Transportation Research Part E 73 (2015) 96–113

Contents lists available at ScienceDirect

Transportation Research Part E

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

Control-based optimization approach for aircraft scheduling in a terminal area with alternative arrival routes

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ARTICLE INFO

Article history:
Received 16 May 2014
Received in revised form 15 October 2014
Accepted 17 November 2014
Available online 11 December 2014

Keywords:
Air traffic flow management
Air traffic control
Arrival scheduling
Optimization
Decision support tool

ABSTRACT

This paper presents an optimization approach for dynamically scheduling aircraft operations and supporting air traffic controllers in both determining and implementing operationally feasible landing and departure times at an airport. The mixed integer linear programming model proposed incorporates air traffic control infrastructure in terms of route network, introduces the concept of alternative approach routes and is designed to generate an output that can be converted into effective advisories for executable flight commands. It shows reasonable computational times for obtaining the optimal solution and delay reductions of up to 35% with practical size instances from Sao Paulo/Guarulhos International Airport.

1. Introduction

As a component of air traffic control systems worldwide, air traffic flow management (ATFM) has the primary objective of preventing local demand-capacity imbalances by adjusting the flows of aircraft at one or more elements of the system. It has been receiving much attention lately since it appears as a prominent way to reduce congestion in cases where there is no more room for common solutions such as expanding airport infrastructure. In this context, mathematical models have been developed over the years for assisting the establishment of ATFM strategies and generating benefits for the airspace users (Odoni, 1987; Vranas et al., 1994; Bertsimas and Patterson, 1998; Bertsimas et al., 2011; Frankovich, 2012). For this, these models should target three main objectives: reducing congestion and delays, being computational tractable and effectively supporting decision making. These objectives compose what we call sustainability tripod of ATFM models.

According to Ball et al. (2007), the sequencing of arrival aircraft at an airport composes the group of the most important types of control actions for developing and implementing ATFM strategies. At this tactical stage, the air traffic controllers must organize the flow coming from different locations of the airspace and sequence the aircraft towards the runway quickly, efficiently and safely, ensuring the regulated separation between aircraft. This task can be very complex and demanding since the arrival flow is essentially a random process (Willemain et al., 2004) and air traffic controllers have in general a short time frame in which they must determine and transmit control actions so as to perform the sequencing.

The development of models for sequencing and scheduling aircraft landings have been discussed in the literature since 1980s. However, few studies have been conducted under the sustainability tripod mentioned above, especially because of the usual disregard of the third dimension of objective. It is noticeable that many models leave aside the control problem

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http://dx.doi.org/10.1016/j.tre.2014.11.004
1366-5545/

associated with the sequencing and scheduling or neglect the dynamic environment where the decision needs to be taken. As a result, the operational feasibility of the output and the effectiveness of the approach as a real time decision support tool for air traffic control bodies are seriously affected. Some works have tried to overcome these problems by introducing real-world constraints such as landing time windows and precedence restrictions (Beasley et al., 2000; Balakrishnan and Chandran, 2010; Eun et al., 2010) or developing approaches for dynamically handle the process (Beasley et al., 2004; Saraf and Slater, 2006; Samà et al., 2013). However, neither of them introduces enough flexibility for assisting air traffic controllers in establishing usual control actions (other than holding pattern or speed adjustment) during the approach to the airport.

In this work, in accordance with the modeling proposed by Murça (2013), we developed a mixed integer linear programming model for aircraft sequencing and scheduling for landing that incorporates the problem of controlling the traffic flow towards an airport through specific terminal arrival routes. Also, we developed a dynamic approach for running the model that can be used in a real-time implementation. The model seeks to minimize the deviations from the target landing time by determining discrete delays and time advances associated with the execution of alternative arrival routes or holding procedures so that separation is ensured between all aircraft. To the best of our knowledge, this is the first optimization approach that ties the arrival sequencing and scheduling to the configuration of the terminal area in terms of approach routes. A real case study for the Sao Paulo/Guarulhos International Airport in Brazil exemplifies how helpful this approach can be in assisting the establishment of control actions to the arrival flights in the terminal area by air traffic controllers.

The detailing of the work is presented in this paper as follows. Section 2 presents a literature review about the arrival sequencing and scheduling problem. The mathematical model formulation, the dynamic approach, the case study and the optimization methodology are presented in Section 3. Section 4 presents and discusses the results of the optimization run under the sustainability tripod viewpoint. Finally, the conclusions of the work are presented in Section 5.

2. Literature review

The sequencing and scheduling of landings at an airport is one of the ways to improve the management of aircraft queues in a congested terminal area. It has to be accomplished under impacting operating conditions such as the criteria of separation between aircraft, the criteria of sequencing and the runway system configuration. The criterion of separation between aircraft is a safety requirement and it usually depends on the wake turbulence categories of the leading and trailing aircraft. The criterion of sequencing determines how flexible the management of the aircraft queue will be. A "first come, first served" strategy is commonly used which means that an aircraft with an earlier estimated time of arrival at a metering point (for example, the runway threshold) will land first. Finally, the runway system configuration determines whether departures have to be taken into consideration in the arrival problem. For example, in case of runways with mixed operations, the departure flights need to be inserted into the landing queue with appropriate separations.

Guided by these operating conditions, the establishment of sequencing and scheduling decisions is accomplished through control actions emitted by air traffic controllers to aircraft during the approach to the airport through Standard Terminal Arrival Routes (STAR) or even in route before entering the terminal area. Speed adjustment, airborne holding and vectoring are the most common practices for managing the arrival flow. It is observed that hardly ever only one type of control action is used to organize the traffic because of the concern of not much affecting the aircraft performance. Sometimes, the ability of the air traffic controller in vectoring and moving aircraft through shortened or lengthened arrival routes instead of just commanding a holding procedure generates significant savings in travel time and fuel consumption.

The aircraft sequencing and scheduling problem has been widely addressed in the literature since 1980s, either taking or not into account all the facets above mentioned. Analyzing the major differences between the works, it is possible to identify four topics of distinction: methodology, scope, objective and environment.

Regarding methodology, analytical models of mathematical programming, heuristics and simulation models are the most common methodological approaches used. Bennell et al. (2011) performed a detailed literature review on the topic and observed that the core solution techniques include dynamic programming, branch and bound, heuristics and meta-heuristics. Some of these methodological approaches are discussed below.

Andreussi et al. (1981) used simulation models to evaluate different sequencing strategies at Rome terminal area. For this, they modeled the terminal area considering a structure based on a variable number of feeder fixes and alternative approach paths from these fixes to the runways. When an aircraft gets to the feeder fix, the model takes one of three decisions as follows: keeping the aircraft at the feeder fix by a holding procedure, releasing the aircraft so that it performs a standard approach procedure to the airport or releasing the aircraft so that it performs an alternative approach procedure to the airport. The decision to be taken depends on the existence of slot for landing that ensures the regulated separations, the priority class of the aircraft (in terms of fuel consumption, number of passengers, etc.) and the amount of delay that the aircraft has already accumulated. D'Ariano et al. (2010) and D'Ariano et al. (2012) considered a similar structure of terminal area and formulated the problem of rerouting and scheduling aircraft landings using alternative graph formulations. Rome terminal area was also used as case study. D'Ariano et al. (2010) used scheduling rules, heuristic and exact methods for solving the problem. D'Ariano et al. (2012) focused on developing a tabu search algorithm and showed its effectiveness in reducing delays and travel times when compared to heuristics and exact methods.

Dear and Sherif (1989, 1991) developed an algorithm based on Constrained Position Shifting (CPS) to establish the sequence of aircraft for landing. Considering a landing sequence based on the "first-come, first served" (FCFS) principle with