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Strategic flight assignment approach based on multi-objective parallel evolution algorithm with dynamic migration interval

Zhang Xuejun [a,b], **Guan Xiangmin** [a,b], **Zhu Yanbo** [a,b,c,*], **Lei Jiaxing** [a,b]

[a] *School of Electronic and Information Engineering, Beihang University, Beijing 100191, China*
[b] *National Key Laboratory of CNS/ATM, Beihang University, Beijing 100191, China*
[c] *Aviation Data Communication Corporation, Beijing 100191, China*

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Abstract The continuous growth of air traffic has led to acute airspace congestion and severe delays, which threatens operation safety and cause enormous economic loss. Flight assignment is an economical and effective strategic plan to reduce the flight delay and airspace congestion by reasonably regulating the air traffic flow of China. However, it is a large-scale combinatorial optimization problem which is difficult to solve. In order to improve the quality of solutions, an effective multi-objective parallel evolution algorithm (MPEA) framework with dynamic migration interval strategy is presented in this work. Firstly, multiple evolution populations are constructed to solve the problem simultaneously to enhance the optimization capability. Then a new strategy is proposed to dynamically change the migration interval among different evolution populations to improve the efficiency of the cooperation of populations. Finally, the cooperative co-evolution (CC) algorithm combined with non-dominated sorting genetic algorithm II (NSGA-II) is introduced for each population. Empirical studies using the real air traffic data of the Chinese air route network and daily flight plans show that our method outperforms the existing approaches, multi-objective genetic algorithm (MOGA), multi-objective evolutionary algorithm based on decomposition (MOEA/D), CC-based multi-objective algorithm (CCMA) as well as other two MPEAs with different migration interval strategies.

* Corresponding author at: School of Electronic and Information Engineering, Beihang University, Beijing 100191, China. Tel.: +86 10 82338626.
E-mail address: zyb@adcc.com.cn (Y. Zhu).
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1. Introduction

In the past decade, the air transportation of the whole world has increased rapidly. The increasing growth of the number of flights in the airspace has caused severe airspace congestion which not only threatens the safety of airspace operation, but also leads to massive economic loss. For instance, the flight

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delay in China has wasted billions of dollars in the past decades.[1,2]

How to reduce the air congestion and flight delay is always the research highlight for researchers from air traffic management.[3] In general, this problem is solved by strategically adjusting the departure time and flight routes of the involved flights to balance the air traffic flow among different sectors. For instance, when a sector is predicted to undergo congestion, the involved flights are delayed at the departure airports or their routes are partly changed in order to avoid aggravating the congestion of this sector. However, the flight assignment problem includes thousands of flights with tightly coupled decision variables and constraints, and it has been proved to be NP hard which is very difficult to deal with.

In the early research, the problem is simplified as a mono-objective instance. The researchers assigned ground delays for flights in single or multiple airports, which is known as ground holding program.[4,5] With the aim to ensure safety and save fuel energy, this strategy transfers the flight time in the air to the delay on the ground by optimizing the departure time for flights. Abad and Clarke proposed a routes assignment method for flights based on mixed integer linear programming to reduce airspace congestion.[6] However, when the number of flights increases, it will provide more flexible solutions for controllers with the consideration of both the time and the space adjustment. Delahaye and Odoni introduced stochastic optimization techniques to optimize the routes and time slots simultaneously.[7] They used genetic algorithm to solve the problem.[8,9] Bertsimas and Patterson presented an efficient deterministic approach with consideration of both the time and route assignment.[10] Sun et al. proposed a large-capacity cell transmission model for air traffic flow management[11–13] and applied integer program to solve it. Recently, the cooperative co-evolution multi-objective algorithm (CCMA) was introduced to resolve the flight assignment problem in a simplified network.[14]

These works only formulate the minimization of the airspace congestion or the flight delay as a mono-objective problem. However, in the real operation, controllers are more likely to seek a good trade-off between the airspace congestion and the flight delay. Hence, Daniel et al. used a multi-objective genetic algorithm (MOGA) to optimize the airspace congestion and flight delays at the same time.[15] Real data in French airspace is used to verify their method. Similar work has been considered using the empirical data of China.[16] However, MOGA is apt to fall into the local optima because of the huge search space.

The parallel evolution algorithms (PEAs) show great superiority when dealing with large-scale combinatorial optimization problems because there are several populations evolving simultaneously. During the evolving process, different populations will exchange individuals, which is called migration.[17–20] The migration interval is a critical problem in PEAs which can affect the solution quality dramatically.[21–23] Currently, the migration interval is considered as a constant.[24,25]

In order to avoid premature and obtain better solutions, we propose a multi-objective parallel evolution algorithm to solve this problem. Firstly, multiple evolution populations are constructed to solve the problem simultaneously to improve the optimization capability. Then, a dynamic migration interval is proposed to improve the efficiency of the cooperation of populations. Finally, the cooperative co-evolution (CC) algorithm combined with non-dominated sorting genetic algorithm II (NSGA-II) is introduced for each population. Experiments with the real air traffic data from the China air route network and daily flight plans show that the proposed approach can improve the solution quality effectively and efficiently, and it is superior to the existing approaches such as the multi-objective genetic algorithm (MOGA), the multi-objective evolutionary algorithm based on decomposition (MOEA/D), CC-based multi-objective algorithm as well as other two MPEAs with different migration interval strategies.

The paper is organized as follows. The problem formulation is described in Section 2. Section 3 presents the framework of the multi-objective parallel evolution algorithm and the dynamic migration interval strategy. Experimental results on the real data of the national route of China are given in Section 4. Finally, we conclude the work in Section 5.

2. Problem formulation

A flight path will be re-arranged with the extra cost as less as possible when congestion happens.[26] Fig. 1 demonstrates how a flight will choose another path. The rectangular airspace includes several sectors and there are several waypoints (circle points) in the sectors. It is supposed that a flight from airport A in the left bottom will fly to airport B in the top right corner. In real operation, the aircraft does not fly along a straight line from A to B. It will fly along the waypoints between airport A and airport B, because a waypoint is a navigation marker and flights need the information, such as the desired track and heading direction, which can be provided by the ground navaids. It is assumed that there are three paths passing through different sectors from A to B in Fig. 1. For example, if congestion in sector 6 becomes severe, then the flight can choose path 3 which does not pass through sector 6.

A flight plan L is previously determined by the air traffic management department, airlines and airports which can be described as follows:

$$L = \{(S_1, T_{\text{in}1}, T_{\text{out}1}),(S_2, T_{\text{in}2}, T_{\text{out}2}), \ldots, (S_k, T_{\text{in}\,k}, T_{\text{out}\,k}), \ldots\} \tag{1}$$

where S_k is the kth sector the aircraft will pass, $T_{\text{in}\,k}$ is the time slot it enters into the sector and $T_{\text{out}\,k}$ is the time slot it leaves the sector.

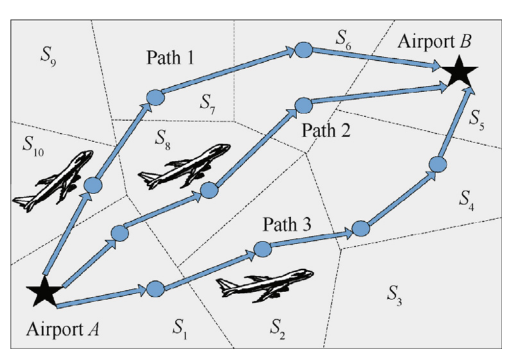

Fig. 1 Description of airspace structure.