilizing the airspace to the maximum extent. Hence, from the ATFM point of view, the sector capacity should reveal how efficiently the airspace is utilized. In addition, it may not be accurate if we estimate the capacity only by ATCO’s workload. In this paper, we try to solve the problems mentioned here and improve the accuracy, reliability, and applicability of capacity estimation methods through the points as follows.

1) We employ the integrated index system proposed in one of our previous literatures [7], which covers 14 indicators about operational performance, airspace complexity handling, safety, economic efficiency, and ATCO’s. We use the PCA to analyze the indicators in order to dig out the most important ones that have impact on the airspace utilization efficiency and to calculate the score of the airspace utilization efficiency.

2) We use a fitting function to define the correlation between the airspace utilization efficiency and the dense of air traffic flow which is defined as the quantity of flights traversing a sector during a unit of time. We set the sector capacity as the value of the dense of air traffic flow corresponding to the maximum airspace utilization efficiency. We also show better correlation between the airspace utilization efficiency and the dense of the flow than that between the ATCO’s workload and the dense of the flow by some statistical attributes of the fitting functions.

2. Multivariate Index System for airspace utilization efficiency

Airspace utilization efficiency of an ATC sector should reveal its relationship with both the safety and the operating efficiency. We put forward an improved integrated and universal multivariate index system systematically for the airspace utilization efficiency of an ATC sector based in one of our previous literatures [7]. The notations and the definitions of the indicators are listed in table 1.

| Variable                  | Indicator               | Definition                                                      | Notation (Unit) |
|---------------------------|-------------------------|----------------------------------------------------------------|-----------------|
| Performance Efficiency    | Flight Miles            | Total flight miles in sector per hour                          | $X_1$ (km)      |
|                           | Flight Time             | Total flight time in sector per hour                          | $X_2$ (min)     |
| Complexity Handling Efficiency | Aircraft Climbing Frequency | Total aircraft climbing times in sector per hour             | $X_3$ (time)   |
|                           | Aircraft Descending Frequency | Total aircraft descending times in sector per hour         | $X_4$ (time)   |
|                           | Aircraft Speed Changing Frequency | Total aircraft speed changing times in sector per hour | $X_5$ (time)   |
|                           | Aircraft Heading Changing Frequency | Total aircraft heading changing times in sector per hour | $X_6$ (time)   |
| Safety Efficiency         | STCA Frequency          | Total STCA times in sector per hour                          | $X_7$ (time)   |
|                           | MSAW Frequency          | Total MSAW times in sector per hour                          | $X_8$ (time)   |
| Economic Efficiency       | Sector Queue Length     | Total waiting flight number in sector per hour               | $X_9$ (flight) |
|                           | Delay Percentage        | Ratio of delayed flight number and total flight number in sector per hour | $X_{10}$ (%)     |
|                           | Delay Time              | Total delay time of flights in sector per hour               | $X_{11}$ (min) |
|                           | Average Delay Time      | Average delay time of total delayed flights in sector per hour | $X_{12}$ (min) |
3. The processes of sector capacity assessment
We set 3 basic steps to estimate the capacity of an ATC sector as follows.

   Step 1: Set the data set.
   Collect operating data of an ATC sector hourly and calculate the values of those 14 indicators in Table 1. Each sample data represents the state of an ATC sector during single hour.

   Step 2: Principal components analysis.
   Based on the sample data, apply principal component analysis to reduce the dimension of the data and calculate the score of the airspace utilization efficiency of the sector.

   Step 3: Function fitting.
   Fit the dense of the air traffic to the evaluated score of the airspace utilization efficiency. Set the sector capacity as the value of the dense of the air traffic flow corresponding to the highest value of the airspace utilization efficiency.

4. The PCA and the function fitting

4.1. Principal component analysis
We use the principal component analysis (Amos G, 2008) to reduce the dimension of the collected data set and calculate the value of the airspace utilization efficiency. The procedures are as follows:

   (1) The preprocessing of the source data.
   The input data should be normalized to eliminate the dimension differences among all indicators. Set \( x_{ij} \) as the value of indicator \( j \) \((j=1,2,\ldots,14)\) of \( i \) \((i=1,2,\ldots,N)\) sample data.

   The empirical mean of indicator \( j \) is
   \[
   \overline{X}_j = \frac{1}{N} \sum_{i=1}^{N} x_{ij}
   \]
   (1)

   The standard deviation of indicator \( j \) is
   \[
   \sqrt{V(X_j)} = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (x_{ij} - \overline{X}_j)^2}
   \]
   (2)

   Then the normalized matrix, \( Z = (z_{ij})_{N \times 14} \), which is computed using the empirical mean and standard deviation of each indicator is composed with elements like
   \[
   z_{ij} = \frac{x_{ij} - \overline{X}_j}{\sqrt{Var(X_j)}}
   \]
   (3)

   (2) Compose the correlation matrix.
   Set \( R = (r_{ij})_{14 \times 14} \) as the correlation matrix. Its element, \( r_{ij} \), denotes the correlation between the \( j \) \(_a\) indicator and the \( j' \) \(_a\) indicator, where
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\[ r_{j,j'} = \frac{N}{N-1} \sum_{i=1}^{N} \left( x_{ij} - \bar{X}_j \right) \left( x_{ij'} - \bar{X}_{j'} \right) \]

(3) Calculate the eigenvectors and eigenvalues of the correlation matrix.
Set the eigenvalues of correlation matrix as \( \lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_{14} \) with corresponding eigenvectors array \( U = (U_1, U_2, \ldots, U_{14})^T \)

(4) Calculate the evaluated scores.
Calculate the principal component value matrix as below,
\[ Y = (y_{ij})_{14 \times 14} = (Y_1, Y_2, \ldots, Y_{14}) = Z^* U \]

Calculate the contribute rate of the \( j \)-th eigenvalue as below,
\[ w_j = \frac{\lambda_j}{\sum_{j=1}^{p} \lambda_j}, \quad j = 1, 2, \ldots, P \]

Choose \( m \) eigenvalues from the biggest to the smallest whose cumulative contribute rate is no less than 0.8,
\[ \sum_{j=1}^{m} w_j \geq 0.8 \]

Calculate the evaluated scores of the air space utilization efficiency of each sample as,
\[ E = \sum_{j=1}^{m} w_j Y_j \]

4.2. Function fitting
We measure the dense of the air traffic flow with the quantity of flights traversing a sector during single hour. Then, we fit the values of the dense of the air traffic flow relative to the samples data to the evaluated scores of the airspace utilization efficiency with three different fitting functions: linear, polynomial, and Fourier function. We choose the function with least R-square or SSE (Sum Squared Error) values to define the correlation.

5. Empirical Study
Since Chengdu area is one of the busiest air traffic area in China, one sector in Chengdu area is taken as the typical example for empirical study.

5.1. Data set
We collect 648 sets of source data, each for single hour, during rush hours. Table 2 is an example of one sample data.

| Table 2. A sample of the source data |
|--------------------------------------|
| Indicator | \( X_1 \) | \( X_2 \) | \( X_3 \) | \( X_4 \) | \( X_5 \) | \( X_6 \) | \( X_7 \) |
| data      | 1679     | 334     | 5        | 13       | 55       | 158      | 119      |
| Indicator | \( X_8 \) | \( X_9 \) | \( X_{10} \) | \( X_{11} \) | \( X_{12} \) | \( X_{13} \) | \( X_{14} \) |
| data      | 72       | 1       | 7.69%    | 12       | 12       | 42%      | 66       |
We apply MATLAB2014a to execute the principal component analysis and decompose 14 indicators into 6 principal components with the cumulative contribute rate of 0.8294.

5.2. Results of the function fitting
Figure 1 to figure 3 shows the fitting images and parameters for three functions.

Figure 1 Fitting image by Linear function for the airspace utilization efficiency and the dense of the air traffic flow

Figure 2 Fitting image by Polynomial function for the airspace utilization efficiency and the dense of the air traffic flow

Figure 3 Fitting image by Fourier function for the airspace utilization efficiency and the dense of the air traffic flow

It’s clear that the polynomial function and the Fourier function work better than the linear function in terms of higher R-square and lower SSE (Sum Squared Error). In detail, the R-square and the SSE of polynomial and Fourier functions are both 20.64% higher and 36.76% lower than those of the linear function. The R-square values for polynomial and Fourier fitting are both 0.7726, which reveals strong correlation between the airspace utilization efficiency and the dense of the air traffic flow. Since the fitting qualities of the polynomial function and the Fourier function are the same in terms of the values of the R-square and the SSE, we formulate both the functions below,

Polynomial function:
\[ y = -0.001213x^2 + 0.1164x - 2.046 \] (9)

Fourier function:
\[ y = -3.786 \times 10^7 + 3.786 \times 10^7 \cos(-8.006 \times 10^{-6}x) - 1.454 \times 10^4 \sin(-8.006 \times 10^{-6}x) \] (10)
where $x$ represents the dense of the air traffic flow and $y$ represents the score of the airspace utilization efficiency.

We derive both the functions to get the extreme points corresponding to the highest score of the airspace utilization efficiency. The value of the $x$ - axis is 48 at the extreme point which means that the sector capacity for this case can be set as 48 flights per hour. We test the values of ATCOs’ workloads corresponding to the value of 48 flights per hour. Results show that the workloads in such a flow dense are all under the safety threshold, which support the claim that our method can take care of both the safety and the efficiency.

Furthermore, the values of the R-square and the SSE for all 3 functions are pretty worse. R-square and SSE for both the polynomial function and the Fourier function are 0.4824 and 99300 and the results for the linear function are 0.4007 and 114980. This result obviously shows that the correlation between the ATCO’s workload and the dense of the air traffic flow is worse that the correlation proposed in this paper, which supports the claim that the method proposed here can estimate the sector capacity more accurately than those only considered the ATCO’s workload.

6. Conclusion
This paper proposed a sector capacity estimation method based on airspace utilization efficiency. We employ an integrated index system with 14 indicators in total, which helps the comprehensive evaluation of the airspace utilization efficiency. We make use of the principal component analysis to dig out the most important components among the 14 indicators and calculate the score of the airspace utilization efficiency. We employ a series of fitting functions to build up the correlation between the score (or value) of the airspace utilization efficiency and the dense of the air traffic flow. We derive the most fitting function to obtain its extreme point which corresponds to the highest airspace utilization efficiency. Hence, the sector capacity can be set as the value of the dense of the air traffic flow corresponding to the extreme point. We validated our method through empirical study based on real operating data of one sector in Chengdu area, China. We get a reliable value of the sector capacity and the experiment result also shows that the airspace utilization efficiency proposed here fits much better with the dense of the air traffic flow than traditional ATCO’s workload. These results show the superiority of our method in terms of better accuracy, reliability, and applicability in the field of sector capacity estimation.

References
[1] ICAO, Doc4444 (15th Edition)-2007, Procedures for Air Navigation Services-Air Traffic Management [S], Montreal, Canada: ICAO, 2007.
[2] Richmond G C. (1988). An interim description of the DORATASK methodology for Assessment of Sector Capacity. DORA Report 8818. London: Civil Aviation Authority.
[3] Richmond G C. (1989a). The DORATASK Methodology of Sector Capacity Assessment: an Interim Description of its Adaptation to Terminal Control (TMA) Sectors. DORA Report 8916. London: Civil Aviation Authority.
[4] ICAO. Doc9426-AN/924 (1st Edition)-1984. Air transport service planning manual, Part II, Appendix C [S]. Montreal, Canada: ICAO, 1999.
[5] Pellegrini P, Rodriguez J. Single European sky and single European railway area: A system level analysis of air and rail transportation [J]. Transportation Research – Part A: Policy and Practice, 2013, 57 (1): pp. 64–86.
[6] Ball M, Barnhart C, Nemhauser G, et al. Air transportation: irregular operations and control [J]. Handbooks in Operations Research and Management Science, 2007, 14(1): 1–67.
[7] Zhang J, Duan L, Guo J, et al. A Genetic Algorithm Based BP Neural Network Method for Operational Performance Assessment of ATC Sector [J]. Promet - Traffic & Transportation, 2016, 28(6): pp. 563–574.