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Hybridized encoding for evolutionary multi-objective optimization of air traffic network flow: A case study on China

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A B S T R A C T

This paper presents a novel hybridized indirect and direct encoding (HybrID) genetic algorithm for solving air traffic network flow optimization problems. A heuristic, which uses the Dijkstra algorithm for generating different types of shortest paths on a graph while controlling the weights on each arc, is proposed for selecting optimal flight routes based on current air traffic. A novel HybrID chromosome representation is employed along with the proposed heuristic and a genetic algorithm for optimization. Experiments on synthetic problems and real data of the Chinese airspace show the proposed method outperforms the direct encoding method on efficiency and efficacy metrics.

1. Introduction

The world air traffic management (ATM) system is undergoing a major reform (ICAO, 2011). Next Generation Air Transportation Systems in the USA (FAA, 2016), European ATM Master Plan in Europe (SESAR, 2015), the work in Australia (Airservices, 2009), China (PRC, 2016), Japan (JCAB, 2010), and Asia/Pacific (ICAO, 2016) are all current examples of international activities aiming at improving the future ATM system.

In air transportation systems, the continued increase of air traffic demand and limited airspace capacity have resulted in severe congestions and delays (Roosens, 2008; Britto et al., 2012). Congestion is a traffic situation that emerges in the airspace (including airports and en route sectors) when traffic demand approaches or exceeds the capacity safety-threshold over a period of time. It can lead to potential violation of separation incidents and safety hazards. Hence, the question of how to alleviate traffic congestion and flight delays over the national airspace to keep all aircraft flying safely and efficiently has become a focal concern to researchers as well as practitioners in the air traffic flow management (ATFM) domain (Vossen et al., 2012; Kistan et al., 2017).

An air traffic network flow optimization (ATNFO) problem (Delahaye et al., 2005; Cai et al., 2017) is a combinatorial optimization problem arising in the ATFM domain that has drawn significant attentions over the years, including recently. It seeks to reduce the occurrence of congestion and delays by optimizing the allocation of airspace resources (e.g., airports, sectors and time-slots) to meet traffic demand. All airports and sectors in an air traffic management system are capacitated entities due to the capacity limitations imposed as a consequence of a number of safety factors including the workload of an air traffic controller (ATCo) (Brooker, 2003). The ATNFO problem can be simply defined as an attempt to construct optimal flight plans for all scheduled flights over a period of time horizon (usually 1–24 h) based on latest known capacity information. Here, a flight plan is a collection of information including flight routes, expected departure time-slot, expected arrival time-slot and expected time-slots of entering and

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exiting sectors. An optimized flight plan can provide support for the decision-making cycle during various ATFM actions, such as ground-delays, rerouting, speed control and airborne-holding, to ensure air traffic safety and efficiency during the tactical phase of operations. The choice of the time window for planning is crucial in practical ATFM situations. If replanning occurs over a short time horizon, it could interfere with tactical ATM decisions by ATCo. However, this issue is outside the scope of this paper since the decision support system proposed in this paper is general enough to accommodate any required time horizon.

In early research, most work in the literature models ATNFO as a single objective optimization problem, considering only flight efficiency (i.e., the less delay, the better) (Agustín et al., 2010; Bertsimas and Odoni, 1997). However, the ATNFO problem, by its very core nature, has at least two conflicting objectives, i.e., minimization of the ATCo workload and minimization of flight delays, which correspond to safety and efficiency, respectively. In theory, the more workload allowed, the more flights could simultaneously fly in an airspace, thus reducing flight delays. Likewise, the more flight delays allowed, the less airspace congestion emerging and less ATCo workload needed. Moreover, the comprehensive quantification of workload is hard to be expressed in a linear function (Delahaye et al., 2005). Hence, a more appropriate formulation of ATNFO problem necessitates the use of a multi-objective nonlinear mathematical model (Delahaye et al., 2005; Xiao et al., 2015; Gardi et al., 2016; Lü et al., 2016; Yan and Cai, 2017; Fadil et al., 2017; Cai et al., 2017). The multi-objective formulation is more desirable as it provides more choices for decision-makers in real-world ATFM situations; thus offering more flexibility and more alternatives to choose from when they need to make hard decisions that trade-off efficiency and workload.

Solving the multi-objective nonlinear ATNFO problem is a challenging task because it essentially consists of two coupled subproblems, i.e., the flight scheduling problem for deciding optimal departure time-slots and flight rerouting problem for deciding optimal flight routes over the airspace. Moreover, a large number of flights over the national airspace need to be optimized, especially during peak hours. Although previous work (Delahaye et al., 2005; Lü et al., 2016; Fadil et al., 2017; Cai et al., 2017) has proposed a bi-objective model considering both flight safety and efficiency, the flight rerouting within a predefined set of routes, without operational information of air traffic, can become a serious limitation for selecting an optimal route for each flight and lead to lower utilization of airspace capacity. In this paper, instead of optimizing the flight route independently by itself, we will evolve the method of selecting the route for each flight, while constraining the choice with other flights routes. A specific heuristic for selecting an optimal flight route based on current traffic situation awareness information in an airspace is designed. In order to obtain Pareto-optimal solutions for the multi-objective nonlinear ATNFO problem, we introduce a hybridized chromosome representation inspired by (Baker et al., 2007; Clune et al., 2011; Ozdamar, 1999) that uses indirect encoding of flight route and direct encoding of departure time-slot. In previous work, flight route is encoded directly as an index (Delahaye et al., 2005; Xiao et al., 2015; Lü et al., 2016) or a probability (Cai et al., 2017), and then selected from a predefined set of routs based on the index or probability without operational information of air traffic. The indirect representation of flight route consists of a sequence of heuristic weight and a timetabling, which together form the basis to schedule flights based on current traffic situation awareness information. Solutions are evolved with Genetic Algorithms (GA) using dominance relations.

The contributions of this paper are threefold. First, a heuristic is designed for routing the aircraft while dynamically constraining the route to previously chosen ones. Second, a novel Hybridized Indirect and Direct Encoding (HybrID) scheme for the ATNFO problem is presented. Third, a large scale case study utilizing real data from the Chinese airspace is presented. Moreover, we point out in the future work section practical implications of this work.

The rest of this paper is organized as follows: Section 2 presents a literature review about ATNFO problem. Section 3 introduces the multi-objective mathematical model of ATNFO problem. Section 4 presents the Hybridized Indirect and Direct Encoding Genetic Algorithm (HybrID-GA) for solving ATNFO problem, including the details of the proposed heuristic for selecting flight routes, solution representation and genetic operators. An experimental study is presented in Section 5 to evaluate the effectiveness of the proposed HybrID-GA algorithm. Finally, Section 6 concludes this paper.

2. Literature review

In early research, air traffic flow optimization was applied to alleviate congestion in airports (Bertsimas and Odoni, 1997; Bertsimas and Frankovich, 2013). With the rapid development of air transportation, it has become difficult in both airport and airspace sector to accommodate the increasing amount of air traffic, leading to an intense air traffic congestion over the air traffic network (ATN). ATN congestion has motivated some research teams to consider the air traffic network flow optimization (ATNFO) problem for real ATFM applications. Here ATN usually refers to a network consisting of airports and sectors.

Bertsimas and Patterson (1998), Bertsimas et al. (2011) pioneered work on classical single-objective linear optimization formulation, in which a basic 0–1 integer programming (IP) model to minimize total flight delay costs by optimizing the departure and arrival time-slots of each aircraft under airports and sectors capacity constraints is introduced. Inspired by the work of Bertsimas and Patterson (1998), Agustín et al. (2012) presented a Mixed 0–1 IP (MIP) model, which considers several types of delay costs to minimize and allows for flight cancellation and rerouting in an ATN, for the ATNFO problem. There are also IP models for the ATNFO problem based on aggregated traffic flow (Sridhar et al., 2008; Work and Bayen, 2008; Sun et al., 2009, 2010), which were solved with the dual decomposition method (Sun et al., 2011). Aggregate traffic flow models describe the evolution of traffic flows rather than individual trajectories, and can capture traffic patterns in a tractable manner. Employing such aggregate flow models can reduce the problem dimension, but will lose individual flight's information (Work and Bayen, 2008). Additional research is needed to translate problem solutions into actual ATFM flight planning decisions involving aircraft departure times and routes. Currently, there is limited research on the application of aggregate and reduced order flow models for generating ATFM decisions (Sridhar et al., 2008). Rebollo and Cruz (2009) have presented a new hybrid demand and capacity balance model using a flow-based approach for