ARTICLE IN PRESS

Transportation Research Part C xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Metaheuristics for efficient aircraft scheduling and re-routing at busy terminal control areas

Marcella Samà [a], Andrea D'Ariano [a,*], Francesco Corman [b], Dario Pacciarelli [a]

[a] Roma Tre University, Department of Engineering, Section of Computer Science and Automation, via della Vasca Navale, 79, 00146 Rome, Italy

[b] Delft University of Technology, Department of Maritime and Transport Technology, Section of Transport Engineering and Logistics, Mekelweg, 2, 2628CD Delft, The Netherlands

ARTICLE INFO

Article history:
Received 16 January 2015
Received in revised form 14 June 2016
Accepted 22 August 2016
Available online xxxx

Keywords:
Optimal air traffic control
Landing and take-off operations
Disruption management
Disjunctive programming
Variable neighbourhood search
Tabu search
Hybrid algorithms

ABSTRACT

Intelligent decision support systems for the real-time management of landing and take-off operations can be very effective in helping air traffic controllers to limit airport congestion at busy terminal control areas. The key optimization problem to be solved regards the assignment of airport resources to take-off and landing aircraft and the aircraft sequencing on them. The problem can be formulated as a mixed integer linear program. However, since this problem is strongly NP-hard, heuristic algorithms are typically adopted in practice to compute good quality solutions in a short computation time. This paper presents a number of algorithmic improvements implemented in the AGLIBRARY solver (a state-of-the-art optimization solver to deal with complex routing and scheduling problems) in order to improve the possibility of finding good quality solutions quickly. The proposed framework starts from a good initial solution for the aircraft scheduling problem with fixed routes (given the resources to be traversed by each aircraft), computed via a truncated branch-and-bound algorithm. A metaheuristic is then applied to improve the solution by re-routing some aircraft in the terminal control area. New metaheuristics, based on variable neighbourhood search, tabu search and hybrid schemes, are introduced. Computational experiments are performed on an Italian terminal control area under various types of disturbances, including multiple aircraft delays and a temporarily disrupted runway. The metaheuristics achieve solutions of remarkable quality, within a small computation time, compared with a commercial solver and with the previous versions of AGLIBRARY.

1. Introduction

1.1. The investigated problem

The ever increasing level of air traffic flows poses a difficult challenge for air traffic controllers, that work to ensure the safety and efficiency of operational schedules. This is a difficult task, particularly in bottleneck areas, and the SESAR project and CDM compliance (Eurocontrol, 2011; SESAR, 2015) are pushing for the implementation and use of automated traffic control systems. One typical bottleneck of the entire air traffic system is the Terminal Control Area (TCA). During operations, aircraft delays are considered to cause a substantial cost from both airlines and passengers' points of view. The computation

* Corresponding author.
E-mail address: dariano@ing.uniroma3.it (A. D'Ariano).

http://dx.doi.org/10.1016/j.trc.2016.08.012
0968-090X/

of optimal aircraft landing and take-off schedules is thus one of the most relevant operational problems. These facts stimulated the interest for effective intelligent transport system solutions that can show how to better use the existing resources (Zhang, 2008).

This paper aims to improve substantially the quality of solutions, in terms of value of the objective function and computation time, for the Air Traffic Control in a Terminal Control Area (ATC-TCA) problem. The investigated problem consists of simultaneously determining the routing (i.e. the resources to be traversed), sequencing (i.e. the orders between aircraft in each resource) and timing of landing and take-off aircraft on the TCA resources, which may include several runways and air segments. While there is no generally recognized objective function in the literature (Samà et al., 2016), this paper considers a relevant objective function that aims to minimize the maximum positive deviation from the target landing and take-off times.

The resolution of air traffic control problems requires to consider several factors related to safety, efficiency and equity. In this work, safety requires the careful modelling of practical TCA constraints, efficiency consists of reducing aircraft delays with global conflict detection and resolution approaches, equity is achieved by minimizing the largest delay due to the resolution of conflicts. These factors require to consider the routing, sequencing and timing of all aircraft moving in the network during the studied traffic horizon. Further relevant safety, efficiency, equity, and even environmental impacts are addressed, e.g., in Soomer and Franx (2008), Soomer and Koole (2008), and Solveling et al. (2011).

1.2. The related literature

In the aircraft scheduling literature, it is often mentioned a big gap existing between the level of sophistication of published results and algorithms, and the simple methods that are employed in practice. One motivation reported for this gap is that the theory typically addresses very simplified problems for which (near-) optimal performance can be achieved, while the practice must face all the complexity of real-time operations. However, poorly performing aircraft scheduling and routing methods that are used in practice directly impact the quality of service offered to the passengers, the effect being more evident as traffic density gets close to saturation. In fact, any small disturbance related to few aircraft may propagate to the other aircraft, altering the regularity of air traffic even some hours after the end of the original disturbance.

There is a recent trend of research to incorporate more practical objectives and constraints in the detailed (microscopic) models that have not been adequately captured in published models, since too simplified (macroscopic) models may have a limited impact on the practice of air traffic control. In view of the extensive reviews reported in Ball et al. (2007), Barnhart et al. (2012), Bennell et al. (2011), Kohl et al. (2007), Kuchar and Yang (2000), and Pellegrini and Rodriguez (2013), we limit our review of the recent related literature to two streams of research: (i) the development of microscopic models for the management of aircraft flows in terminal control areas and (ii) the development of algorithmic methods for solving the models of stream (i).

Regarding stream (i), there are a few microscopic models that incorporate the detailed characteristics of the airport infrastructure and of the individual flight paths. Such a level of detail is required to safely detect and solve potential conflicts at the level of runways, ground and air segments of the TCA. The most detailed model used in this context is the job shop scheduling model in which each *operation* denotes the traversal of an air/ground segment, runway (*resource*) by an aircraft (*job*). The variables are the start time of each operation to be performed by an aircraft on a specific resource. A *no-wait* version of this model has been firstly proposed in Bianco et al. (2006) and successively extended in D'Ariano et al. (2015, 2012), Mascis and Pacciarelli (2002), and Samà et al. (2014) as a *blocking and no-wait* version. In the latter approach, air segment resources are treated as no-wait resources with time windows for modelling minimum/maximum aircraft travel times, while runway resources are treated as blocking resources which can host at most one aircraft at a time. Objective functions are based on a makespan minimization.

Regarding stream (ii), exact and heuristic algorithms have been proposed for the ATC-TCA problem. Among the literature on exact algorithms, Psaraftis (1978) and Balakrishnan and Chandran (2010) propose a combination of the constrained position shifting approach (originally introduced by Dear (1976)) and of the dynamic programming approach to solve aircraft sequencing and runway scheduling problems, D'Ariano et al. (2015) describe a branch and bound algorithm for the aircraft scheduling problem with fixed routes, Faye (2015) present a dynamic constraint generation algorithm for an aircraft landing problem. However, exact algorithms can quickly compute near-optimal solutions only for quite small instances or simplified problems. Consequently, numerous metaheuristics have been recently proposed to search for good quality solutions in a short computation time, the most used being the following: genetic algorithms (Beasley et al., 2001; Hu and Chen, 2005; Hu and Di Paolo, 2008, 2009), scatter search (Pinol and Beasley, 2006), tabu search (Atkin et al., 2007; D'Ariano et al., 2012; Furini et al., 2015; Samà et al., 2014), ant colony (Jiang et al., 2014; Zhan et al., 2010), simulated annealing (Hancerliogullari et al., 2013; Salehipour et al., 2013), variable neighbourhood search (Alonso-Ayuso et al., 2015; Salehipour et al., 2013, 2009). Several of the proposed algorithms have also been hybridized in order to combine interesting properties and to take the best from each of them. Furthermore, some approaches (e.g., Furini et al., 2015; Hu and Chen, 2005; Hu and Di Paolo, 2008, 2009; Murça and Müller, 2015; Samà et al., 2014; Zhan et al., 2010) have been implemented in a rolling horizon (or receding horizon) control framework in order to solve large instances in a short computation time compatible with real-time applications, and to deal with the dynamic and uncertain nature of the ATC-TCA problem. All these approaches have proposed significant improvements compared to the commonly used air traffic control rules, such