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Using computational intelligence for large scale air route networks design

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ABSTRACT

Due to the rapid development of air transportation, Air Route Networks (ARNs) need to be carefully designed to improve both efficiency and safety of air traffic service. The Crossing Waypoints Location Problem (CWLP) plays a crucial role in the design of an ARN. This paper investigates this problem in the context of designing the national ARN of China. Instead of adopting the single-objective formulation established in previous research, we propose to formulate CWLP as a bi-objective optimization problem. An algorithm named Memetic Algorithm with Pull–Push operator (MAPP) is proposed to tackle it. MAPP employs the Pull–Push operator, which is specifically designed for CWLP, for local search and the Comprehensive Learning Particle Swarm Optimizer for global search. Empirical studies using real data of the current national ARN of China showed that MAPP outperformed an existing approach to CWLP as well as three well-known Multi-Objective Evolutionary Algorithms (MOEAs). Moreover, MAPP not only managed to reduce the cost of the current ARN, but also improved the airspace safety. Hence, it has been implemented as a module in the software that is currently used for ARN planning in China. The data used in our experimental studies have been made available online and can be used as a benchmark problem for research on both ARN design and evolutionary multi-objective optimization.

1. Introduction

Due to the increase in air transportation and the limited airspace, how to improve the efficiency and safety of Air Traffic Services has become a major concern to both researchers and practitioners in the Air Traffic Management (ATM) domain. This problem is especially important to China, since the number of flight operations in China has doubled during the past 10 years [1].

Air Route Network (ARN), which determines the routes of every flight traveling from one city to another, is the backbone of ATM. The "hardware" basis of an ARN is the airports and the ground navaids, which have been deployed in advance all over the country. For each flight, the aircraft is required to fly along a sequence of navaids. The navigation system on the aircraft can receive signals from a navaid when approaching it, and thus keeps the pilot informed about the current position of the aircraft. Since the routes for different flights may share a common navaid in an ARN, there is a potential risk that two aircrafts approach the same navaid at the same time. In such a case, a flight conflict or even a collision may occur. Besides, even if two routes do not share a common navaid, it is still possible that the flights on them will come across each other in some region in the airspace. Fig. 1 demonstrates both of the above scenarios. In the ARN, the regions that two aircrafts may encounter each other are denoted as points, and thus are referred to as the Crossing Waypoints (CWs) [2]. The path between a pair of points (either CWs or airports) in the ARN is called an air route. Correspondingly, the path of a flight traveling from one airport to another along the ARN is called its trajectory.

Since the trajectories of all flights are determined based on the ARN, designing the topology of ARN is of great importance to ATM. Determining the location of CWs, which will be referred to as the Crossing Waypoints Location Problem (CWLP) hereafter, is the major step of designing an ARN. In early times, CWs were deployed solely based on human experience since the total numbers of CWs and flights were relatively small. However, with the rapid increase of air traffic demand, the number of CWs in an ARN has increased significantly, and manual design is no longer practical. More important, much more air routes are now sharing common CWs and more potential flight conflicts may emerge. Therefore, the location of CWs must be determined even more carefully than in the past so as to guarantee the airspace operational safety, and an automatic approach to CWLP is in great need.

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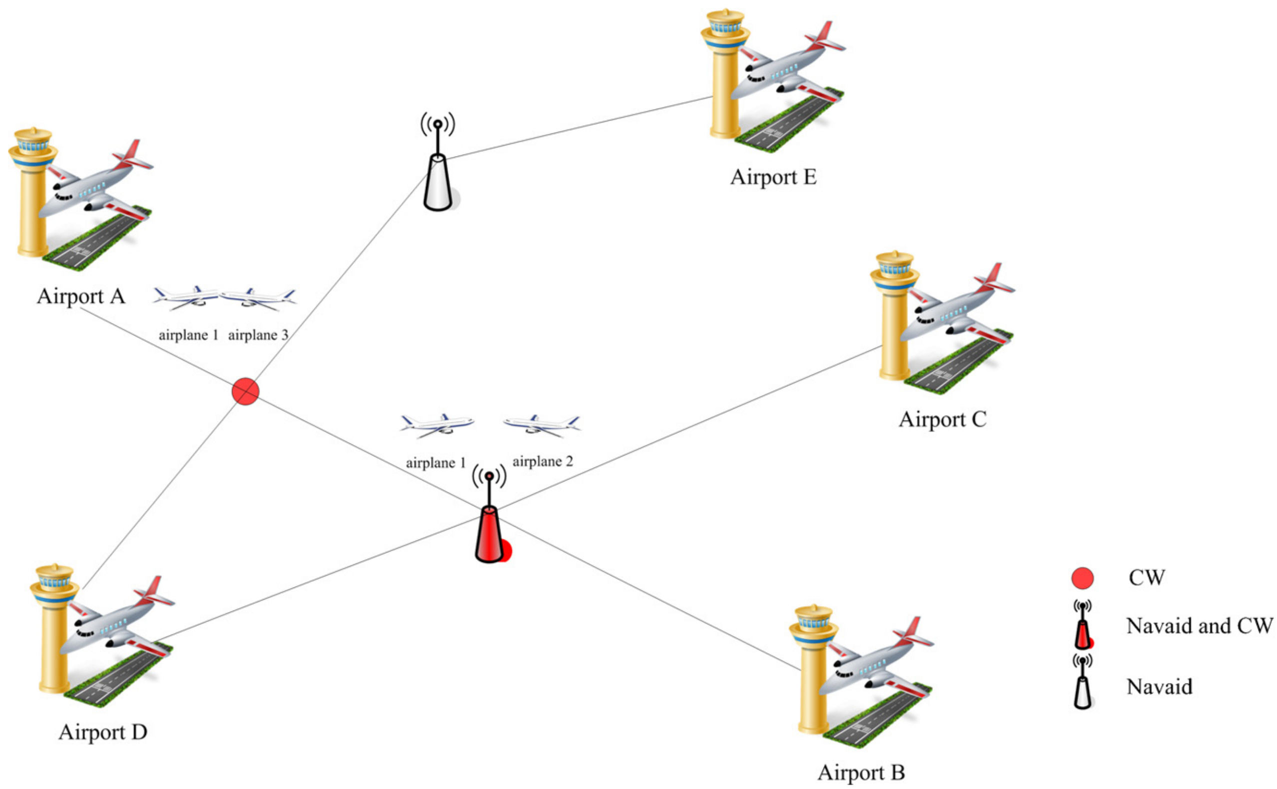

Fig. 1. A demonstration of ARN.

In spite of its importance to the real world, research on CWLP and even the design problem of ARN are still in their infancy. A pioneer work that brought the ARN design problem to academia was conducted by Siddiquee [3]. In that paper, a number of mathematical models were formally established to quantify various attributes of an ARN, such as the number and duration of potential flight conflicts at CWs and the capacity of air routes. These attributes can be employed as criteria for measuring the quality of an ARN, and thus defined the target for later investigations. However, to the best of our knowledge, it was not until recently that some effort had been devoted to developing advanced computational methods to address CWLP. In [4], Mehadhebi proposed an approach in the free route scenario. Aiming at minimizing the total airlines cost subject to the air traffic control constraints, the approach contains two main steps: one is merging two or more CWs, and the other is moving the merged nodes to the optimal locations in order to reduce the density of congested airspace. More recently, Rivière [5,6] introduced Simulated Annealing (SA) algorithm [7] into the design of ARN in the context of Sector-Less ATM. Specifically, SA is employed to fine-tune the positions of CWs so that the total airlines cost is minimized.

This paper investigates the application of computational intelligence approaches to CWLP in the context of real-world ARN design in China. Briefly speaking, an ARN can be defined as a planar graph, the nodes of which represent the airports and the CWs. The edge between a pair of nodes stands for the air route between them, and the trajectory of a flight is denoted by the path connecting the departure airport, the arrival airport, and all the CWs it passes by. CWLP aims at fine-tuning the location of the nodes corresponding to CWs, so that some criterion measuring the quality of the ARN is maximized/minimized. The challenges brought by the CWLP are mainly two-fold: first, a typical CWLP may involve a large number of design variables. For our case, the ARN of China includes more than 100 airports and several hundred CWs (see Fig. 2 for an illustration). When representing it with a planar graph, the position of each CW is defined by two design variables. Hence, the CWLP to be solved is a large scale continuous optimization problem with hundreds of design variables. Second, the objective functions of CWLP are all non-differentiable or even non-continuous [3–6]. Therefore, many conventional optimization techniques that are capable of handling large scale problems (e.g., such as Newton/Quasi-Newton method and conjugate gradient method [8,9]), are not applicable for the CWLP.

The criteria used for measuring the quality of ARNs arise from two major considerations, that is, the operational cost and safety of airspace. For example, total airline cost was employed in both [4] and [5]. In addition, the safety issue has also been taken into account by pre-defining an upper-bound for the flights density at every CW (a criterion measuring the safety at a CW) [4]. Such a scheme may cause difficulties in practice because it is usually hard

Fig. 2. The National Air Route Network of China.