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Research on air route network nodes optimization with avoiding the three areas

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ABSTRACT

For the sake of easing the large-area flight delays and relieving the increasing pressure of the safe operation due to growing air traffic, the optimization model of air route network (ARN for short) nodes was established with avoiding "three areas" (prohibited area PA for short, restricted area RA for short, danger area DA for short) under the condition of flight safety and operating cost. The objective function was the shortest path of ARN in this model, and the cellular automata (CA) model with fixed boundary and the neighbors of Moore was used to find solution for the model. As a case study, flight paths A596, B458 and H33 in the busy airspace of ZBPE (Beijing Flight Information Area) were selected. Under the condition of the current flight flow, radar control operation interval of 20 km, standard cruise speed of 800 km/h and no controller's intervention, the optimization design of ARN nodes was accomplished successfully with avoiding the three areas. The number of the nodes was reduced by 10.526%, the probability of the flight conflict risk of the two important cross network nodes "Tian Zhen" and "Nan Cheng Zi" was reduced by 0.99% and 66.33% respectively, and their safety level is acceptable, total cost of flight path was reduced by 0.009%, and the nonlinear coefficient of ARN was reduced by 0.332%. The cost of the above mentioned optimization results was that the total distance of route segments was increased by 0.329%.

The previous ARN planning methods pay more attention to the flight paths after planning, and their purposes are to get more convenient, efficient, or safer flight paths. China has a giant airspace with many three areas, and the three areas must be avoided in the process of ARN planning inevitably, which is not implemented in the previous work. CA model proposed in this paper improved the safety of the ARN. It also completed the ARN node optimization and avoided the three areas. It provided not only an effective solution method for the ongoing ARN planning and adjustment under China airspace management system, but also a new train of thought about ARN node optimization for other countries with similar airspace characteristics.

0. Introduction

With the rapid development of the aviation industry, air traffic flow and safety pressure are both increasing. The scientific planning of ARN is an effective means of optimizing airspace resources, increasing the airspace capacity, and breaking through the bottleneck of the transportation development. At present, the ARN optimization researches mainly focus on two methods, one method is to plan the new ARN overall and abandon the existing network structure; another method is to adjust and/or optimize nodes based on the existing ARN.

There are two kinds of global planning solutions of ARN. One solution is to establish the high-speed free route in the air by referencing the concept of the ground highway. In USA, Alipio et al. (2003), Yousefi et al. (2004), Wing et al. (2008) and others, have respectively conducted the research incrementally. In European, under the idea of "Single European Sky", the EEC (2000) put forward the concept of free flight. Florent (2004) Riviere, 2004a,b presented a tube network, and Eurocontrol (2005) raised the concept of high-speed free route. Until now, the study of high-speed ARN has never been stopped in Europe. Another solution is to set up ARN by planning the latitude and longitude of every node. Riviere (2004), aiming at air traffic operation management concept for sector-less, adopted a very simple square grid to cover Europe and optimized it by simulated annealing (SA) algorithm and genetic algorithm (GA). Riviere and Brisset (2005), put forward the shortest path algorithm in view of invariant, and created a European ARN from the angle of improving the performance of ARN optimization algorithm (Doan et al., 2004).

Due to the airspace management systems of some countries are different with that of Europe and the United States, the global ARN

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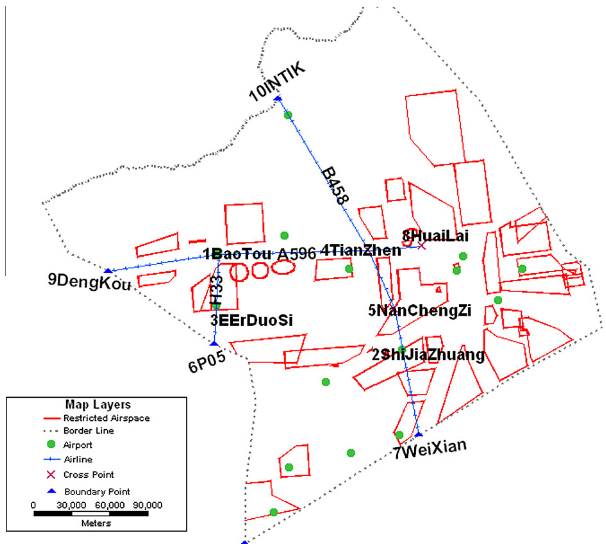

Fig. 1. The map of ZBPE airspace.

optimization technology is not applicable to these countries with many restricted airspace. Taking China as an example in this paper, China airspace contains many prohibited area, restricted area, and danger area (commonly known as the three areas). Fig. 1 shows the airspace of ZBPE, the three areas is expressed by the irregular areas which is bounded by line. It can be seen that the flight paths B458, A596 and H33 all go through or are included in many three areas airspace, which have serious influence on flight safety. So three areas should be avoided in ARN optimization.

By learning from the ARN design concept which was raised by M. W. Siddiquee in USA (Siddiqee, 1973a,b, 1974) and the air route structure with minimum operating cost which is designed by Karim Mehadhebi in France (Mehadhebi, 2000), domestic researchers then optimized the nodes of the existing ARN through the quantified mathematical model and methods. Zhou Jin introduced a bi-level programming mode into the ARN planning without take any constraints into account (Jin, 2008). Zhao Shuang, established a hierarchical analysis model of ARN nodes, put forward the network design method with avoiding three areas (Shuang, 2008), but the node capacity did not be considered, the entire route network would fall into a traffic jam quickly when a cross point is congestion. In order to solve the airspace congestion, Chen Cai-long, proposed a heuristic Particle Swarm Optimization (PSO) with betweenness guiding to solve the layout problem of ARN cross nodes (Cai-long, 2011). However, this method does not consider these nodes' actual location restrict and operating limits. At present, most of the solution algorithms for route network optimization model, such as GA, PSO algorithm (Cai et al., 2010), Differential Evolution (DE) algorithm (Zheng-wei, 2013) and other algorithm are not only complex, but easy to convergence to local optimal solution because of limited exploration ability of the new space. Moreover, these algorithms are random, so they need multiple computations, the computation is time-consuming,[2] and the result reliability is poor, even it cannot get stability solution.

In this paper, an optimization model of ARN nodes is established based on CA theory by taking the minimum ARN traffic impedance – path as objective function. According to the risk management requirements which was put forward by the International Civil Aviation Organization (ICAO), with satisfying the requirements of safety risk level of China, the three areas were avoided successfully by using the model put forward above, and optimal solution was obtained quickly under the constraint conditions of route cost, economic cost and the boundary of ARN nodes. Then a typical busy airspace was selected as an example to verify the feasibility of the algorithm.

1. Cellular automaton model

CA is defined in a space consists of discrete and finite cell state. It is a dynamic system which evolutes on the discrete time dimension according to certain rules. All cells follow the same evolution rules and update in a certain rule. A large number of cells make up the dynamic system evolution through a simple interaction (Bin et al., 2007).

In the CA, cell space is divided by regular grid into many units. Each unit of these grids is called cell. The distribution, shape and size of these cells are the same. These cells obey the same laws (i.e., the CA evolution rules) in the limited state of discrete values. CA is a discretization model which is equivalent to "field" in traditional physics. The CA evolution is carried out in accordance with the same time interval step by step, such as t, $t+1$, $t+2,\ldots$, and the cell state in the time t only has an effect on the cell state in time $t+1$, i.e., each cell state in the next time $t+1$ depending on that in t time, which shows that CA has the limitations characteristics of time and space.

CA can be regarded as a set of a cell space and a transformation function which is defined in this space, including cell, cell space, neighbors, rules and cell state, as shown in Fig. 2 and its expression is shown in the following formula:

$$A(L_q, S, J, R) \tag{1}$$

In formula (1), A represents a CA system; L_q indicates cell space, and q indicates space dimensionality. The set of grid points in the space where cell distributes is cell spaces; S is a set of cell state, it can have binary forms such as $\{0,1\}$, $\{\text{black}, \text{white}\}$, it also can be a discrete set in the integer form $\{s_0, s_1, s_2, \ldots, s_k\}$ according to the difference of the research question; J indicates space vector which is formed by all cell neighbors n in the neighborhood, labeled as $J = (s_0, s_1, s_2, \ldots, s_n)$; R is a dynamic function which determines the next moment state of cell according to the current state of the cell and its neighbors.

In summary, the working process of CA model is that each cell in cell space is traversed and turned into a center cell to evolve according to CA evolution rules until all cells are not satisfied the evolution condition. When the CA evolution is finished, the global optimal solution will be obtained. This is a reason why the CA model is adopted in this paper.

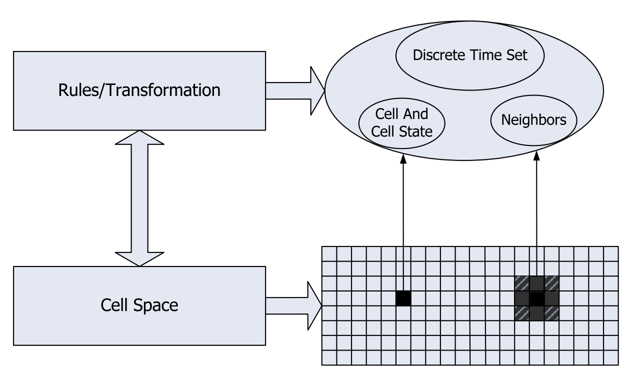

Fig. 2. CA composition sketch map.

[2] For the same optimization problem, the DE algorithm was token as a representative of random algorithms, compared with the CA model used in this paper, and the comparison results of computer time consuming were shown in Appendix A.