

Article

Airspace Capacity Assessment with Augmented Cell Transmission Model

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Abstract: Air traffic congestion is caused by the unbalance between increasing traffic demand and saturating capacity. Flight delay not only causes huge economical lost, but also has very negative environmental impact in the whole air transportation system. In order to identify the impact of extended TMA on airport capacity, an airspace capacity assessment method based on augmented cell transmission model was proposed. Firstly, the airspace structure was modeled with points, segments, layers, and cells. Secondly, mixed integer linear programming model was built up with maximum throughput or capacity as the objective function. Finally, genetic algorithm was used to find the optimal result, and the results were validated by comparing with the fast-time simulation results generated by total airspace and airport modeler (TAAM) software. It is found that the proposed method could achieve a relatively accurate result in a much affordable and fast way. The numerical results could be very helpful for air traffic controllers to analyze the dynamic traffic flow entering and exiting TMA, so as to make decisions via reasonable analysis and do planning in advance by referring to the airport capacity.

Keywords: Air transportation; air traffic control; airspace capacity; cell transmission model

1. Introduction

Air traffic congestion is caused by the unbalance between increasing traffic demand and saturating capacity. Flight delay not only causes huge economical lost, but also has very negative environmental impact in the whole air transportation system. Air delays will normally trigger a large number of aircraft to either hold in the holding stacks for more than 30 minutes, or force aircraft to reroute and fly a longer distance, which require more fuel consumption, consequently causing more pollution in the air.

In the last 30 years, civil aviation in China has been in a fastest development in the world. With the continuous improvements of airspace planning and management, the operational efficiency of Terminal Control Areas (TMAs) at China's busiest airports, such as Beijing, Shanghai and Xi'an, has been largely improved. Thus, the bottleneck of capacity at the airport has been gradually shifting to the extended TMAs, where aircraft are entering or exiting the en-route cruising phase between airways and busy airports.

In order to reduce the delays in extended TMAs, four key factors needs to be considered: flow management, topological structure, traffic complexity, and dangerous weather. Insufficient route capacity will cause heavy traffic delay [1]. Operational cost to mitigate the traffic delay could be changed with dynamic flow management strategies [2]. Thus, an efficient flow management should be able to optimize traffic flow with reference to the different levels of delay, safety cost and capacity. A safety-capacity trade-off approach could be considered to calculate a maximum sector capacity under an acceptable level of safety risk, so as to reduce delay in a practical way [3]. Route network design has naturally impact on capacity and complexity. On one side, the airway converging points layout plays an important role in the network complexity analysis. Normally, the closer and denser the

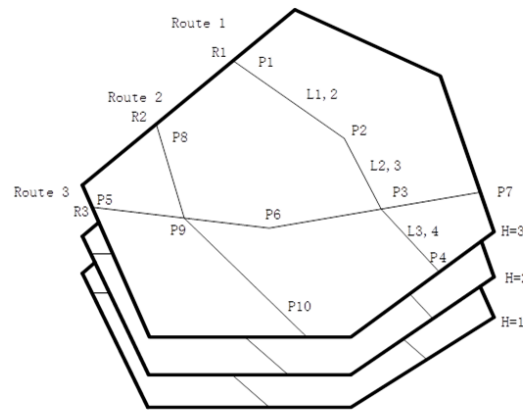


Figure 1. Example of a 3D route network

converging points are in a specific airspace, the route network complexity is getting higher. The complex network modeling is considered to optimize the route convergence point layout problem [4]. On the other side, the number and locations of airway intersections, the length of airway segments, and the angle of airway intersections are also important factors to airway network complexity. By merging and changing some positions of intersections could result in a better route network structure [5]. In addition, other factors, such as traffic flow complexity or traffic pattern, and dangerous weather, have extremely severe impact on route network dynamic performance. Prediction plays crucial role in handling the abnormal situation in airspace, so as to keep the airspace capacity in a reasonable level. By considering the coming traffic flows in 30 minutes' to a few hours' time window, the airspace dynamic capacity could be predicted, then different controllers' strategy and decisions could be made to avoid heavy delays happening in extended TMAs [6]. In term of dangerous weather, prediction normally be made at least hours in advance, so as to avoid chaos happening in extended TMA airspace [7].

The concept of cell transmission model (CTM) was firstly proposed by C. F. Daganzo in 1994, which is a discrete separation form of the kinematic model Lighthill, Whitham and Richards (LWR) [8–10]. This method simulates the dynamic flow in the network by discrete separation and decentralization, which is suitable for the research of macroscopic traffic flow. Through the continuous improvement and perfection of scholars, it has been widely used in the field of road traffic, such as dynamic traffic assignment [11], autonomous vehicle flow control [12]. In the aviation field, some researchers applied CTM to en-route air traffic flow management [13]. However, most of their studies were based on two-dimensional space, which is not the best assumption for aviation. In this paper, we are developing a 3D augmented cell transmission model by adding the altitude to the 2D model.

2. Augmented Cell Transmission model

2.1. Airspace and cell structure

As shown in Figure 1, the extended TMA airspace is a three-dimensional space, which could be divided into several different layers with a vertical separation of $1000ft$ or $300m$. Each layer is represented by H_m , as shown in Figure 1, there are three layers H_1, H_2, H_3 . On each layer, the two-dimensional route network consists of points, segments, routes, sector boundaries, and cells.

Points $P_i, i \in \mathcal{N}$ could be the turning point, the intersection of two different routes, or the crossing point of boundary and route. As shown in Figure 1, there are 10 points, where P_2 and P_6 are turning points, P_3 and P_9 are route intersections, the others represent different intersections of airspace sector boundary and routes.

A segment is the part between two points P_i, P_j on the same route, which is represented by $L_{i,j}, i, j \in \mathcal{N}$. For instance, there are 9 segments in Figure 1, where $L_{1,2}$ represents the

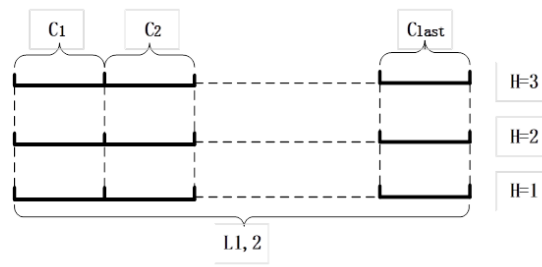


Figure 2. Example of a cell structure in a segment

part of the route between point P_1 and point P_2 , the direction of which is from point P_1 to point P_2 , and the direction of the segment $L_{1,2}$ is the same as that of the route.

Routes are composed of segments, which are represented by $R_k, k \in \mathcal{N}$. In this paper, routes are divided into two types: 1) routes for aircraft to enter/leave the TMA from/to the extended TMA and 2) routes for aircraft to cruise through the extended TMA airspace. There are three routes in Figure 1. Taking route R_1 as an example, route R_1 is composed of segments $L_{1,2}, L_{2,3}, L_{3,4}$. Thus, $R_1 = \{L_{1,2}, L_{2,3}, L_{3,4}\}$ and its direction is $P_1 \rightarrow P_2 \rightarrow P_3 \rightarrow P_4$. The boundary of a specific airspace is represented by a thick solid line in Figure 1.

Each segment is further divided into several cells according to the control separation minimum, represented by $C_z, z \in \mathcal{N}$. For example, in radar control environment, the minimum horizontal separation between two aircraft on the same route in the same direction generally is 5 NM. Therefore, each cell could be 5 NM wide. Depending on the traffic delay situation, the size of cell is not a fixed value. For instance, if there is a heavy delay in TMA, then the size of cell could be bigger up to 10-15 NM. From an operational point of view, cell is the most basic unit of route network, which demonstrates the spacing between two successive aircraft. It also represents the traffic flow density in a dynamic route network. Taking the segment $L_{1,2}$ as an example, as shown in Figure 2, there are three layers, H_1, H_2, H_3 , on each layer, there are several cells $C_1, C_2, \dots, C_{last}$, and the length of each cell is fixed at time range according to the area control minimum separation or air traffic flow control requirement. Remark that the segment length and the area control separation are not integer corresponding, thus it is necessary to round up the last cell of each segment.

Assume that the length of the cell is D_{C_z} , the length of the segment $L_{i,j}$ is $D_{L_{i,j}}$, then the total number of cells n in a segment in $L_{i,j}$ is calculated by the following formula:

$$n = \frac{D_{L_{i,j}}}{D_{C_z}}, i, j \in \mathcal{N} \quad (1)$$

2.2. Aircraft speed analysis

By radar data analysis, aircraft ground speed changes with different altitude and position. Figure 3 shows the distributions of aircraft ground speed at two different altitudes, i.e. 31100ft and 37000ft, in the same segment. Obviously, the mean value and variance of aircraft speed are different at different altitudes. The higher aircraft fly, the faster they travel. As shown in Figure 4, the distributions of aircraft ground speed in different segments at the same altitude is also different. In this case, the mean value of aircraft speed in segment 2 is faster than that in segment 1. Through data analysis, it is found that majority of aircraft fly within a certain speed range at a specific altitude of a specific segment. Therefore, in this paper, to simplify the study, the mean value of the normal distribution of aircraft speed could be taken as a reference speed, which will not cause excessive calculation error and meet the accuracy requirements. In other words, the reference speed will be the function of altitude H_m and cell C_z .

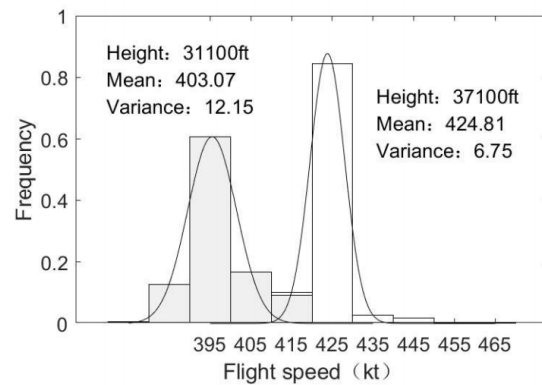


Figure 3. Example of speed changing with altitudes

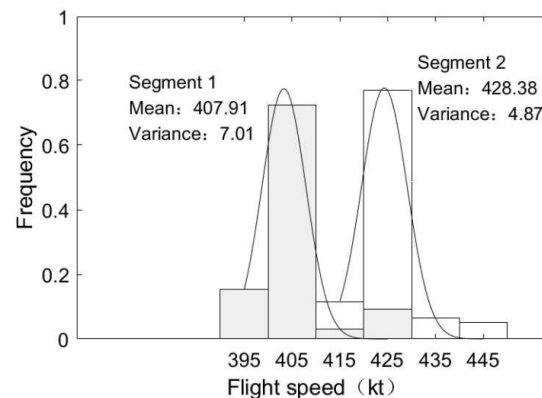


Figure 4. Example of speed changing with segments

2.3. Cell transmission modelling

First, several assumptions need to be set up to make a reasonable modelling in a given condition. They are:

- The aircraft ground speed in a cell is constant, and the reference speed is determined by the position and altitude of the segment where the cell is located.
- The time is calculated in minutes.
- The model does not consider the influence of random factors such as weather.
- Cruising aircraft on the overflight route will not change their altitudes.
- When aircraft need to change altitude, it starts from the beginning of one cell and finishes at the end of another cell where this aircraft is going to level off. The total altitude change has to be accomplished within one length of a cell, as shown in Figure 5. The speed of aircraft during level change is the average value of two reference speeds in those two cells.
- Aircraft must not change altitude at all intersections due to safety.

Second, several variables need to be calculated in the cell transmission modelling to describe the aircraft dynamic status. They are: status of aircraft into extended TMA, aircraft



Figure 5. Example of aircraft level change

level changes, elapsing time inside one cell, entering cell timestamp, exiting cell timestamp. If at absolute time T_f^E , one aircraft f is entering extended TMA from route R_k at flight level H_m , then its status is described by:

$$f_{R_k}^{H_m}(T_f^E) = \begin{cases} 1, & \text{if entering extended TMA} \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

Assume that aircraft f is entering the extended TMA, then the elapsing time t inside cell $C_z, z \in \mathcal{N}$ at flight level H_m is described by:

$$t_f(C_z, H_m) = \frac{D_{C_z}}{v_f(C_z, H_m)} \quad (3)$$

where, $v_f(C_z, H_m)$ is the reference speed of aircraft f inside C_z at altitude H_m .

Along one route R_k , aircraft altitudes in different cells C_z could be described as a matrix:

$$\mathbf{H}_f^{R_k} = \begin{bmatrix} H_1^{C_1} & H_1^{C_2} & \dots & H_1^{C_Z} \\ H_2^{C_1} & H_2^{C_2} & \dots & H_2^{C_Z} \\ \vdots & \vdots & \vdots & \vdots \\ H_m^{C_1} & H_m^{C_2} & \dots & H_m^{C_Z} \end{bmatrix} \quad (4)$$

where, $H_m^{C_z}$ equal to 0 or 1, and $z \in \mathcal{Z}$. If it is 1, it means aircraft pass through C_z at altitude H_m . As mentioned above, the timestamp of aircraft entering the cell depends on the location of the cell C_z and the absolute timestamp of entering extended TMA T_f^E . Therefore, the timestamp of entering cell $T_{C_z}^{in}$ could be described by:

$$T_{C_z}^{in} = \sum_{y=1}^{y=m} f_{R_k}^{H_y}(T_f^E) \times T_f^E + \sum_{x=1}^{x=z-1} \sum_{y=1}^{y=m} \mathbf{H}_f^{R_k} \times \mathbf{t}_f(\mathbf{C}_x, \mathbf{H}_y) \quad (5)$$

The timestamp of exiting cell $T_{C_z}^{out}$ will be:

$$T_{C_z}^{out} = \sum_{y=1}^{y=m} f_{R_k}^{H_y}(T_f^E) \times T_f^E + \sum_{x=1}^{x=z} \sum_{y=1}^{y=m} \mathbf{H}_f^{R_k} \times \mathbf{t}_f(\mathbf{C}_x, \mathbf{H}_y) \quad (6)$$

Third, throughput defines the number of aircraft passing in a specific airspace in a specific time range. It is important for calculating the delays. The smallest airspace unit is cell, so the cell throughput could be labelled as $X_{C_z}^{R_k}$. Then, a sector consists of several routes, and sector throughput is defined as the number of aircraft passing through the sector within a given time, labelled by S ,

$$S = \sum_{x=1}^{x=\mathcal{Z}} \sum_{y=1}^{y=\mathcal{M}} X_{C_x}^{R_y} \quad (7)$$

Control area includes several sectors, similarly control area throughput, labelled by A , could be defined as:

$$A = \sum_{q=1}^{q=\mathcal{Q}} S_q \quad (8)$$

Fourth, the maximum throughput in a specific airspace is the airspace capacity. By definition, the cell capacity is 1, which means only 1 aircraft could be flying in one cell due to safety. The objective function is to find the capacity of control area with the hard constraint of only one aircraft in each cell.

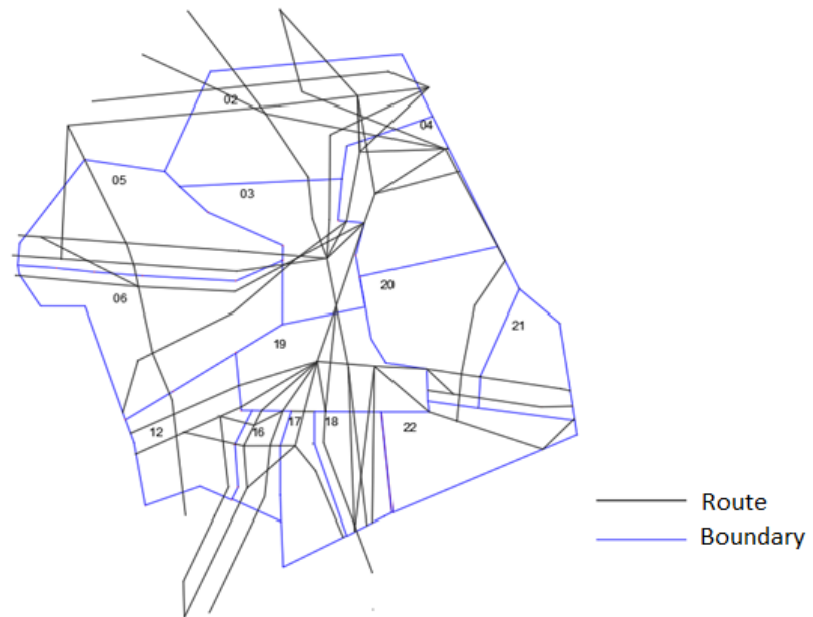


Figure 6. Study case: Beijing extended TMA

3. Simulation and results

The study case is the extended TMA around Beijing Capital international airport, with 13 sectors shown in Figure 6. Beijing Capital International Airport was the world's second busiest airport for passenger traffic in pre-COVID period, with 100 million passengers in 2019.

By applying our method, there are 143 way-points, 269 segments, 725 cells and 153 routes. Among the 153 routes, 90 routes pass through the airspace for cruising purpose, 32 routes guide aircraft to descend and enter the TMA, and 31 routes guide the aircraft to climb and enter the extended TMA in area control airspace. The airspace altitude range in Beijing extended TMA is from 7800m to 12500m. According to the cruising level allocation regulations, the routes to the East are divided into 8 levels, i.e. 8100m, 8900m, 9500m, 10100m, 10700m, 11300m, 11900m and 12500m. While the routes to the West are divided into 8 altitudes, i.e. 7800m, 8400m, 9200m, 9800m, 10400m, 11000m, 11600m and 12200m.

Then Genetic Algorithm (GA) is applied to find the optimal result. GA was first proposed by Professor Holland.J of the University of Michigan in 1975. It is an intelligent search algorithm inspired by the theory of biological evolution [14]. The algorithm uses biological populations to eliminate disadvantaged individuals and retain dominant individuals so that species continue to evolve as a search mechanism to perform multiple iterations of feasible solutions to the problem to select the optimal solution. This method is suitable for complex multi-variables linear programming problems. Compared with traditional algorithms, GA needs to randomly generate a set of initial feasible solutions, and performs iterative selection on the basis of the initial feasible solutions. This initial solution set is called population. Each feasible solution in the solution set is called an individual, and each individual is composed of a string of gene sequences, where the gene sequence is the variable value corresponding to the problem. GA continuously integrates and reorganizes individuals through the selection, crossover, and mutation of gene sequences between individuals to obtain the optimal individual, which is the optimal solution. The flowchart of application of GA in our research is shown in Figure 7.

In the experiment, 1 hour is selected as the total time to calculate the maximum capacity of regional airspace in one hour. Pre-defined parameters are as following:

- the control separation is 20km,
- the number of individuals in the initial population is 100,
- the crossover probability is 0.6,

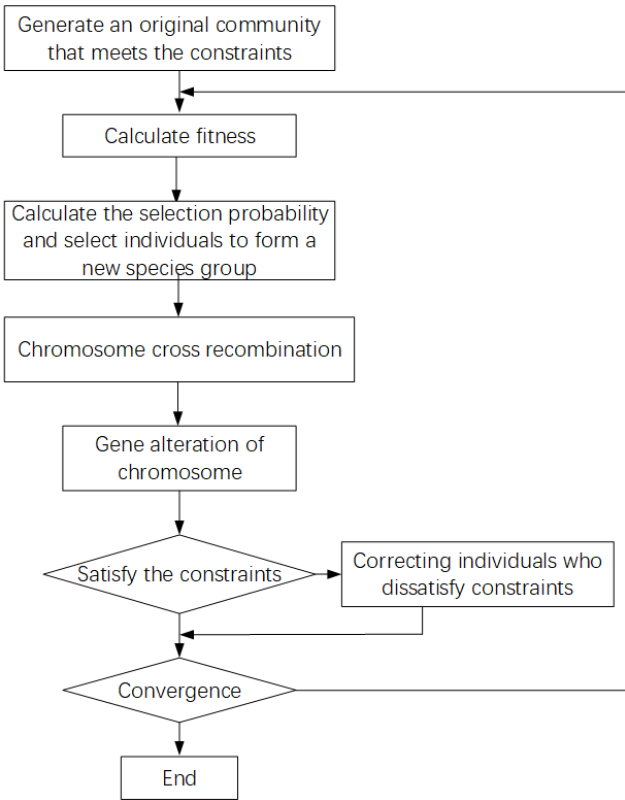


Figure 7. Flowchart of GA method

- the variation probability is 0.01.

After 60 iterations, the GA results are converging, as shown in Figure 8. The average value of the final convergence is 987.42. It means the hourly capacity of the airspace is 987 aircraft, of which 185 is the hourly capacity for aircraft entering or leaving the extended TMA from/to TMA, 802 is the hourly capacity for aircraft passing or cruising through the extended TMA.

In order to further validate the Augmented Cell Transmission Model (ACTM), TAAM simulation is applied and compared. TAAM is a fast-time delay and travel time computer simulation model that is being used to calculate delays and travel times. It has been successfully used in many simulation-based capacity assessment, such as runway capacity [15], airspace demand [16]. In this research, an individual of the convergent group from ACTM is selected as a sample to generate a timetable for TAAM. The TAAM simulation results are then compared with those of ACTM model. Table 1 shows the hourly capacity of each sector through different methods, one is ACTM which is proposed in this paper,

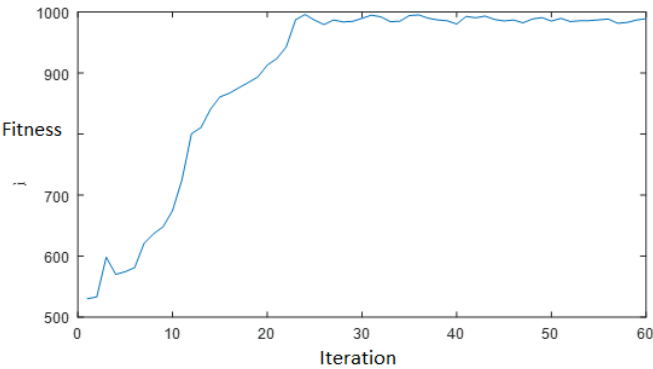


Figure 8. Fitness iteration

and the other is TAAM. It is found that the traffic flow is mainly concentrated in sector 02, sector 16, sector 17 and sector 19. Generally, the capacity generated by ACTM is slightly higher than the TAAM simulation results.

Table 1. Results of Hourly Sector Capacity

Sector ID	Capacity by ACTM	Capacity by TAAM
Total airspace	986	975
AR02	132	128
AR03	109	103
AR04	59	53
AR05	98	94
AR06	49	47
AR12	114	109
AR16	123	121
AR17	121	119
AR18	49	45
AR19	135	131
AR20	101	98
AR21	39	39
AR22	80	78

4. Conclusions

In this paper, the augmented 3 dimension cell transmission model is firstly proposed to describe the traffic flow in extended TMA, then genetic algorithm is applied to generate the maximum airspace capacity. The numerical results are validated by comparing with fast-time simulation by TAAM software. This research shows that the proposal ACTM is suitable for the large scale airspace capacity assessment, and does not need to purchase expensive simulation platform, such as TAAM. The modelling method and results are very reliable. As long as the airspace structure is given, its capacity can be analyzed in a fast and affordable way, which is very helpful for air traffic controllers to analyze the dynamic traffic flow entering and exiting TMA, so as to make decisions via reasonable analysis and do planning by referring to the airport capacity. However, in current study, we did not consider the impact from military activities and dangerous weather, which is interesting to discover in the future research.

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Conflicts of Interest: The authors declare no conflict of interest.

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