

Method to Analyse Air Traffic Situation Based on Air Traffic Complexity Map

Zhao Yifei, Zhang De, Yue Rentian, Wang Hongyong

Air Traffic Management Research Base

Civil Aviation University of China

Tianjin, China

yfzhao@cauc.edu.cn, dzhang_yjs08@cauc.edu.cn, rtvue@cauc.edu.cn, hywang@cauc.edu.cn

Abstract—The matching rate between traffic flow and capacity has been the key metric for evaluation on air traffic situation for long. When facing the more flexible traffic flow planned by NextGen and SESAR, the traditional capacity assessment methods based on controller workload have shown its big limitation. On the contrary, the complexity assessment methods with a microscopic characteristic have begun to prove its advantage. The re-definition of air traffic complexity and traffic complexity parameter are given through the deep discussion of its connotations and characters. Based on the idea of traffic flow turbulence analysis, the sector-aircraft model is established and the mapping analyses method to air traffic complexity is designed, followed with a further analysis on time revolution of complexity map. Results show that the method can accurately describe the microscopic behavior of multi-aircraft, visually display the sector traffic situation, and provide effective strategy to controllers in a more complex airspace and a more flexible flight condition.

Keywords—air traffic complexity; air traffic management; complexity metric; disturbance analysis; complexity parameter; complexity map

Intellectualization and automation is the trend of air traffic management system. With the new concepts and technology putting forward constantly, methodological changes are also imperative. Air traffic management system has for long been evaluated by the matching rate between traffic flow and capacity. That is, we have a threshold of capacity in specific airspace under specific situation. When the air traffic flow is over the threshold, we consider it a saturation of the airspace system. Service quality and safety that the system provided will drop quickly. For example, flight delay increases, accident rate rises, passengers' satisfaction reduces, etc. Therefore, the flow control restriction is unavoidable. In recent years, along with the rapid development of air transportation industry, the traffic flow has been increasing continuously. The saturation of airspace and the flow control restriction have brought about serious influence for air transport.

On the other hand, along with the application of satellite-based navigation technology and equipment gradually, aircraft

will no longer be restricted by ground based beacons and fixed routes, but achieve free flight capability in airspace. Obviously, presently used sector capacity assessment method which is applicable to fixed route operation can't adapt to the relatively disordered traffic behavior. Air traffic complexity redefined the macroscopic properties of airspace and sector on the basis of its description on the microscopic behavior of aircraft. Therefore it provides a way for solving the problem.

In the research field of air traffic management, the concept of complexity has already appeared in the 1960s, mainly as a means of analyzing controller workload [1-2]. Due to the lack of visual ways in air traffic situation analysis that the complexity research had not yet provided, the controller workload evaluation methods based on flight number is still dominant. In recent years, with the growing sophistication of air traffic situation, those methods gradually exposed its deficiency on accuracy and predictability, while the complexity study began to show its advantage in the analysis of complex situations [3-5]. Therefore, complexity research in the field of air traffic management have been listed in the significant events of NextGen [10-11], also the basis of SESAR research [12] in the project of track management, complexity management and flexible use of airspace.

Currently there are two representative research directions of complexity. The first is the complexity assessment techniques based on the operation concept of dynamic density. Researchers thought that dynamic density is a kind of multidimensional complexity parameters which is not directly observable, and the value change is the cause of controller workload change. The second is the complexity study based on traffic intrinsic properties. Researchers thought that to some extent, the complexity measure can be considered an objective description of traffic situation complexity using traffic intrinsic properties such as aircraft speed and heading. The traffic flow disturbance analysis that this article uses belongs to such research.

I. DEFINITION OF AIR TRAFFIC COMPLEXITY

The original meaning of “complex” includes two aspects. On the ontological aspects, it refers to object made up of many closely connected parts, on the epistemological aspects, it means difficult to understand or explain because there are many different parts. “Complexity” means the character or state of “complex”. The word “complexity” first appeared in system science and information science. It was expressed as a kind of objective property of things. This is reverse to the traditional view, but it is undoubtedly more reasonable. According to the traditional understanding, simple and complex are opposite, things in unrecognized are complex, once be recognized, they become simple. To look from the process of human recognize things, that idea seems common. But the development of modern science and technology shows that we can't leave complexity just by reason of inadequacy in the process of cognition, but must admit there exists objectively complexity. The real complexity shall have its own characteristics, even if it have been known and have found a way of solution, it is still complex.

For air traffic complexity, Dirk Schaefer etc. think: “traffic complexity neither considers operational procedures specified to the airspace nor individual factors that determine controller’s response to a potentially difficult situation. Complexity is limited to the characteristics of the traffic situation itself, and may thus be considered as a factor causing workload [6].” Harry Swenson etc. think: “traffic complexity is a measure of the controller’s workload [7].” Keumjin Lee etc. think: “air traffic complexity is a measure of the control activity required to accept a hypothetical aircraft entering into the sector [8].” D. Delahaye etc. think: “the airspace complexity is related with both the structure of the traffic and the geometry of the airspace [9].” The researchers have described complexity from different point of view, but did not give a strict definition. This paper argues that the understanding of complexity should consider the following several aspects.

Firstly, air traffic complexity is an objective concept. It does not vary from the difference of controller's ability or workload. For a particular air traffic situation, once its relevant objective factors determine, the degree of its complexity is determined. The complexity will not be lower because the controller's ability is high nor his workload is low. That means complexity is event-oriented, rather than human-oriented. We can reflect or analyze the controller workload through complexity, while contrarily inappropriate.

Secondly, the air traffic complexity is a multi-level concept which includes two aspects. One is the structural complexity, including airspace geometric configuration, air route structure, the number of intersection point and navigation facility, weather conditions, etc. Second is the traffic flow complexity, including flight number, separation standard, velocity and heading, aircraft close rate, etc.

Thirdly, the air traffic complexity is a time-dependent dynamic concept. Although the structural complexity hardly changes with time, but traffic flow complexity evolves with the process and state of aircraft. Therefore, the whole complexity also changes with time.

Through the above conceptual analysis of air traffic complexity, we present the following definition: air traffic complexity is an objective description to the internal order of the air traffic system in certain time or period for a given airspace, sector or route system, which is a synthesis of its structural characteristics and traffic flow characteristics. And air traffic complexity parameter is the measure and metric of the complexity in that system.

In the definition, “in certain time or period” reflects the dynamic characteristics of air traffic complexity, “synthesis of structural and traffic flow characteristics” reflects the multi-level characteristics, and “objective description to the internal order” reflects the objective characteristics.

II. SECTOR-AIRCRAFT MODEL

Air traffic system is a control system against to disturbance. Both traffic flow and environmental change will bring disturbance to the system, affect the intrinsic order of the air traffic, and generate the traffic complexity. Our study on air traffic complexity is based on the idea of traffic flow disturbance analysis.

For a sector of which traffic initial configuration is conflict-free, the traffic complexity is indicated by the disturbance that an aircraft entering from the sector boundary, illustrated in Figure 1.

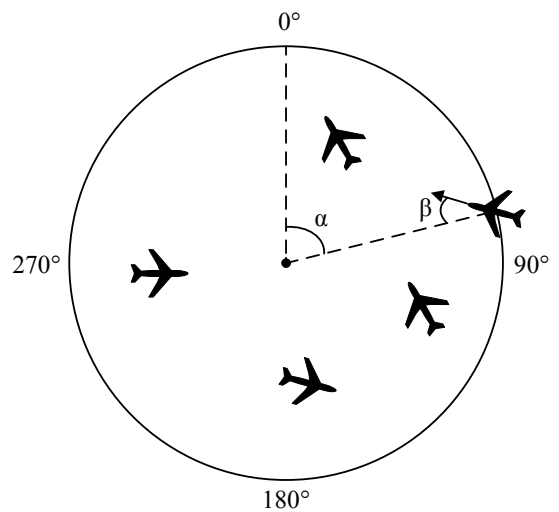


Figure 1. Aircraft Enter Sector from the Boundary

We define two angles to the entering aircraft to describe its property.

Position angle: The angle between true north and connected line which from the entry point to center of sector. Position angle is marked as α in Figure 1.

Heading angle: The angle between the entering aircraft’s heading and connected line which from the entry point to center of sector. A heading angle of zero means that the entering aircraft is moving toward the center of the sector. The angle β in Figure 1 illustrates a negative heading angle.

For a circular sector boundary admitting aircraft from any direction, the position angle $\alpha \in [0^\circ, 360^\circ)$ and the heading angle $\beta \in [-90^\circ, 90^\circ]$.

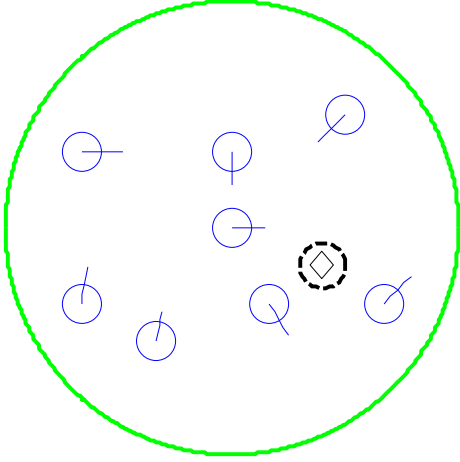


Figure 2. Initial Situation of The Sector

Besides impact to aircraft in the sector, the disturbance brought by the entering aircraft also perform on restricted areas like hazardous weather areas and prohibited areas, which will affect the entering aircraft on its flight process. Based on restricted areas, impact between sector and aircrafts can be modeled. At the instant that the entering aircraft flies into the sector through the boundary, the initial situation of the sector is illustrated in Figure 2. The large circle represents the sector boundary and the small circles demarcate the safety regions of the aircraft. The velocity vectors of the aircraft are indicated by the line segments originating from the location of the aircraft. The diamond indicates the location of the restricted area and the dotted circle represents its sphere of influence. The initial configuration of traffic in the sector is conflict-free.

III. AIR TRAFFIC COMPLEXITY MAP

Since the sector-aircraft model is built, we can now analyze the disturbance on traffic flow. When the entering aircraft enters the sector on different position angle and heading angle, the degree of disturbance will also be also different. With the former definition of traffic complexity and traffic complexity parameter, we take TCP (Traffic Complexity Parameter) as the metric that measures the degree of disturbance.

For the TCP calculation, we use the simplified collision risk model [13]. Since we concentrate on the horizontal movement of the aircraft, the two-dimensional model is enough. So when the horizontal distance between two aircraft is less than the separation standard, it is considered as a conflict.

Set $Separ$ as the separation standard, then the aircraft protected area is a disc with a radius of $r = Separ/2$. Therefore, the conflict between two aircraft occurs when the two discs collide. The degree of collision risk could be represented by the overlap area, illustrated as S in Figure 3. The closer the

distance between aircraft, the larger the area is, corresponding to higher complexity. So it can be used to characterize TCP.

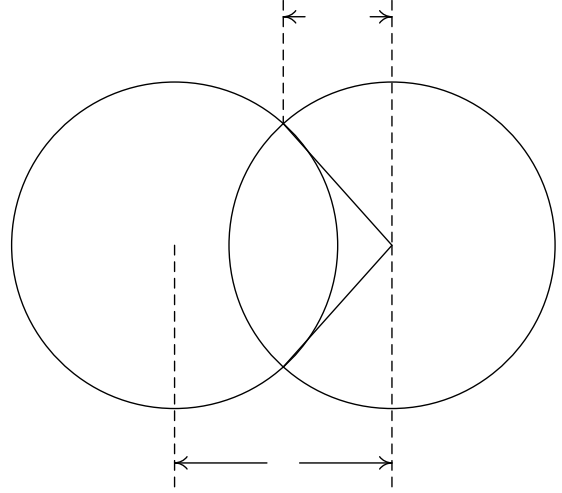


Figure 3. Aircraft Conflict Model

Set d as the distance between two aircraft, so:

$$S = [2 \arccos \frac{d}{2r} - \sin(2 \arccos \frac{d}{2r})] \cdot r^2$$

The situation that entering aircraft collide with block area is similar as former. Now sum up S generated by all the aircraft P_i and block areas O_j , we got TCP that represents the disturbance to the sector brought by the entering aircraft.

$$TCP = \sum_{i=1}^{N_p} S_i + \sum_{j=1}^{N_o} S_j$$

For position angle $\alpha \in [0^\circ, 360^\circ)$ and heading angle $\beta \in [-90^\circ, 90^\circ]$, we got complexity map for traffic situation Figure 2 as following Figure 4.

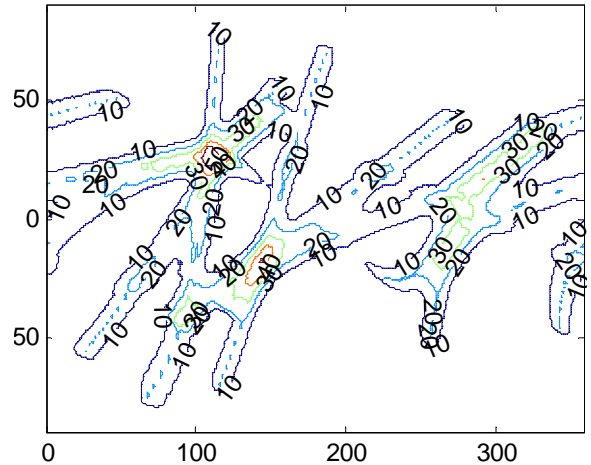


Figure 4. Corresponding Complexity Map for Situation in Fig. 2

The horizontal axis stands for position angle and the vertical axis stands for heading angle. The boundary line in different color represents TCP in different value, i.e. the TCP contour line (with its value marked on the line). We can see 2 peak values of TCP in Figure 4. One is 60+ located at (109,27), the other is 50+ located at (143,18).

Through the complexity map, we can analyze the sector traffic situation in quantification, and thus achieve decision making based on complexity. For example, from the topology of Figure 4 we can see, the peak value of TCP occurs in position angle 100° - 150° range, so controllers could restrict aircraft enter from that range of direction. A more effective control strategy according to complexity map is re-planning the location and heading of the entering aircraft to avoid the occurrence of high complexity situations. For example, the point (143, -17) in Figure 4, which means the entering aircraft enter the sector at a position angle of 143° and a heading angle of -17° , brings a large disturbance on the sector, with the TCP value of 49.2, shown as the bottom right black spot in Figure 5. However, when maintain the position angle of 143° , if we make the entering aircraft at a heading angle of 5° to enter the sector, the TCP value significantly reduced to 2.6. Also, when maintain the heading angle of -17° , if we make the entering aircraft at a position angle of 5° to enter the sector, the TCP value is reduced to 2.2.

Another two ways to reduce the TCP value are also shown in Figure 5. With comparison among the 4 arrows we can see that the arrow points to upper left is the best control strategy. Both position angle and heading angle only need tiny changes to make the complexity of the sector decreases rapidly.

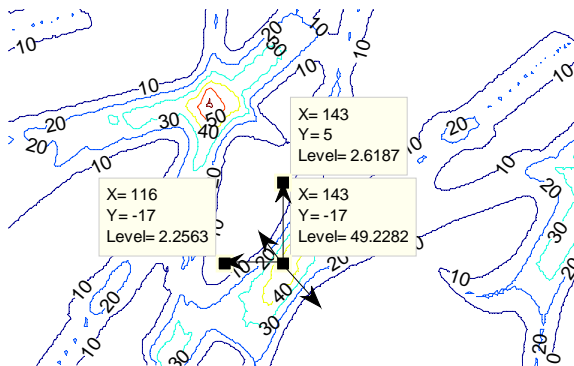


Figure 5. Adjustment under High Complexity Situation

Now remove an aircraft P1 from the sector in Figure 2, illustrated as Figure 6. The corresponding complexity map is Figure 7.

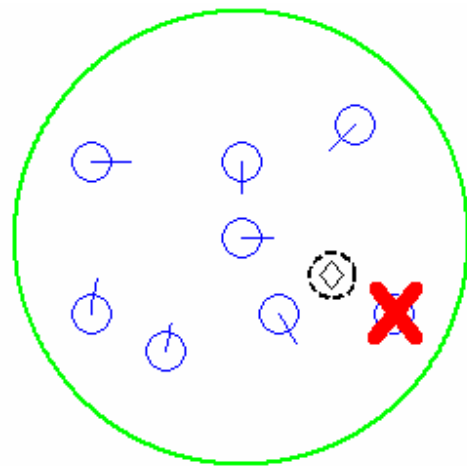


Figure 6. Remove Aircraft P1 from Sector

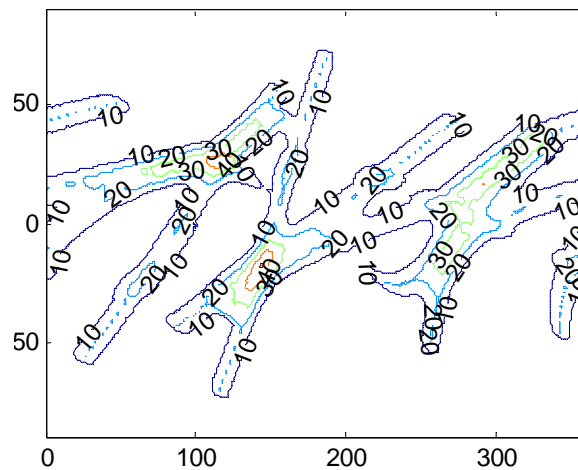


Figure 7. Complexity Map after P1 Removed

Comparing this complexity map with the original complexity map in Figure 2, we can notice that complexity has decreased for all entering aircraft. The difference between maps in Figure 4 and Figure 7 is given in Figure 8.

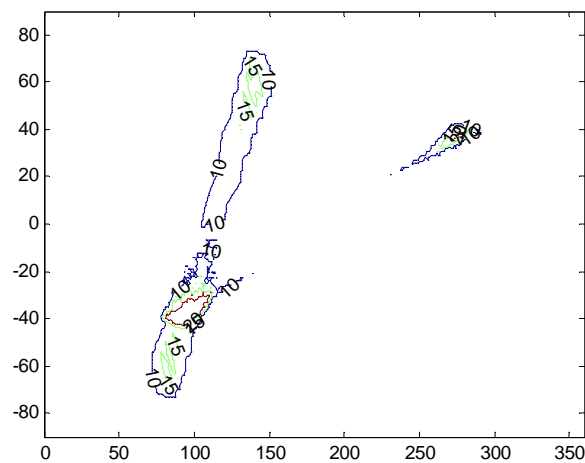


Figure 8. Complexity Increment Brought by P1

Figure 9 gives the complexity map with aircraft P1 alone in the sector. With comparison between Figure 8 & 9 we can easily find the difference, which means an increased complexity for aircraft P1 and those for an alone aircraft P1 are different to the system.

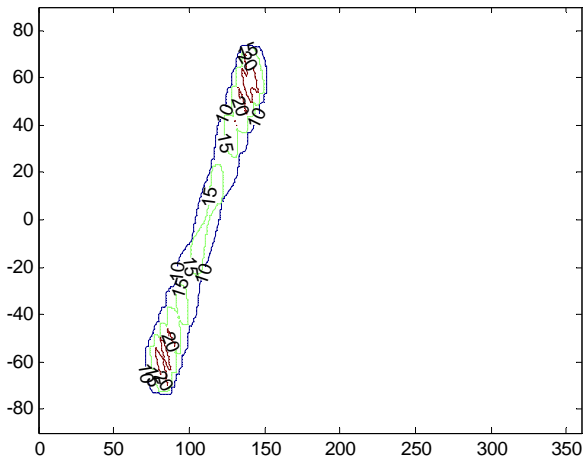


Figure 9. Complexity Map with P1 Alone

This shows that the sector complexity is not the simple addition of the complexity brought by each aircraft inside the sector, but a nonlinear relationship. Air Traffic Situation of sector is therefore also a complex, nonlinear systems. Presence of an aircraft not only brings its own complexity, but also the complexity of other aircraft within the sector. The greater the number of aircraft, the higher degree of nonlinearity.

IV. TIME REVOLUTION OF COMPLEXITY MAP

We have discussed the disturbance to the sector caused by the entering aircraft at a fix time point with complexity map. In practice, due to uncertainty and variability of the air traffic system, people tend to pay more attention to the sector complexity over time. So we are going to make a further study on the complexity caused by the entering aircraft within a certain period of time.

In the actual process of air traffic control, before aircraft entering the target sector, it is likely to have a delay in other sectors because of control factors or other reasons, and cannot reach the sector boundary on time. Obviously we cannot analyze the complexity at the planned time, but should reconsider the time variability, establish related complexity map, and assess the impact using certain statistics.

Set Delay as the delay time that entering aircraft get into the sector. The initial sector situation and the corresponding complexity map of Delay=10 (Delay to 10 time units) is shown in Figure 10.

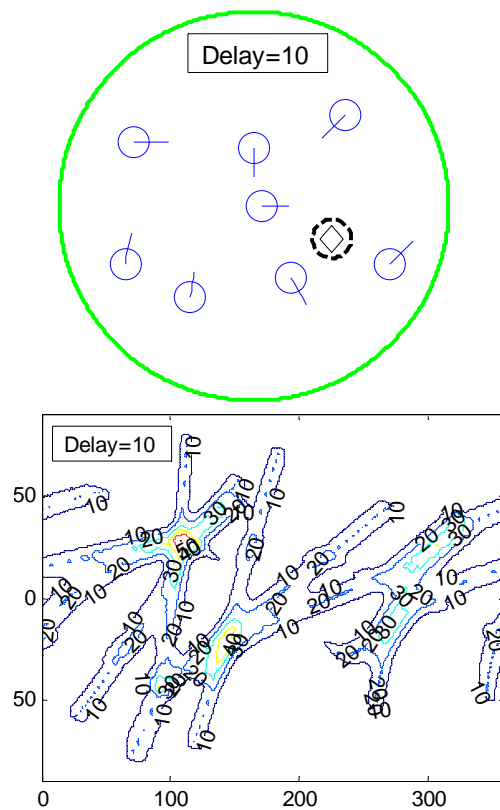


Figure 10. Situation and Complexity Map of Delay=10

Compared with Figure 4, the high complexity area around (143,-18) disappears in Figure 10. Also known by the statistical results that the average TCP of Delay=10 is 6.2724, less than 6.4120 for Delay=0. It indicates that after a delay of 10 time units, the disturbance caused by the entering aircraft will be less than the situation of no delay.

The TCP value of sector with time revolution is given by Table 1. The delay time spans 0 to 120 time units.

TABLE I. TCP VALUE OF SECTOR WITH TIME REVOLUTION

Delay	Average of TCP	Peak of TCP	Difference of average TCP compared with Delay=0
0	6.4120	61.1875	
10	6.2724	60.3961	-0.1396
20	6.1261	61.3622	-0.2859
30	6.0169	60.1603	-0.3951
40	5.8984	56.3191	-0.5136
50	5.8020	55.7123	-0.6100
60	5.6973	51.6904	-0.7147
120	4.7027	40.2834	-1.7093

There are 3 statistical parameters in Table 1: average TCP, peak value of TCP and the difference of average TCP compared with Delay=0. We can inform from Table 1 that as

Delay increases, the TCP of sector decreases, which means when the entry delays, the corresponding sector situation tends to simple. Especially for Delay=120 when aircraft P1 has flown out of the sector, it can be seen from the table that the average TCP reduced with a large extent of more than 1.7.

In practice, time evolution of the complexity map can guide controllers to regulate the sector situation. If the complexity decreases with the delay time increases, it could be considered to instruct the entering aircraft slow down, delay the time to enter the target sectors in order to reduce the disturbance of the sector. On the other hand, if the complexity increases with the delay time increase, the controller should try to accelerate entering aircraft, in order to avoid the increase of complexity.

V. CONCLUSIONS

When facing the increasingly complex air traffic situation, the traditional capacity assessment methods have shown its big limitation. On the contrary, the complexity assessment methods have begun to prove its potential in dealing with complex problem due to its flexibility and adaptability brought about by its microscopic characteristics. In future air traffic management, we may foresee that complexity related indexes will replace capacity to become a foundation of CNS/ATM and the new evaluation criteria of airspace system. This paper has designed a air traffic complexity map analyzing method for sector traffic situation based on traffic flow turbulence analysis. It not only provides an assistant analysis tool for controllers to understand traffic situation, but also open up a new field of vision to design and optimize of airspace system. Further research will consider flight level dimension and focus on air route traffic complexity under use of the complexity map.

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AUTHOR BIOGRAPHIES

Zhao Yifei, received the Ph.D. degree in 2003 from Beihang University, Beijing, China.

He is currently a Professor of Civil Aviation University of China and deputy director of the Air Traffic Management Research Based which founded by CAAC headquarter.

He is one of main researchers of air traffic flow management in China. He was in Charge of the first ATFM

research project in national high technology research and development program and had set up several ATFM application system in practice.

Zhang De, received the M.S. degree in transportation engineering from Civil Aviation University of China, Tianjin, China in 2011. He is currently an air traffic management researcher at Air Traffic Management Bureau Technology Research Center of CAAC.

Yue Rentian, received the Ph.D. degree in 2008 from China University of Geosciences, Beijing, China. His research areas include air traffic flow management, aviation safety, airspace management, controller workload assessment.

Wang Hongyong, received the M.S. degree in transportation engineering from Civil Aviation University of China, Tianjin, China in 2008. His research areas include air traffic flow management, air traffic system simulation.

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