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Evaluation Method of ATC Controllers' Workload Based on the Metric of Traffic Complexity

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Abstract: Evaluation of controlled airspace capacity based on the controllers' workload is the most wildly used theoretical evaluation method of controlled airspace capacity currently in China. This method uses the aircraft sorties to be the only metric. It identifies some quantitative relationship between the metric of aircraft sorties and controllers' workload. The method then figures out the controllers' workload and evaluates the capacity value limited by the controllers' workload ability in the controlled airspace according to the DORATASK method. But in actual operation, aircraft sorties is not the only Influencing factor of controllers' workload. Therefore, a new evaluation method of controllers' workload based on the metric of traffic complexity is proposed. This new method uses a group of multidimensional metric of air traffic complexity to research and solve the problem of evaluating the controllers' workload, Instead of using a traditional single traffic measurement- aircraft sorties. The method is applied in the capacity evaluation project of control sector 02 in Shanghai. The evaluation results are recognized by the front-line ATC experts. Meanwhile they also verify the feasibility and correctness of the method applying to the airspace capacity evaluation.

Key words: Controllers' workload, traffic complexity, dynamic density, metric, regression analysis

INTRODUCTION

The evaluation of controllers' workload has great significance to ensuring the stability and security of the ATC system. The air traffic control is designed to keep the security and efficient flight of aircraft in the airspace. Ensuring that the controllers have been working beyond the load limit is the important condition of ensuring flight safety. Therefore, the research on evaluation of controllers' workload is an important research subject involving air traffic safety in the field of ATC (Zhang and Han, 2008).

With the deepening awareness and research on the controllers' workload, the evaluation is also extended to the specific traffic situation which is presented to the controllers and can be described quantitatively, from the research on the controllers' physiology and behavior. That is the study on traffic characteristics of different controlled airspace. The object of this study is the traffic complexity defined by (Prandini *et al*., 2011; Prandini *et al*., 2010; Prandini and Hu, 2009).

It's the base of the current research on controllers' workload to build the metric system of traffic complexity and study the traffic characteristics quantitatively.

In this study, we associate sampling data of traffic situation with the controllers' workload by using metric of traffic complexity and put forward the evaluation method of controllers' workload based on the metric of traffic complexity. This method enables aircraft sorties, the single dimension of traffic measurement, to be replaced by the metric system of traffic complexity which is multidimensional and can reflect more traffic characteristics. It provides more explanatory factors for changes of controllers' workload. And we will prove the feasibility and correctness of the method by giving examples of successful application.

EVALUATION METHOD OF CONTROLLERS' WORKLOAD

Researches on evaluation method of controllers' workload mainly focus on the choosing of methods and expand this viewpoint from the following three aspects:

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Firstly, applying the achievements of physiological and behavioral sciences to researches on control workload.

Figure out the intensity of control workload by the air traffic controllers' physiological and behavioral measurement (Collet *et al*., 2002; Averty *et al*., 2004).

Secondly, make subjective evaluation of controllers' workload through the methods of observation and questionnaire.

There are mainly two kinds of subjective evaluation methods of controllers' workload, self-evaluation and expert evaluation of workload. Self-evaluation takes different test methods which evaluate the workload by compiling, testing and commenting questionnaires applied to the controllers' workload (Casso and Kopardekar, 2001; Collet *et al*., 2003; Reid and Nygren, 1988). The evaluation method DORATASK of predicting the controllers' workload, proposed by British Operations Council, is the most wildly applied expert evaluation method (Parkes and Burnett, 1993). The method is essentially to measure and figure out the necessary time for all of the control work-controllers' workload. It also needs to work out the relationship between this necessary time and all of the available time. It concludes that, the average workload with the capacity must be lower than 80% of the total workload and the 90% workload shall not hold more than 2.5% of the total working time. Dealing with the controllers' workload quantitatively, establishing multiple linear regression model of workload in accordance with the relevant data, using the regression model and the method of DORATASK when it comes to the limit of controllers' workload (The workload is equal to 80% of the total workload), all of these steps can work out the maximum capacity of airspace.

Thirdly, evaluate controllers' workload level through the measurement of traffic complexity of different controlled airspace.

Measurements and researches on the workload based on traffic complexity appeal to many scholars currently. They determine different workload level by studying the traffic complexity of different airspace. The operation concept of Dynamic Density (DD) researched and developed by NASA, FAA, Metro, MITRE and other organizations, is the most representative evaluation technology of the complexity in the field of ATM.

In 1995, the United States Aviation Radio Committee (RTCA) firstly proposed the idea of establishing a quantitative description of spatial complexity-dynamic density. This idea is purposed to study the influencing factors (mainly includes traffic density, interval criteria and flow complexity) of conflict rate in terminal area and sector boundaries and to measure the complexity of the situation of air traffic (RTCA Task, 1995). Meanwhile, the commission points out that, the key technology to finish the evaluation of controllers' workload in the future operation environment are the measurement and prediction aimed at Dynamic Density. Researchers in this field believe that the dynamic density is a kind of multidimensional metric of complexity and it's difficult to observe and measure directly. The change of dynamic density's value is the root cause of the increase or decrease of controllers' workload. It's the core of dynamic density to know how to determine the weight of different dimensional complexity metric. And searching for the complexity factor-complexity metric that influences dynamic density and building the metric of complexity have become the research foundation of dynamic density (Zhang *et al*., 2009).

We put forward the evaluation method of controllers' workload based on the metric of traffic complexity by referring to the research of dynamic density and associating the sampling data of traffic situation with the controllers' workload by using metric of traffic complexity. This evaluation method is based on the establishment of the metric system of traffic complexity.

THE EVALUATION METHOD OF CONTROLLERS' WORKLOAD BASED ON THE METRIC OF TRAFFIC COMPLEXITY

Construction and refinement of metric system of traffic complexity. It's the foundation of research on the complexity of all fields in ATC to build the multidimensional metric system. We have a lot of examples. R.H.Mogford and other scholars have concluded about 40 complexity indexes (Mogford *et al*., 1995; Laudeman *et al*., 1998) have been the first to make mathematical description on dynamic density and define 8 complexity indexes. National Aeronautics and Space Administration (NASA) have put forward 16 kinds of index that influence complexity. The Technology Center William J.Hughes of Federal Aviation Administration (FAA) have projected 9 traffic complexity indexes (Kopardekar and Magyarits, 2003). And researchers in Euro-control Experimental Center (EEC) have summed up 108 traffic complexity indexes in a report about complexity and airspace capacity project (Hilburn, 2004).

Summarizing research findings about complexity metric of all fields in air traffic system, using the standards of clear definition, feasible calculation and widespread application, directly choosing the indexes that can contribute to quantitatively describing the operation situation of air traffic system, or splitting, choosing the indexes that can reasonably and quantitatively describing the operating situation of air traffic system from the original indexes as the new indexes, implementing all these steps can build metric system that can show the situation of air traffic. This metric system consists of traffic index and airspace index (Zhang, 2012).

Traffic index is an index set which directly describes traffic behaviors and complexity in the air. It's used to explain the traffic condition of different parts and sides of traffic system's general situation. This index can be classified into density indexes, dynamic indexes and conflict indexes in reference to the classification method of DD-traffic flow complexity metric.

Airspace index is a description of the external environment and organization method of air traffic. This kind of index applies to all levels in the field of ATM. It does not directly describe the realistic state of air traffic. And the index only plays an additional role in the processes of defining traffic index and analysising traffic behaviors and their complexity

Be limited to the length of the study, the following presentation will introduce the connotative definition and mathematical description of the part of traffic indexes that will be referred to in this study.

For the unification of mathematical description of index, sec_i represents any sector in the airspace, $t_k \in T$ represents that T is the collection of all moments at any time. Index value of the moment of t_k can be regarded as the average index value during the corresponding period, owing to the discreteness of the sample data of calculation.

- **Quantity of aircrafts in the sector:** If $Ac_{j,t_k} \in Ac_{Sec_i,t_k}$ and AC_{Sec_i,t_k} represents the aircraft set that sec_i contains at the moment of t_k, then the quantity of aircrafts in this sector- ACT_{Sec_i,t_k} can be concretely represented as the following equality:

$$ACT_{Sec_i,t_k} = \sum_{Ac_{j,t_k} \in Ac_{Sec_i,t_k}} Ac_{j,t_k} \tag{1}$$

- **Sector control fly mileage:** If $CtFL_{j,t_k}$ represent the control fly mileage of Ac_{j,t_k} then the sector control fly mileage- $CtFL_{Sec_i,t_k}$ at the moment of t_k and in sec_i can be concretely represented as the following equation:

$$CtFL_{Sec_i,t_k} = \sum_{Ac_{j,t_k} \in Ac_{Sec_i,t_k}} CtFL_{j,t_k} \tag{2}$$

- **Average control fly mileage:** According to the equation of 1 and 2, the average control fly mileage- $AvgCtFL_{Sec_i,t_k}$ can be concretely represented as the following equation:

$$AvgCtFL_{Sec_i,t_k} = \frac{CtFL_{Sec_i,t_k}}{ACT_{Sec_i,t_k}} \tag{3}$$

- **Sector control fly time:** If $CtFT_{j,t_k}$ represent the control fly time of Ac_{j,t_k}, then the control fly time- $CtFT_{Sec_i,t_k}$ at the moment of t_k and in sec_i can be concretely represented as the following equation:

$$CtFT_{Sec_i,t_k} = \sum_{Ac_{j,t_k} \in Ac_{Sec_i,t_k}} CtFT_{j,t_k} \tag{4}$$

- **Average control fly time:** According to the equation of 1 and 4, average control fly time of the sector- $AvgCtFT_{Sec_i,t_k}$ can be concretely represented as the following equation:

$$AvgCtFT_{Sec_i,t_k} = \frac{CtFT_{Sec_i,t_k}}{ACT_{Sec_i,t_k}} \tag{5}$$

- **Quantity of climbing aircraft in the sector:** If climbing aircraft $Acclm_{j,t_k} \in Acclm_{Sec_i,t_k}$ and $Acclm_{Sec_i,t_k}$ represent the aircraft set that is at the condition of climbing flight(rate of climb>200feet per minute)at the moment of t_k and in Sec_i, then the quantity of climbing aircraft in the sector- $ACTC_{Sec_i,t_k}$ can be concretely represented as the following equation:

$$ACTC_{Sec_i,t_k} = \sum_{Acclm_{j,t_k} \in Acclm_{Sec_i,t_k}} Acclm_{j,t_k} \tag{6}$$

- **Total climbing time I n the sector:** If climbing aircraft $Acclm_j \in Acclm_{Sec_i}$, climbing time is $TClm_j$ and $Acclm_{Sec_i}$ is the set of all climbing aircraft in Sec_i, then the total climbing time in the sector- $TClm_{Sec_i}$ can be concretely represented as the following equation:

$$TClm_{Sec_i} = \sum_{Acclm_j \in Acclm_{Sec_i}} TClm_j \tag{7}$$

- **Quantity of aircrafts in sectors of which the altitude has been changing:** If $Acac_{j,t_k} \in Acac_{Sec_i,t_k}$ represent the aircraft of which the rate of change in altitude is higher than 375 Feet/minute and $Acac_{Sec_i,t_k}$ represents all aircraft set of which rate of change in altitude is higher than the threshold level at the moment of t_k and in Sec_i, then quantity of aircrafts in sector of which the altitude has been changing- $ACTAC_{Sec_i,t_k}$ can be concretely represented as the following equation:

$$ACTAC_{Sec_i,t_k} = \sum_{Acac_{j,t_k} \in Acac_{Sec_i,t_k}} Acac_{j,t_k} \tag{8}$$

In order to reduce the dimension of index and keep on the representative index that can reflect all of the situation of air traffic at the same time, we can mine the regularities of distribution of the index value through all kinds of clustering methods and finish the extraction and refinement. The major clustering method consists of the following kinds: Partition method, hierarchical method, method based on density, method based on net and method based on model. But all of these methods have some drawbacks, as described below. They need a lot of datum and it's difficult to find out the regularities with few amount of datum. These methods request that samples obey a typical probability distribution or that there is linear relationship between the data of each factor and that characteristic data of the system and various factors are unrelated to each other. These requirements are difficult to satisfy in the reality. So we adopt the grey clustering method (Cong *et al*., 2012). We use methods related to grey system theory to do research on the uncertain system that "part of the information is known, part is unknown, small sample and lack of information". We realize the exact description and recognition of regularities of data mainly by the generation and development of the "part" of known information (Liu *et al*., 2010).the grey clustering method makes up for the drawbacks of traditional analytic methods. We analysis and measure the related degree between different sequences with the method of grey correlation. And then we can build up characteristic value of grey correlation matrix that is dimensionless and classify the index into categories that can be defined. the grey clustering method is not sensitive to sample data or the regularities. This method does not need a lot of computations. So, the situation that quantifiable result does not conform to the result of qualitative analysis will not appear (Laudeman *et al*., 1998). Therefore, we can cluster merge the complexity of factors of the same kind though the grey system method.. We can choose the representative index according to concrete traffic problems after classification, reduce the expressive dimension of index and cut down the amount of similar information.

The evaluation method of controllers' workload based on the metric system of traffic complexity. The process of this method can be divided into the following several steps:

Step 1: Determine the dependent variable x_i and the independent variable y_i that is needed. The dependent variable x_i represents the controllers' workload. Concrete workload can be refined into smaller classification of workload. Independent variable x^0_i is the explanatory variable of controllers' workload. These variables are factors that cause the controllers' workload. We can choose appropriate parameters of independent variable according to sector characteristics and the characteristics of traffic flow. In this study, we adopt the complexity metric that passed the process of cluster refine and dimensionless in the complexity metric system as the independent variable y^0_i of the regression analysis model. And we adopt the 去量纲的 y_i as the dependent variable y^0_i of the regression analysis model. The dimensionless relational expression is like the following equation:

$$\phi_i^0 = \left(\frac{\phi_i(1)\text{-}\min(\phi)}{\max(\phi_i)\text{-}\min(\phi_i)}, \frac{\phi_i(2)\text{-}\min(\phi)}{\max(\phi_i)\text{-}\min(\phi_i)}, \ldots, \frac{\phi_i(n)\text{-}\min(\phi)}{\max(\phi_i)\text{-}\min(\phi_i)}\right) = \left(\phi_i^0(1), \phi_i^0(2), \ldots, \phi_i^0(n)\right) \tag{9}$$

Step 2: Carry on the process of data collection of some work factors by using the multi channel digital radar and voice recorder (MDR). And adopt the method of measuring and timing on the spot to do the data collection of other kinds of work factors like control action. In this way, the duration and frequency of every kind of work factors can be kept in the record. The handling of data source mainly contains two sections£ºdata processing of MDR, flight schedule and data processing of the actual schedule flight.

Step 3: Associating the controllers' workload and the metric of traffic complexity after the process of clustering and refining, we can evaluate the controllers' workload by the method of regression analysis

EXAMPLES

There are 9 legs in the control sector 02 in Shanghai. They are P180-SHZ-AND, P22-P243-SHZ-AND, P180-SHZ-BK-ATRIP,P22-P243-SHZ-BK-ATRIPand-SJZ-P2ER and-SHZ, FK, ZSNB-PAA, PAA-ZSNB and FK-AND.

In the sector, radar control services is available. When choosing the air traffic control automation system, they adopt the application system EUROCAT-X which consists of control command seat and control coordination seat.

Based on the all-day flight radar data in control sector 02 of Shanghai on April 28, 2011, the snapshot time starts from 00:00:04 on April 28, 2011 to 23:59:57 on November 10, 2010 with a statistic time unit of 900 sec, including 96 time slice. We choose 8 indexes in

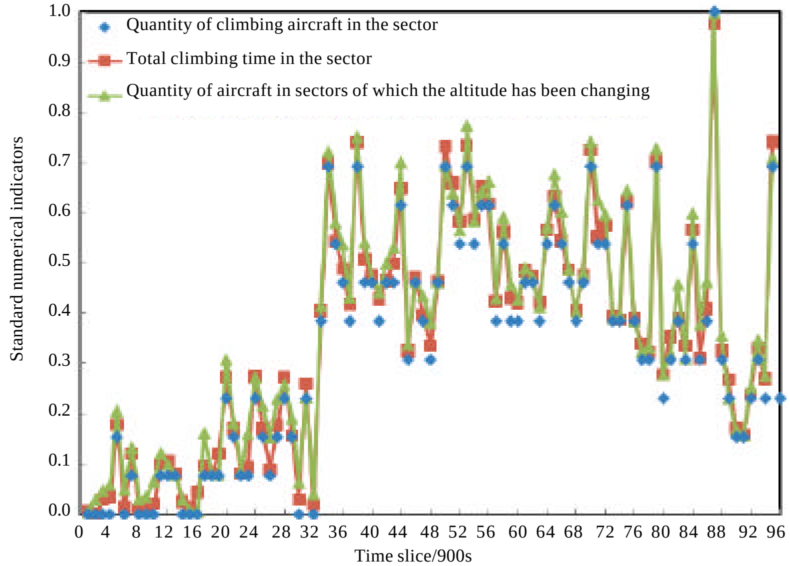

Fig. 1: Third category index numerical sequence

Table 1: Correlation degree matrix of index

index series	1	2	3	4	5	6	7	8
1	100	0.97	0.56	0.99	0.53	0.64	0.66	0.53
2		1.00	0.61	0.98	0.64	0.69	0.65	0.62
3			1.00	0.63	0.99	0.34	0.34	0.37
4				1.00	0.60	0.68	0.66	0.59
5					1.00	0.35	0.34	0.31
6						1.00	0.97	0.98
7							1.00	0.67
8								1.00

the traffic indexes to be the sample, they are quantity of aircrafts in the sector, sector control fly time, average sector control fly time, sector control fly mileage, average sector control fly mileage, quantity of climbing aircraft in the sector, total climbing time in the sector and quantity of aircrafts in sectors of which the altitude has been changing. We use the index series 1-8 to represent them correspondingly. Using Matlab and Excel to process the data and calculate the index, we can figure out each value of the 96 time slice. Work out the correlation degree matrix of index according to the grey clustering method as shown in the Table 1.

Setting r = 0.9, we can get the following conclusions after observing the numerical value of matrix.

$$\varepsilon_{1,2} = 0.97, \varepsilon_{1,4} = 0.99, \varepsilon_{2,4} = 0.98,$$
$$\varepsilon_{3,5} = 0.99, \varepsilon_{6,7} = 0.97, \varepsilon_{6,8} = 0.98$$

Because there is not too much indexes, we can quickly find out that 7 indexes show the following 3 clusters, the first category is quantity of aircrafts in the sector, sector control fly time and sector control fly mileage, the second category is average sector control fly time and average control fly mileage, the third category is quantity of climbing aircraft in the sector, total climbing time in the sector and quantity of aircrafts in sectors of which the altitude has been changing. There is high degree of grey correlation between indexes that belong to the same category of cluster. And the related degree of index is lower between different clusters. For instance, the related degree between quantity of aircrafts in the sector and average sector control fly mileage is only 0.53, much less than 0.9 which can also illustrate that there is less deviation in the clustering result.

Figure 1 shows the numerical sequence of quantity of climbing aircraft in the sector, total climbing time in the sector and quantity of aircrafts in sectors of which the altitude has been changing in the third category of index. After the observation of Fig.1, we can find out that geometrical distance of the index numerical sequence that belong to the same kind of cluster is very close to each other. Meanwhile, the shapes of the curves are similar and variation tendencies are basically the same and even part of the curves are overlapping. All of these conclusions fully illustrate that the grey correlation degree is very high of the index numerical sequence that belongs to the same kind of cluster and that the clustering result is correct. Similarly, we can get the same conclusion by observing the numerical sequence of the first and second category of index.

When using the traffic indexes to explain the traffic characteristics in sectors, the number of indexes is refined to 3 from the original 8, they are quantity of aircrafts in the sector, average sector control fly time and quantity of

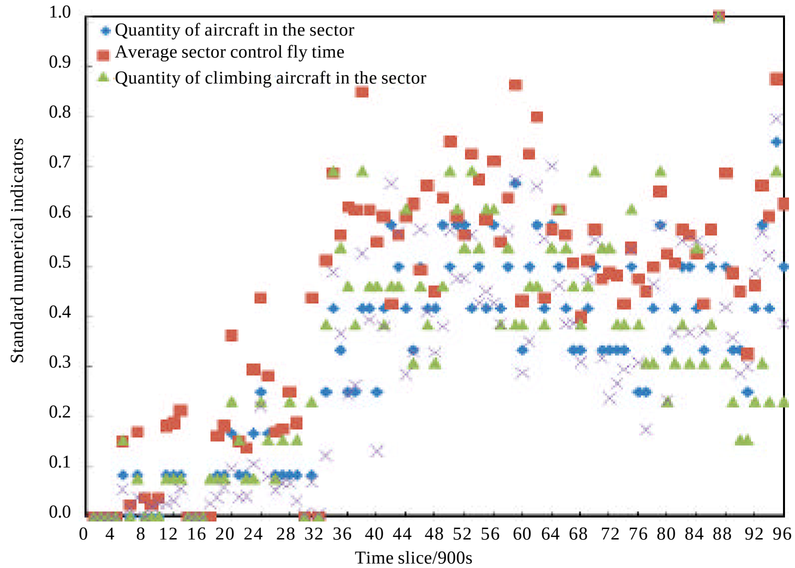

Fig. 2: Initial statistical data scatter diagram

climbing aircraft in the sector. They can provide a complete statement, greatly reducing the amount of information that controllers are required to receive.

Choose the three indexes-quantity of aircrafts in the sector, average sector control fly time and quantity of climbing aircraft in the sector -which have been clustered, refined and nondimensionalized by the relation Eq. 9 to be the argument of multiple linear regression model. The concrete multiple linear regression model can be represented as follows:

$$y_i^0 = \beta_0 + \beta_1 x_{1i}^0 + \beta_2 x_{2i}^0 + \beta_3 x_{3i}^0 + e_i \tag{10}$$

Subscript i represents the case i, (y_i, x_{1i}, x_{2i}, x_{3i}), i = 1, 2,…, m Superscript 0 represents that index is dimensionless according to representation 9; y_i represents the workload within evaluation time slice i; x_{1i} represents the quantity of aircrafts within time slice i, x_{2i} represents average sector control fly time within time slice i, x_{3i} represents the quantity of climbing aircraft in the sector within time slice i, β_i (i = 0, 1, 2, 3) is regression coefficient, e_i is random error, $E(e_i) = 0$, $D(e_i) = \sigma^2$.

Building the multiple regression model according to the evaluation method of controllers' workload based on the metric system of traffic complexity. Using the data $(y_i^0, x_{1i}^0, x_{2i}^0, x_{3i}^0)$ in Fig. 2, we can finally work out the following multiple linear regression equation after the process of fitting:

$$y^0 = 0.747x_1^0 + 0.668x_2^0 + 0.578x_3^0 + 0.063 \tag{11}$$

When y_i is an arithmetic number that is between the maximum and the minimum, putting it into relation Eq. 9 and 11, we can get a three-variable linear equation with x_1, x_2, x_3 being the arguments. We can figure out the non-negative integer solution set of this The three element indefinite equation and the $(\max)x_1$ of the set by the method of variable cycle traversal algorithm (Zhan, 2011).

According to the method of DORATASK (set $y_i = 0.8 \max(y_i)$), then we figure out that $\max(x_1) = 10$. Thereby, we can work out the sector capacity value that is in accordance with controllers' ability to bare the job, i.e., N = 10 sorties/15 min. The result is consistent with the operating situation in control sector 02 of Shanghai and have been recognized by the front-line control experts.

CONCLUSION

In this study, we have analysed the controlled airspace in Shanghai and got following conclusions:

- We have developed the evaluation method of controllers' workload based on the metric of traffic complexity and quantized the effect of traffic complexity on the evaluation of controllers' workload
- We have carried out the evaluation of controllers' workload according to the evaluation method of controllers' workload based on the metric of traffic complexity. The evaluation results as the component of the capacity evaluation of control

sector 02 in Shanghai have received unanimous recognition of the front-line control experts in the coordination meeting. The evaluation results are in accordance with the actual operation situation. This illustrates the feasibility and correctness of the method in the field of workload evaluation and capacity evaluation

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