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 respect to the arrival at the runway, no aircraft will be assigned to land more than a pre-specified number of positions (forward or backward) from its FCFS position. This pre-specified number of positions is known as Maximum Position Shift (MPS). They used fast-time simulation to perform the analysis and concluded that adopting a sequencing strategy based on the CPS concept instead of the FCFS principle tends to generate better solutions in terms of total delay, especially at peak hours and for heterogeneous fleets.

Balakrishnan and Chandran (2006, 2010) also developed algorithms based on the CPS concept for scheduling runway operations. They included various operational considerations such as time window restrictions and precedence constraints and used dynamic programming on a CPS network to solve the problem. They also presented algorithms for the problem of mixed operations, with simultaneous arrival and departure scheduling on a single runway, and showed that it is possible to achieve computational tractability.

Some studies handled the aircraft sequencing and scheduling problem as a job-shop scheduling problem (problem of sequencing a group of jobs in a group of machines), with setup, processing and release times (Bianco and Bielli, 1993). The processing time, for example, could be the separation in time required for the machine (runway) to operate another job (aircraft landing) and a common objective is to minimize the makespan.

Beasley et al. (2000) developed a detailed optimization approach through a mixed integer linear programming model. Basically, the model seeks to determine a landing time for each aircraft in a set of aircraft such that each aircraft lands within a predetermined time window and that separation criteria between aircraft are respected. The target (preferred) landing time of an aircraft results from a flight at an optimal speed profile, in other words, a flight that is the most economical. So, any deviation from its target landing time increase costs and should be avoided. Since air traffic controllers are responsible to ensure a safe aircraft flow that respects the regulated separation between aircraft, they may require the planes to slow down, speed up or hold, generating deviation of the actual landing time from the target landing time. The aircraft sequencing and scheduling problem modeled by Beasley et al. (2000) can be viewed as a decision-making problem that seeks to optimize the air traffic controllers' actions related to speed adjustment such that the cost resulting from the deviation of the actual landing time from the target landing time is minimized. This approach was implemented by Dias et al. (2011) for scheduling arrival flights at SBGR through the establishment of a required time of arrival at a metering fix and showed a significant potential for reducing delays.

Still from the optimization viewpoint, some recent works have focused on the mathematical modeling improvement for better representing the problem. Eun et al. (2010) used discrete delays as decision variables in order to enhance the range of executable flight commands. Mesgarpour et al. (2010) considered a multi criteria objective function that seeks to minimize the average delay, to maximize the runway throughput and to minimize the fuel consumption. They also introduced constraints related to CPS and to airline precedence. Tavakkoli-Moghaddam et al. (2012) used a fuzzy approach to deal with two conflicting objectives: the minimization of the deviation of the actual landing time from the target landing time and the minimization of the runway usage to process the whole sequence of landings. Since the problem is NP-hard, a number of heuristics and meta-heuristics, such as simulated annealing (Salehipour et al., 2013), genetic algorithm (Liu, 2010), ant colony optimization (Zhan et al., 2010) and tabu search (D'Ariano et al., 2012), have been tested for generating near-optimal solutions with smaller computational time.

The second topic of distinction is scope. While some works are specifically focused on the runway operations such as those that handle the problem as a job-shop scheduling problem, others incorporate more elements of the infrastructure and take into account, for example, the operations in the airspace. When the infrastructure is looked into with much more detail, simulation models tend to be used (Andreussi et al., 1981).

With respect to objective, once the air traffic control can be seen from the perspective of service providers and from the perspective of users, the aircraft sequencing and scheduling problem can be analyzed under different viewpoints with different goals. A goal commonly pursued by the service providers is to maximize the processing capacity of the runway system, in other words, to maximize the number of operations that can be accommodated in the runway per unit of time. This can be achieved by scheduling the landing time of the last aircraft as early as possible (Dear and Sherif, 1989, 1991; Bianco and Bielli, 1993; Balakrishnan and Chandran, 2006, 2010). From the point of view of users, the minimization of the total costs, which include the cost of waiting for obtaining the service, is a more appropriate goal (Beasley et al., 2000; Eun et al., 2010).

Finally, the fourth topic of distinction is environment. It is related to the extent in which operating constraints are introduced in the model and to the temporal context in which decisions need to be taken (static or dynamic). Preliminary works usually disregard some important real-world operating restrictions such as landing time windows, precedence and mixed operations. This may seriously affect the operational feasibility of the model output and the effectiveness of the approach as a decision support tool. Recent works have tried to overcome this problem by introducing constraints associated with landing time windows and precedence (Beasley et al., 2000; Balakrishnan and Chandran, 2006; Eun et al., 2010) and incorporating departure flights for the case of mixed operations (Balakrishnan and Chandran, 2010). Regarding the temporal context, the approaches are static or dynamic. In the static case, the set of aircraft that are going to land are well known. On the other hand, in the dynamic case, the landing times are updated as time passes and the set of aircraft changes (while some planes land, others appear, etc.). If the goal of the model development is essentially for decision support in the tactical stage, it is essential to handle the problem dynamically. In general, the dynamic nature of the aircraft sequencing and scheduling problem is addressed through concepts such as scheduling window and freeze horizon, as observed in the works of Brinton (1992), Wong (2000), Saraf and Slater (2006), Eun et al. (2010) and Zhan et al. (2010). According to Brinton (1992), the basic idea of these concepts is as follows: if the estimated time of arrival of an aircraft at a particular reference fix is later than the freeze horizon and within the scheduling window, then that aircraft is considered active for scheduling. On the other hand, if the estimated time of arrival falls below the freeze horizon, the scheduled time of arrival is frozen and that aircraft is no longer considered in the list of aircraft that can have a new sequence position and arrival time assigned at each update. This idea is also similar to the rolling horizon approach developed by Samà et al. (2013).

The above literature shows that although some works were concerned about introducing more real-world operating constraints and considering the dynamic environment in which decisions are made, neither of the analytical models incorporates the control problem that happens during the approach to the airport. The work of Eun et al. (2010) was the first to be concerned about enhancing the range of control actions in order to increase the effectiveness of the model in generating advisories for air traffic controllers. For this, they used discrete delays as decision variables, but they did not tie these decision variables to specific executable flight commands. In this work, 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. The model also incorporates operating constraints related to landing time windows and precedence, addresses the case of mixed operations by the introduction of departures and can be optimized under a dynamic environment.

It is worth mentioning that the more detailed the approach in terms of incorporating infrastructure and operating constraints, the more realistic (in the sense it is closer to the actual way operations take place) and the more effective in assisting decision making it is. Also, it tends to be more flexible since it better reflects the preferences of the users. On the other hand, it tends to be more computational intensive and may become mathematically intractable. Therefore it is important the compromise of achieving a balance between the objectives within the sustainability tripod of ATFM models.

In short, it is possible to observe that the major limitations in the current literature of arrival sequencing and scheduling are related to the following issues:

- *Operating constraints:* How to incorporate specific real-world constraints without affecting the computational tractability?
- *Dynamic environment:* How to model the dynamic environment where decisions need to be taken under uncertainty?
- *Air traffic control infrastructure:* How to ensure the operational feasibility of the solutions and enhance decision support?

This paper intends to contribute to the literature of arrival sequencing and scheduling on the third issue by developing a model that incorporates the air traffic control system infrastructure in terms of route network and control actions. In other words, the proposed approach for the arrival sequencing and scheduling problem introduces the associated control problem that happens during the approach to the airport, being designed to generate a solution that supports both the establishment and the implementation of sequencing and scheduling decisions. It means that not only the landing time is a concern, as in the previous works, but also the manoeuvres that are necessary for achieving it. In order to account for these manoeuvres, we also introduced the concept of alternative approach routes in the arrival procedure.

3. Methodology

3.1. Mathematical programming model

As described before, the problem of aircraft sequencing and scheduling for landing is analyzed through an optimization approach in this work. Since each aircraft has to perform a specific approach route to arrive at the destination airport (STAR), the model proposed attempts to encompass part of the associated control problem taking into account these arrival routes. More specifically, a mixed integer linear programming model was developed, which seeks to minimize the cost of the deviation of the actual landing time from the target landing time in determining how each aircraft will perform the arrival route to the airport so that the separation between aircraft on final approach is guaranteed. In other words, the model determines the discrete delays or time advances associated with alternative arrival routes and/or holding procedures that must be imposed to each aircraft in order to avoid a conflict. It is interesting to observe that the idea of this mathematical programming modeling is similar to the airspace structure designed by Andreussi et al. (1981) in their fast-time simulation model. They considered alternative approach routes from the feeder fix to the runway which generated delays with a range of one to five minutes in order to organize the traffic flow.

A STAR usually consists of a fixed number of waypoints and routes linking these waypoints. So, the landing time of an aircraft is the time it passes over the first waypoint of the STAR plus the time spent to traverse the whole arrival route. We considered that the time spent to traverse the STAR is the sum of the standard time spent if a continuous descent approach is performed with discrete delays or discrete time advances resulting from controllers' actions to guarantee the regulated separation between aircraft. These discrete delays or discrete time advances are associated with either alternative arrival routes or holding procedures that can be performed by an aircraft. The type of the arrival route and the number of holding procedures are a controller's decision that impacts the landing time and that is what we aim to optimize.

Here the major difference of the model proposed in respect to the model of Beasley et al. (2000) is noticeable. While the landing times are continuous decision variables in their model, in the model proposed they result from discrete decision variables associated with how an aircraft will perform the approach to the destination airport. Thus, there is a broader flow management conception in terms of implementation, which can even be complementary to a management conducted outside the terminal area.

3.1.1. Notation

Let A be the set of landing aircraft ($i, j \in A$) and B the set of departure aircraft ($q, r \in B$) that use the same runway system of an airport. Due to safety issues, there are specific separations that must be ensured between aircraft. For arrival flights, consider that S^A_{ij} is the required separation in time between aircraft i and j if i lands before j. For departure flights, consider that S^D_{qr} is the required separation in time between aircraft q and r if q takes off before r. For an arrival–departure pair of aircraft, consider that S^{AD}_{iq} is the required separation in time between aircraft i and q if the landing i happens before the takeoff q. In other words, if there is an arrival aircraft i on final approach (after the final approach fix), the departure flight q must wait at least S^{AD}_{iq} units of time before taking off. All these separations must be ensured by air traffic control through a range of control actions that may impose airborne discrete delays or time advances to arrival flights and discrete delays on the ground prior to takeoff to departure flights. As a consequence, these actions generate deviations of the actual landing/departure time from the target landing/departure time, which results from a flight without any interference of air traffic control, in other words, which would ideally occur if there were not any other aircraft in the airspace. Let t^A_{if} be the actual time of arrival of aircraft i at the final waypoint f, t^D_q the actual time of departure of aircraft q, T^A_{if} the target time of arrival of aircraft i at the final waypoint f and T^D_q the target (preferred) time of departure of aircraft q.

The range of control actions that can be performed by the air traffic control depends on the infrastructure of the system, especially in terms of route network. In order to land at the airport, there are specific approach routes that must be followed by the flights. Let Π be the set of initial approach fix of these routes ($x \in \Pi$) and let f be the final approach waypoint of these routes (the last waypoint before landing). Depending on the airway where the flight is evolving, a specific approach route (usually the closest one) tends to be used. Let p_{ix} be a parameter that is equal to one if aircraft i performs the approach route that starts at waypoint x and is equal to zero otherwise. In other words, this parameter identifies which approach route will be used by each flight. Consider that the approach routes have a set K of alternative paths that generate a lengthened arrival route ($k \in K$) and a set M of alternative paths that generate a shortened arrival route ($m \in M$). Imposing an alternative path to an arrival aircraft is one of the options used by the controllers to manage the traffic and establish the separations between the flights. Let d^+_{ik} be the discrete delay imposed to arrival aircraft i if it traverses alternative path k and d^-_{im} the discrete time advance imposed to arrival aircraft i if it traverses alternative path m. Controllers may also impose holding procedures and ground holding to arrival and departure flights, respectively. Let d^h_i be the discrete delay imposed to arrival aircraft i if it performs a holding procedure and d^{gh}_q the discrete delay imposed to departure aircraft q if it performs one ground holding period. Moreover, let n^A_i be the maximum number of holding procedures performed by aircraft i and n^D_q the maximum number of ground holding periods performed by aircraft q. They establish the upper limit on the delay amount that can be imposed to a flight through these control actions.

Finally, the delays and time advances that are imposed to aircraft through control actions generate costs that are associated with the extent in which the actual operations deviate from what has been scheduled. Let c^1_i be the penalty cost per unit of time for delays through alternative paths for aircraft i, c^2_i the penalty cost per unit of time for time advances through alternative paths for aircraft i, c^3_i the penalty cost per unit of time for delays through holding procedures for aircraft i and c^4_q the penalty cost per unit of time for ground delays for aircraft q.

3.1.2. Decision variables

The decision variables are linked to the delays and time advances that the air traffic control needs to apply in order to ensure the separations between the flights. In the case of arrival flight, they are associated with how an aircraft will perform the approach to the destination airport in terms of sequencing and route. In the case of departure flight, they are associated with the departure sequencing and with the ground delays that can be imposed prior to takeoff. They are given below.

$$\delta_{ij} = \begin{cases} 1, & \text{if aircraft } i \text{ lands before aircraft } j \\ 0, & \text{otherwise} \end{cases}$$

$$\gamma_{qr} = \begin{cases} 1, & \text{if aircraft } q \text{ takes off before aircraft } r \\ 0, & \text{otherwise} \end{cases}$$

$$\lambda_{iq} = \begin{cases} 1, & \text{if the landing } i \text{ happens before the takeoff } q \\ 0, & \text{otherwise} \end{cases}$$

$$w_{ik} = \begin{cases} 1, & \text{if aircraft } i \text{ traverses the alternative path } k \\ 0, & \text{otherwise} \end{cases}$$

$$u_{im} = \begin{cases} 1, & \text{if aircraft } i \text{ traverses the alternative path } m \\ 0, & \text{otherwise} \end{cases}$$

V_i – number of holding procedures performed by aircraft i

Z_q – number of ground holding periods performed by aircraft q

3.1.3. Objective function

The objective function adopted for the proposed model maintains the main idea of the model conceived by Beasley et al. (2000) in the sense that any deviation of the actual operations in relation to the scheduled operations generates costs and should be avoided. Since the target time of arrival/departure results from a flight without any interference of air traffic control and that strictly follows what has been scheduled, a suitable objective to be pursued is the minimization of the cost related to the deviation of the actual time of arrival/departure from the target time of arrival/departure. In other words, the objective function is given by the minimization of the cost of delays and discrete time advances that are imposed to aircraft either in the approach route or on the ground, as shown in Expression (1).

It is worth mentioning that the choice of objective function is of great discussion in the literature because it relies on perspectives and interests of various players. The objective function in Expression (1) better represents the user's perspective and interest in the individual flight costs and it tends to be used when the scheduling is more tactical than strategic. However, other objective functions or even multi objective functions may be used with the model in order to reflect the preferences of other players. As an example, an objective function that has also a strategic concern of maximizing the runway system processing capacity through better scheduling could be of great interest for airport operators.

$$\text{Min}\ \left(\sum_{i\in A}\sum_{k\in K} c_i^1 w_{ik} d_{ik}^+ + \sum_{i\in A}\sum_{m\in M} c_i^2 u_{im} d_{im}^- + \sum_{i\in A} c_i^3 v_i d_i^h + \sum_{q\in B} c_q^4 z_q d_q^{gh}\right) \tag{1}$$

3.1.4. Constraints

The constraints of the model are given by Expressions (2)–(16). As well as the constraint given by Expression (2) defines the actual time of arrival as the sum of the target time with discrete delays or discrete time advances resulting from controllers' instructions in terms of either alternative paths or holding procedures, the constraint given by Expression (3) defines the actual time of departure as the sum of the target time of departure with discrete ground delays. The constraint given by Expression (4) ensures that, for each pair of aircraft (i, j), just one of these conditions happens: i lands before j or j lands before i. It is worth observing this constraint addresses any precedence between i and j and not just immediate precedence. The constraint given by Expression (5) ensures that for each pair of aircraft (q, r), only one of the following situations occurs: q takes off before r or r takes off before q. Likewise, the constraint given by Expression (6) ensures that for each pair of aircraft (i, q), only one of the following situations occurs: i lands before the takeoff q or q takes off before the landing i. The constraint given by Expression (7) imposes the FCFS principle in respect to the runway threshold (an aircraft lands before other aircraft if its target time of arrival at the runway threshold is earlier than the other's) for sequencing the aircraft in the same STAR (same initial approach fix – IAF), in other words, overtakes are not allowed. The constraint given by Expression (8) imposes that each aircraft can perform the standard approach route with no alternative paths or with just one alternative path of either lengthening or shortening. The constraints given by Expressions (9) and (10) establish that the longitudinal separation between aircraft is ensured for each pair of aircraft and for any landing sequence. If aircraft i lands before aircraft j, Expression (10) is naturally satisfied since N is a large number and Expression (9) ensures the separation between i and j. On the other hand, if aircraft j lands before aircraft i, Expression (9) is naturally satisfied and Expression (10) ensures the separation between i and j. The constraints given by Expressions (11) and (12) ensure that the separation between departures is met for each pair of aircraft whatever the takeoff sequence. The constraints given by Expressions (13) and (14) ensure the separation between arrivals and departures regardless the precedence between them. Finally, the constraint given by Expression (15) imposes a maximum number of holding procedures that can be performed by each aircraft and the constraint given by Expression (16) imposes a maximum ground delay that can be applied to takeoffs. It is important to notice that even though there is not any explicit constraint related to the landing time window of each aircraft, there is an upper limit for the landing time imposed by the maximum number of holding procedures and by the set of discrete delays used in the model and there is a lower limit for the landing time imposed by the set of discrete time advances used in the model.

$$t_{if}^A = T_{if}^A + \sum_{k\in K} w_{ik} d_{ik}^+ - \sum_{m\in M} u_{im} d_{im}^- + v_i d_i^h,\ \text{for}\ \forall i \in A \tag{2}$$

$$t_q^D = T_q^D + z_q d_q^{gh},\ \text{for}\ \forall q \in B \tag{3}$$

$$\delta_{ij} + \delta_{ji} = 1,\ \text{for}\ \forall i,j \in A \tag{4}$$

$$\gamma_{qr} + \gamma_{rq} = 1,\ \text{for}\ \forall q,r \in B \tag{5}$$

$$\lambda_{iq} + \lambda_{qi} = 1,\ \text{for}\ \forall i \in A, \forall q \in B \tag{6}$$

$$\delta_{ij} = 1, \text{ for } \forall i,j \in A \text{ such that } T_{if} < T_{jf} \text{ and } p_{ix} = p_{jx}, \text{ for } \forall x \in \Pi \tag{7}$$

$$\sum_{k \in K} w_{ik} + \sum_{m \in M} u_{im} \leqslant 1, \text{ for } \forall i \in A \tag{8}$$

$$t_{jf}^{A} - t_{if}^{A} \geqslant S_{ij}^{A} - N\delta_{ji}, \text{ for } \forall i,j \in A \text{ such that } i \neq j \tag{9}$$

$$t_{if}^{A} - t_{jf}^{A} \geqslant S_{ji}^{A} - N\delta_{ij}, \text{ for } \forall i,j \in A \text{ such that } i \neq j \tag{10}$$

$$t_{r}^{D} - t_{q}^{D} \geqslant S_{qr}^{D} - N\gamma_{rq}, \text{ for } \forall q,r \in B \text{ such that } q \neq r \tag{11}$$

$$t_{q}^{D} - t_{r}^{D} \geqslant S_{rq}^{D} - N\gamma_{qr}, \text{ for } \forall q,r \in B \text{ such that } q \neq r \tag{12}$$

$$t_{q}^{D} - t_{if}^{A} \geqslant S_{iq}^{AD} - N\lambda_{qi}, \text{ for } \forall i \in A, \forall q \in B \tag{13}$$

$$t_{if}^{A} - t_{q}^{D} \geqslant S_{qi}^{AD} - N\lambda_{iq}, \text{ for } \forall i \in A, \forall q \in B \tag{14}$$

$$v_i \leqslant n_i^A, \text{ for } \forall i \in A \tag{15}$$

$$z_q \leqslant n_q^D, \text{ for } \forall q \in B \tag{16}$$

$$\delta_{ij}, \gamma_{qr}, \lambda_{iq}, w_{ik}, u_{im} - \text{binary}$$

$$v_i, z_q - \text{non-negative integer}$$

It is important to notice here that this model represents a general case in which the precedence between aircraft is not previously determined (except for arrival aircraft in the same STAR). However, if we consider some specific operational conditions, it is possible to adjust the model in order to make it leaner. For example, if we consider that the FCFS principle in respect to the runway threshold applies to all landings, in other words, the precedence between arrival flights is predetermined, constraints (4) and (7) could be eliminated as well as the variables that determine the precedence.

3.2. Dynamic approach

The sequencing and scheduling decisions are made in a dynamic environment where the set of aircraft that are going to land or takeoff and the set of aircraft that has already landed or taken off are constantly changing during the time. This online process has two aspects of dynamics. First, the set of aircraft that the controllers have to schedule changes as time passes, in other words, all the flights to be scheduled are not previously known as they would be in the static case. Second, a previous scheduling decision can be updated as time passes and new aircraft enter the scheduling window such that the rescheduling potential is higher for those aircraft that are farthest from the runway. Therefore, it is necessary to link the analytical model with a dynamic approach so that it can be better evaluated and become useful in a real time situation. In this work, we developed a dynamic approach for running the optimization model that is based on the concepts of scheduling window and freeze horizon described in Section 2.

In our proposal, the scheduling window and the freeze horizon are time based. We considered a scheduling window that is constantly updated at a rate that is equal to 60 min divided by the length of the freeze horizon. For a freeze horizon of x minutes, we considered that the length of the scheduling window is $3x$ minutes and it is characterized as follows: the scheduled time of arrival at the airport for the flights that have estimated time of arrival within the first x minutes of the scheduling window is frozen and the arrival time at the airport for the flights that have estimated time of arrival within the last $2x$ minutes of the scheduling window can still be scheduled (optimized). For every x minutes, the scheduling window is then updated, encompassing a new set of aircraft with frozen scheduled time of arrival and a new set of aircraft with arrival times to be scheduled. Therefore, we ensure that if a plane begins the arrival route within a time window and lands within the next time window, it will be considered in the scheduling of the next sequence of aircraft. It means that the upstream flow and the downstream flow will always be considered for scheduling and that separations will be ensured for all the pairs of aircraft. Fig. 1 summarizes the dynamic approach proposed.

It is important to discuss how this dynamic approach could be used in practice as part of a decision support tool for air traffic controllers. For this, the processes that would happen during an optimization run will be described. First, for all the flights between x and $3x$ minutes from the reference waypoint (fraction B and C of Fig. 1), estimated time of arrival (at the final waypoint of the STAR) would be generated from a set of input parameters such as wind and speed profiles. This prediction could be made either with the information of the radar console at the air traffic control body or with the flight management system of the aircraft (in this case, the predictions could be transmitted to the air traffic control body via data link).

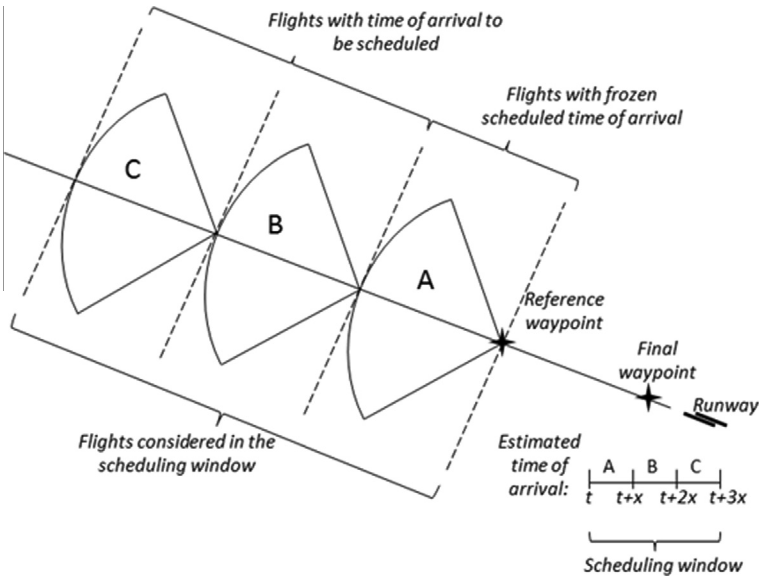

Fig. 1. Scheme of the dynamic approach proposed.

Second, the model input parameter represented by the target time of arrival at the final waypoint of the STAR would be updated by the values determined in the first stage. The scheduled time of arrival of the flights within the first x minutes of the scheduling window (fraction A of Fig. 1) would also be updated with the results of the previous optimization run. Third, the optimization procedure would be initiated. Once the results of the model are generated, in other words, the configuration of the STAR to be traversed and the number of holding procedures to be performed, they would be displayed to the air traffic controllers. Finally, with this information, the air traffic controllers would be able to transmit the appropriate control instructions to the next set of aircraft (fraction B of Fig. 1), which becomes the frozen fraction of the next scheduling window (their scheduled time of arrival are frozen in the next optimization run). Here it is noticeable the benefit of the output type of the proposed model in terms of decision support. Since the scheduled time of arrival is displayed in terms of control actions, air traffic controllers are supported not only in the establishment of an arrival sequencing and scheduling solution but also in the implementation of this solution.

3.3. Case study

The optimization approach proposed was analyzed with practical instances from Sao Paulo/Guarulhos International Airport (SBGR) – the largest Brazilian airport and an important hub in Latin America. It recorded 284,184 aircraft movements and 35,962,000 passenger movements in 2013. SBGR has two parallel runways, one with 3000 m of length (09R-27L) and the other with 3700 m of length (09L-27R). Due to the wind regime, the runway threshold 09 prevails for operations. The runway 09R-27L is usually used for landings while the runway 09L-27R is usually used for takeoffs. Since they are separated by 375 m and there is a displacement threshold of 580 m, the operations of arrivals and departures are dependent. It means that departure flights need to be taken into account in the arrival sequencing and scheduling process.

Real radar data from a typical day of operations (December 07, 2010) were used to perform the analysis in this work. Fig. 2 shows a plot of real SBGR flight trajectories (in blue) at this day of operations, when there were a total of 747 aircraft operations. The configuration of the STAR of SBGR is plotted in red (from each IAF to the airport) so that it is possible to analyze the traffic behavior during the approach. It is noticeable the range of control actions used by the air traffic controllers for sequencing and scheduling the arrival flights. Fig. 2(A) and (B) show two parts of the arrival route with zoom. It is possible to observe that shortcuts and lengthened paths are very used by the controllers to provide the separation between aircraft. For instance, in Fig. 2(B), it is possible to observe holding procedures at waypoints W1, W2 and W3, shortened paths from W2 to W4 (without overflying W3) and lengthened paths from W1 to W4, revealing some of the actions that were probably taken by the air traffic controllers to ensure the separation between aircraft at W4. Similarly, in Fig. 2(A), where it is given a zoom of the final approach, there is a high dispersion before arriving at W12, with many shortened paths from W6 to W8 (without overflying W7) and several lengthened paths from W7 to W8. It is important to mention that it is reasonable to assume that the deviations of trajectories shown in Fig. 2 are mainly because of air traffic control interference and not because of imprecision of flight navigation. First, the geometric profile of actual trajectories shows deviations that are much higher than the current level of precision in navigation and that clearly reveal a deterministic change in the trajectory. Second, in the current stage of technological development, aircraft have been able to fly very precise routes with the introduction of Global Navigation Satellite Systems and Performance Based Navigation, both in use at SBGR flight procedures.

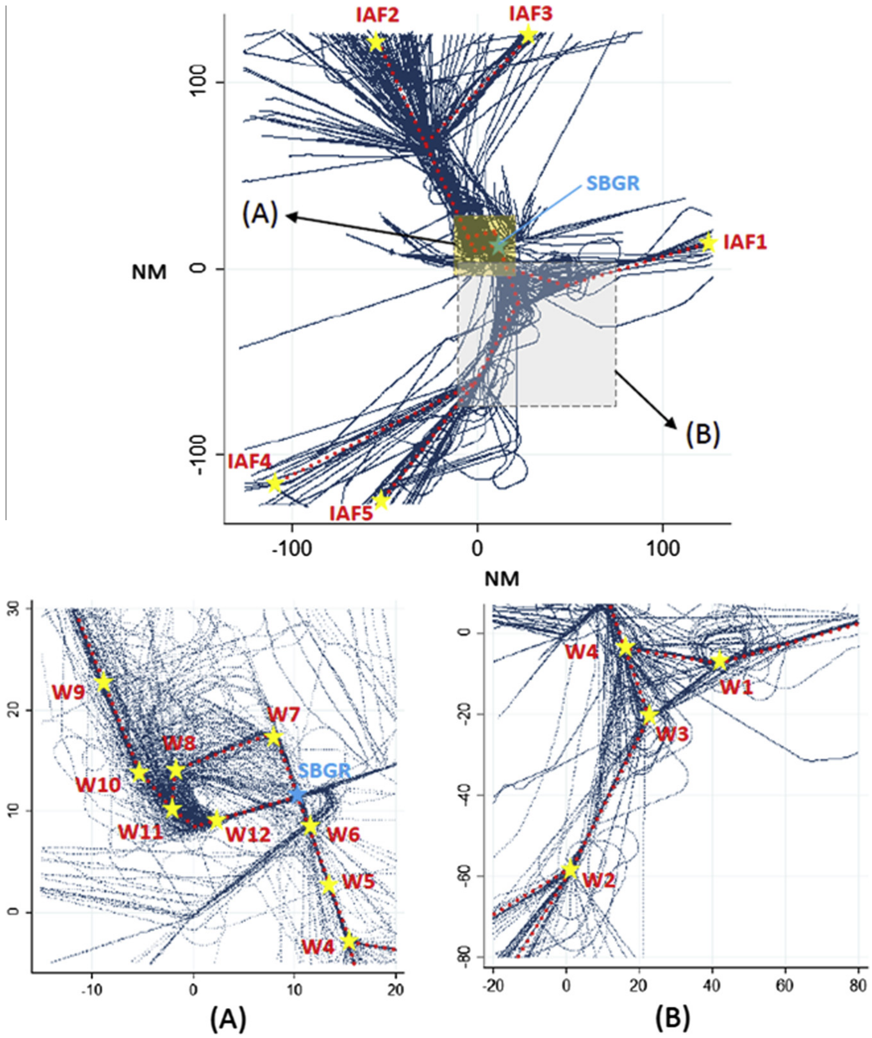

Fig. 2. Radar track of Sao Paulo/Guarulhos International Airport flights.

The visual analysis of the actual approach routes to SBGR suggests that a standardization of these procedures with the establishment of some alternative pre-defined arrival routes could create opportunities for introducing them into an optimization tool for helping the controller in making the best control decisions during the approach. This scenario is a good example that justifies the need of linking the arrival sequencing and scheduling to the control problem associated with it in the terminal area.

3.4. Optimization scenarios

The mathematical model proposed in this work was applied for optimizing the arrival sequencing and scheduling at SBGR at the day of operations described above. AIMMS (Advanced Interactive Multidimensional Modeling System) platform (AIMMS, 2012) was used for implementing the dynamic approach developed and running the optimization with CPLEX solver, which is widely recognized and presents a modern algorithm for solving large mixed integer linear programming models. It is worth noting that the results in terms of computational time to achieve the optimal solution are associated with CPLEX performance and will vary if other solvers are used. Moreover, heuristics may be used in order to generate good solutions with smaller computational times.

Due to the large number of intervening factors, 17 scenarios were developed to represent the various possible operating situations. In order to make the reader's understanding easier, a baseline scenario was established and the other scenarios were defined from changes in the baseline scenario. Table 1 summarizes the considerations made for the baseline scenario, which was constructed to represent the operating condition of SBGR, especially with regard to the criterion of separation between aircraft commonly employed. In order to define the maximum number of holding procedures, we considered that

Table 1
Characteristics of the baseline scenario.

Parameter	Value
Discretization of the set of delays/time advances applied to landings	60 s
Maximum delay through route lengthening	360 s
Maximum advance through route shortening	240 s
Discretization of the set of delays applied to takeoffs	30 s
Criteria of separation	5 NM of separation on final approach between successive landings, takeoff release only if there is no aircraft on final approach for landing and separation between successive departures according to the wake turbulence criteria
Sequencing strategy between landings	FCFS (with respect to the target time of arrival at the airport)
Sequencing strategy between takeoffs	FCFS (with respect to the target time of departure)
Sequencing strategy between landings and takeoffs	Free
Dynamic approach	Scheduling window of 60 min and freeze horizon of 20 min
Cost parameters in the objective function	Unitary penalty cost of airborne delays and advances and penalty cost of ground delays equal to 75% of the penalty cost of airborne delay (Eurocontrol, 2011)

the maximum delay that can be imposed by the model should not exceed the maximum delay that was observed in the database. Regarding the maximum number of ground holding periods, it was determined considering a maximum ground delay of 20 min.

The scenarios simulated in this work for SBGR were developed for the case of operations at the runway threshold 09, which is the prevailing one, and for the case of only one runway being used for landings (runway 09R-27L) because of the current condition of dependent operations. However, it is important to mention that the model designed is applicable to the case of operations at the runway threshold 27 and that it can be extended to become applicable to a possible future operating condition of simultaneous approach. For the case of operations at the runway threshold 27, it is only necessary to define new target landing time for each aircraft based on the approach trajectories to the runway threshold 27 as well as to define discrete delays and advances compatible with such trajectories. There is no change of the model, but only of the model input represented by each aircraft's estimated time of arrival and by the sets of discrete delays and advances. In the case of simultaneous approach, the model can be adjusted in order to introduce a new binary decision variable associated with the runway that each aircraft will use. Moreover, the regulated separations for this specific condition of simultaneous operation must be defined.

4. Results and discussion

The optimization approach proposed was analyzed under the sustainability tripod of ATFM models. First, we analyzed the performance of the model with respect to the amount of delays generated and to the computational time for obtaining the optimal solution under different operating scenarios, then we assessed the model benefits in terms of reducing delays and finally we discussed the effectiveness of the approach as a decision support tool for air traffic controllers. It is important to point out that, whenever presented in the tables of model results, the computational time will be associated with the time spent to obtain the optimal solution for the whole day of operations, in other words, it represents the sum of all time spent for obtaining the optimal solution in each time interval of the dynamic approach employed.

4.1. Model performance evaluation

In order to evaluate the performance of the model, different operating scenarios were established by changing the following intervening parameters: type of sequencing strategy, type of configuration of the terminal area in terms of alternative approach routes, scheduling window and freeze horizon.

4.1.1. Sensitivity analysis with respect to the sequencing strategy

For evaluating the model performance with respect to the sequencing strategy between landings, between takeoffs and between landings and takeoffs, two new scenarios were developed from the baseline scenario through modifications of the rule with which aircraft are sequenced. The scenario called "FCFS-A-D-AD" considers that the FCFS principle is applied between landings, between takeoffs and between landings and takeoffs, in other words, it means that ordering the flights according to their estimated time of arrival at the airport, in the case of landings, and to their estimated time of departure, in the case of takeoffs, creates a FCFS queue that cannot be modified. It is important to note that the baseline scenario, called "FCFS-A-D" here, represents a relaxation of the scenario "FCFS-A-D-AD" since it relaxes the ordering between takeoffs and landings, allowing takeoffs to be best accommodated in the landing queue. Finally, the scenario called "FCFS-A" considers that the FCFS principle is applied only to landings, enabling position changes between takeoffs and between landings and takeoffs. Fig. 3 presents a hypothetical aircraft queue that illustrates the difference between these scenarios. The optimization results for these scenarios are presented in Table 2.

The results in Table 2 show that relaxing the sequencing strategy between takeoffs and landings generate a significant reduction of delays since it is possible to do a better allocation of takeoffs in the landing queue. We observed a reduction of the total deviations of 24% for landings and 85% for takeoffs if the FCFS strategy is relaxed between takeoffs and landings, as shown by the results of scenarios “FCFS-A-D-AD” and “FCFS-A-D”. Moreover, if this relaxation is also applied between takeoffs, reductions in total deviations virtually do not change, as shown by the results of scenarios “FCFS-A-D” and “FCFS-A”. As it turns out, adopting a strategy that is different from the FCFS principle for takeoffs did not bring any benefit in terms of reducing delays and strongly impacted on the computational time, which suffered a large increase and became impractical. In other words, adopting a FCFS strategy for landings and takeoffs (with relaxation of the ordering between takeoffs and landings in order to better allocate the departures in the landing queue) may be considered as the most favorable strategy.

4.1.2. Sensitivity analysis with respect to the configuration of arrival routes

It is important to evaluate how the performance of the model varies according to the configuration of the terminal area in terms of alternative approach routes (which determines the set of discrete delays/time advances that can be applied to landings during the approach) and to the set of discrete delays that can be applied to takeoffs on the ground.

First, changes were made in the baseline scenario with respect to the discretization of the set of delays/time advances associated with alternative approach routes and to the discretization of the set of ground delays. In this first analysis, the maximum delay of 360 s and the maximum advance of 240 s for landings were maintained. For instance, it means that three alternative paths of lengthening and two alternative paths of shortening will be available if a discretization of 120 s is adopted. The optimization results for these new scenarios are presented in Table 3.

As observed in Table 3, the results of the model are highly sensitive to the discretization of the set of delays/time advances applied to the landings through alternative paths and also highly sensitive to the discretization of the set of delays applied to takeoffs on the ground. When we use sets of discrete delays and time advances with more granularity, a reduction of total delays/time advances is achieved, since the model has more options of interference on the traffic flow and the alternative that generates the lower level of deviations will be chosen. Although a delay difference of 30 s may be considered small for an individual flight, for example, when it is aggregated for all the flights of a whole day of operations, the resulting global delay becomes quite different among the scenarios. With respect to the computational time, it proved to be practical for all

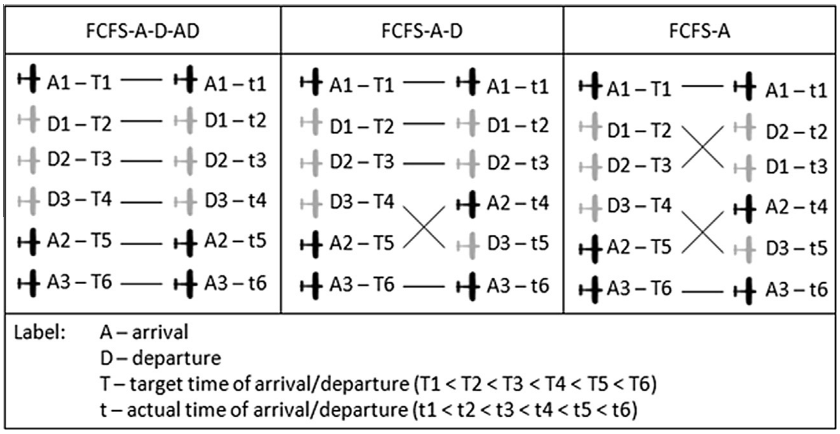

Fig. 3. Scheme of different sequencing strategies between takeoffs and landings.

Table 2
Results of the sensitivity analysis with respect to the sequencing strategy.

Scenario	FCFS-A-D-AD	FCFS-A-D	FCFS-A
Landings			
Total delays through alternative paths (s)	21,600	22,560	23,340
Total delays through holding procedures (s)	51,840	30,480	29,520
Total time advances (s)	3,780	5,580	5,580
Total deviations (s)	77,220	58,620	58,440
Takeoffs			
Total delays (s)	86,370	13,080	13,320
Computational time (s)	938.70	1,429.17	25,625.58

Table 3
Results of the sensitivity analysis with respect to the discretization of the set of delays/advances.

Output variable	Discretization of the set of delays/advances applied to landings (s)	Discretization of the set of delays applied to takeoffs (s)		
		15	30	60
Landings				
Total delays through alternative paths (s)	30	14,820	15,240	18,240
	60	22,080	22,560	27,120
	120	30,360	29,160	29,880
Total delays through holding procedures (s)	30	12,240	19,440	23,760
	60	21,120	30,480	65,760
	120	53,040	52,560	68,400
Total time advances (s)	30	5,340	5,160	5,190
	60	5,400	5,580	4,380
	120	5,400	6,240	5,280
Total deviations (s)	30	32,400	39,840	47,190
	60	48,600	58,620	97,260
	120	88,800	87,960	103,560
Takeoffs				
Total delays (s)	30	8,130	7,590	30,120
	60	11,250	13,080	18,840
	120	23,610	29,970	43,860
Computational time (s)	30	1,091.18	976.66	1,197.60
	60	1,106.31	1,429.17	1,080.23
	120	912.93	929.19	929.22

the scenarios (average of less than 20 s per optimization process) and the variability was not as significant. Thus, it is important to consider the effect of different configurations of terminal area in terms of alternative approach trajectories when assessing the potential benefits of the model.

Since an approach procedure has to be validated to become ready to be flown and this process may take a long time, there is an incentive to consider less alternative paths. Therefore, new changes were made to the baseline scenario regarding the amount of alternative approach paths available. Maintaining the discretization of 60 s for delays/time advances applied to landings and of 30 s or 15 s for delays applied to takeoffs, the following situations were analyzed: availability of four alternative paths of lengthening and two alternative paths of shortening, which imposes a maximum delay of 240 s and a maximum advance of 120 s, and availability of two alternative paths of lengthening and just one alternative path of shortening, which imposes a maximum delay of 120 s and a maximum advance of 60 s. Table 4 presents the results of the scenarios that consider fewer alternative approach trajectories.

As expected, the results in Table 4 show that reducing the number of alternative approach paths produces an increase in the amount of deviations applied to the landings. This occurs due to the decreased number of options for interference on the traffic flow. In terms of computational time, it remained reasonable for all the scenarios and no significant changes were observed.

4.1.3. Sensitivity analysis with respect to the dynamic approach

The use of decision support tools in the tactical stage of arrival sequencing is highly dependent on the accuracy in predicting trajectories to determine the estimated time of arrival of each aircraft. Considering the dynamic approach employed, the larger the scheduling window and the freeze horizon, the larger the prediction horizon and the lower the level of accuracy. In the baseline scenario, we considered a scheduling window of one hour and a freeze horizon of 20 min. It is not part of the scope of this work to determine if this dynamic approach is the most appropriate considering the current level of technology available. Nevertheless, one can evaluate the impact on the total deviations and on the computational time for obtaining the solution if larger and smaller values for the scheduling window and the freeze horizon are used. This evaluation was then performed and the results are shown in Table 5.

According to the results in Table 5, it is observed that the use of different dimensions for the scheduling window and for the freeze horizon did not generate significant changes in the total deviations. The differences are due to the fact that, when enlarging the scheduling window and the freeze horizon, the consideration of the downstream and upstream flows of the aircraft being scheduled is greater, avoiding that conflicts are left for later resolution. Thus, it is possible to obtain a solution that is closer to the global optimum of the system, which could be obtained if the model were optimized at a single stage for the whole day of operations (in a static approach, for example). In fact, there is a reduction of deviations when the scheduling window is increased to 90 min, precisely because the best solutions are sought for a larger set of aircraft at each update and this expands the options of action to manage a conflict, for example. On the other hand, if the scheduling window is very small, conflicts may occur between aircraft of different scheduling windows and they will not be solved simply because they are not “seen” by the model. This fact is one possible explanation for the reduction in deviations when the scheduling window was reduced to 30 min. If the optimization of a scheduling window generates scheduled landing times for the first

Table 4
Results of the sensitivity analysis with respect to the number of alternative approach routes.

Discretization of the delays/advances applied to landings, discretization of the delays applied to takeoffs	(60 s, 30 s)			(60 s, 15 s)		
(Number of alternative lengthened paths, number of alternative shortened paths)	(6,4)	(4,2)	(2,1)	(6,4)	(4,2)	(2,1)
Landings						
Total delays through alternative paths (s)	22,560	15,240	11,460	22,080	15,180	9,960
Total delays through holding procedures (s)	30,480	44,880	57,360	21,120	35,520	51,840
Total time advances (s)	5,580	3,120	3,000	5,400	3,360	3,180
Total deviations (s)	58,620	63,240	71,820	48,600	54,060	64,980
Takeoffs						
Total delays (s)	13,080	14,520	15,810	11,250	12,930	11,070
Computational time (s)	1,429.17	956.77	913.04	1,106.31	952.18	905.60

Table 5
Results of the sensitivity analysis with respect to the dynamic approach.

(Scheduling window, freeze horizon, update rate per hour)	(30 min, 10 min, 6)	(60 min, 20 min, 3)	(90 min, 30 min, 2)
Landings			
Total delays through alternative paths (s)	21,000	22,560	20,820
Total delays through holding procedures (s)	29,520	30,480	26,880
Total time advances (s)	4,980	5,580	5,820
Total deviations (s)	55,500	58,620	53,520
Takeoffs			
Total delays (s)	13,800	13,080	14,250
Computational time (s)	1,926.10	1,429.17	9,212.28

fraction of flights (fraction A of Fig. 1 which will be frozen at the following update) that conflict with the last fraction of flights of the following scheduling window (fraction C of Fig. 1), these conflicts will not be solved by the model and, therefore, fewer deviations will be applied.

Furthermore, the analysis of the results presented in Table 5 shows that increasing the scheduling window and the freeze horizon may increase the computational time for obtaining the solution since more flights are processed in a single optimization with greater probability of existing conflicts to be resolved. This may result in more iterations then. However, the reduction of the scheduling window and the freeze horizon can also increase the computational time because, for the entire day of operation, more updates and more optimization processes will occur. In short, it can be inferred that, in the first case, the computational time increased due to the increase in the individual computational time spent to obtain the optimal solution for each optimization process, whereas in the second case, the computational time increased due to the increase in the amount of optimization processes (updates).

In this case, a scheduling window of 60 min with a freeze horizon of 20 min seems to be appropriate because this length is compatible with the maximum delay that was set, in other words, it prevents a conflict between flights of two consecutive scheduling windows of not being detected. Moreover, it is practicable in terms of computational time.

It is worth noting that, in practical terms, the definition of the length of the scheduling window and the freeze horizon should also be made considering the need of ensuring enough time for the aircraft to receive control instructions and perform the procedures assigned to them and the need of ensuring readiness for accommodating unpredictable traffic into the sequencing.

4.1.4. Sensitivity analysis with respect to the cost parameters

In the baseline scenario, we considered the same penalty cost for delays and for time advances. It means that both types of deviation from the target time were considered equally harmful to the system. From the airline and from the airport perspectives, this hypothesis is reasonable, since punctuality is one of the compromises of an air carrier and operations should occur as close to the schedule as possible. Nevertheless, taking an environmental point of view, route lengthening can be more harmful to the system than route shortening in terms of emissions. Thus, it is reasonable to consider different costs for delays and time advances.

The last sensitivity analysis was performed with respect to the cost parameters of airborne delay (c^1 and c^3), airborne time advance (c^2) and ground delay (c^4) of the objective function. Regarding the cost of ground delay, the baseline scenario considered that it represents 75% of the cost of airborne delay, according to the average values recommended by Eurocontrol (2011). However, this same study recommends the use of other values for extreme scenarios so that it is possible to perform a sensitivity analysis. It is worth noting that although these costs do not apply to the Brazilian reality, the proportion between the overall cost of ground delay and the overall cost of airborne delay may not change too much.

For the above, changes were made in the baseline scenario with respect to the cost parameters of the objective function, considering different percentage shares according to the type of deviation in the sum of total deviations. The optimization results of these new scenarios are presented in Table 6.

The results in Table 6 show how the distribution of the deviations from the target landing time varies according to the weights of each component of the objective function. It is noted that the smaller the weight of a given component, the greater the amount of deviations allocated to this component due to its relative "less importance" in the minimization process. It can be seen that there is more sensitivity of the total deviations applied to landings in relation to the proportion between the cost of airborne delay and the cost of ground delay and there is less sensitivity in relation to the proportion between the cost of airborne delay and the cost of airborne time advance.

4.2. Delay reduction potential evaluation

After analyzing the performance of the model for different scenarios that intended to evaluate the sensitivity with respect to the intervening parameters, an assessment of the potential benefits of the model in terms of reducing delays was done. Fig. 4 shows the total deviations with respect to the target landing time (in absolute values) associated with both the actual solutions taken by air traffic controllers and the solutions resulting from the model, considering the baseline scenario (which best represents the actual operations of SBGR), for each time block of 20 min (freeze horizon considered) at the day in study. It also presents the number of aircraft with target landing time within each time block.

It is observed in Fig. 4 that, for most of the time blocks, the deviations associated with the solutions of the optimization model are smaller than the deviations associated with the actual solutions taken by air traffic controllers and that this reduction occurred for both low traffic periods and high traffic periods. It is also possible to observe delay propagation over time when a time block contains many aircraft to land at the airport since the peaks of deviations happen, in general, after the peaks of aircraft. Considering the whole day of operations, the model generated a reduction of approximately 22%, regarding the total time deviations that were applied to landings.

In order to better investigate the differences observed in certain periods, an analysis of the number of aircraft approaching per STAR and the number of departures for each time block was performed. With Figs. 4 and 5, we can contrast the actual deviations and the model deviations with the number of aircraft that used the common approach paths W4-W12 and W9-W12 and with the total number of operations (takeoffs and landings).

Table 6
Results of the sensitivity analysis with respect to the cost parameters.

Relative share of the cost components in the objective function	Airborne delays (s)	Airborne time advances (s)	Ground delays (s)
$c^2 = c^1 = c^3$ $c^4 = 0.75\ c^1$	53,040	5,580	13,080
$c^2 = 0.75\ c^1 = 0.75\ c^3$ $c^4 = 0.75\ c^1$	51,960	7,080	12,000
$c^2 = 0.50\ c^1 = 0.50\ c^3$ $c^4 = 0.75\ c^1$	51,300	8,580	12,510
$c^2 = 0.75\ c^1 = 0.75\ c^3$ $c^4 = 0.80\ c^1$	52,440	6,900	12,300
$c^2 = 0.75\ c^1 = 0.75\ c^3$ $c^4 = 0.50\ c^1$	43,080	6,180	27,000

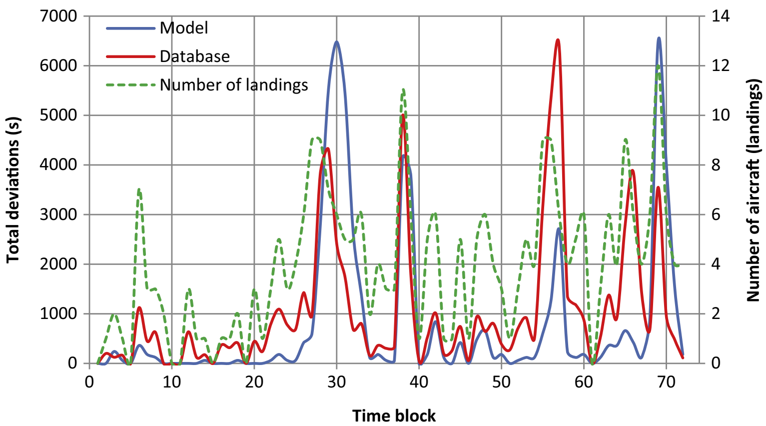

Fig. 4. Actual (database) and model deviations versus number of landings.

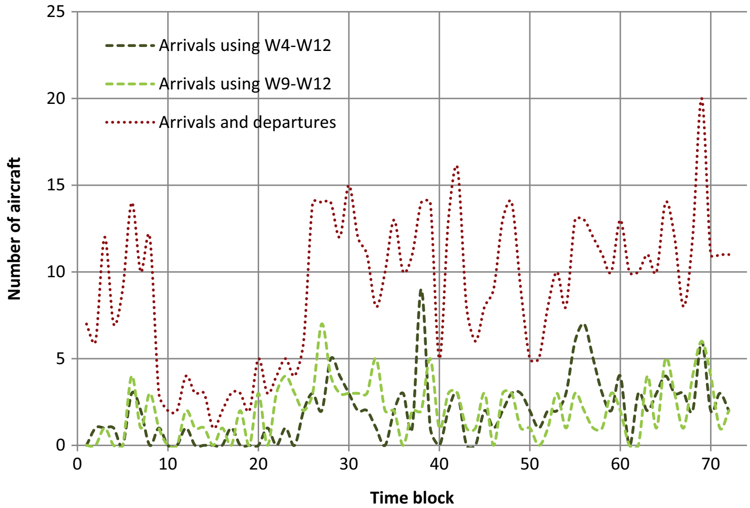

Fig. 5. Total number of operations and number of landings per common approach path.

Fig. 5 shows that the three major peaks of actual deviations (periods 38, 56 and 57) occurred in situations where the number of aircraft using the common approach path W4-W12 is quite significant and substantially greater than the number of aircraft using the common approach path W9-W12. This may suggest that it may be more difficult to manage air traffic flow when there are more aircraft using the common path W4-W12. In fact, the path W4-W12 is associated with three IAF that receive flights from two distinct regions, which can bring greater complexity to the control, while the path W9-W12 is associated with two IAF that receive flights from the same region. For these time blocks, the actual deviations were higher than those resulting from the model. Fig. 5 also shows that the two largest peaks of model deviations (periods 30 and 69) occurred in two very specific situations: first, after an abrupt change in the total level of operations (arrivals and departures) and, second, at the maximum level of operations. This suggests that the model has certain inability to handle demand shocks, which might be one explanation for the discrepancy observed in the time blocks mentioned above.

In order to evaluate the fairness in delay assignment, we also analyzed how the model deviations were distributed between flights of different airlines. Fig. 6 shows the average deviation per arrival flight for the three airlines with the greatest number of aircraft movements. It is possible to observe that the model distribution of deviations (delays and time advances) maintained the pattern of distribution of actual deviations extracted from the database, with percentage reductions between 20% and 40%. Achieving a distribution of deviations that can be considered fair tends to be difficult, especially because there is no consensus of what an ideal fairness criterion would be. However, if a more equal distribution of deviations is desired (same average deviation independently on the number of movements of a carrier), it is possible to adjust the objective function and replace the individual deviation per flight by the average deviation per airline.

Since the results of the model have high sensitivity to the level of discretization used for the set of delays and advances associated with alternative approach routes as well as to the number of alternative trajectories available (for the same level of discretization), it is important to evaluate the potential benefit of the model for these different configurations of terminal area in terms of alternative approach trajectories. Therefore, we calculated the percentage change of the total deviations of

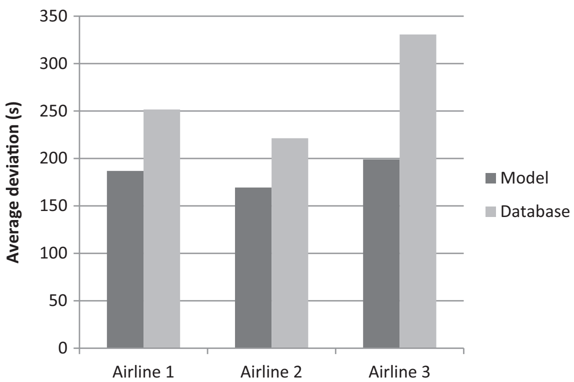

Fig. 6. Average deviation per flight per airline.

Table 7
Model benefits assessment for different levels of discretization.

Percentage change (model total deviations in relation to the actual total deviations)	Discretization of the set of delays/advances applied to landings (s)		
	30	60	120
Discretization of the set of delays applied to takeoffs (s)			
15	−57.30%	−35.94%	17.04%
30	−47.49%	−22.74%	15.94%
60	−37.80%	28.19%	36.50%

Table 8
Model benefits assessment for different numbers of alternative arrival routes.

Percentage change (model total deviations in relation to the actual total deviations)	Number of alternative paths of lengthening, Number of alternative paths of shortening		
	(6, 4)	(4, 2)	(2, 1)
Discretization of the set of delays/advances applied to landings, discretization of the set of delays applied to takeoffs			
(60 s, 15 s)	−35.94%	−28.75%	−14.35%
(60 s, 30 s)	−22.74%	−16.65%	−5.34%

the model for the scenarios evaluated in Section 4.1.2 in relation to the total deviations associated with the actual ATFM solutions that had been taken. The results are shown in Tables 7 and 8. In Table 7, one can evaluate the delay reduction potential for different levels of discretization of the set of delays/advances applied to landings and takeoffs while, in Table 8, one can evaluate the delay reduction potential for different numbers of alternative approach routes (for two fixed levels of discretization).

According to the results of Table 7, it should be adopted a discretization level of less than or equal to 60 s for the set of time deviations applied to the landings through alternative paths of lengthening and shortening for the model to be able to generate benefits in terms of reducing delays/advances. For these cases, the potential of reducing total deviations varied from 22% to 57%, depending on the level of discretization used. As discussed before, when we use sets of discrete delay/time advance with low granularity (in this case, higher than 60 s), the model has less options of interference on the traffic flow and can generate worse solutions in terms of deviations from the target landing/departure time, especially when managing conflicts that require small time adjustments. Conversely, if the set of delay/time advance is best discretized, the model seems to have great potential for reducing delays.

For landings, the use of small values of discretization can become operationally infeasible. On the other hand, for takeoffs, this problem may not arise (although we would not recommend a discretization of less than 10 s). Considering the average speed and altitude restrictions of SBGR approach routes, it is possible to assume that a delay of 60 s could be achieved through a trajectory lengthening of approximately 5 NM. This distance seems to be reasonable to be implemented through an operationally feasible offset route with appropriate lateral separation. However, lower distances could turn more difficult to design alternative routes with appropriate lateral separation. Considering 60 s as the lower limit for the discretization of set of delays/advances applied to landings, we analyzed in more detail the model potential of reducing deviations for different numbers of alternative trajectories. The results in Table 8 show that this reduction potential of deviations varied from 5% to 35%.

4.3. Decision support effectiveness evaluation

Most of the approaches developed for the arrival sequencing and scheduling problem presuppose a flow control conception characterized by en route delay absorption through speed adjustments to meet a required time of arrival (RTA) at a metering fix, which is the continuous decision variable determined after processing the estimated time of arrival of all approaching aircraft. This conception is entirely dependent on the use of embedded technology in aircraft (sophisticated onboard computers with high predictability of trajectories) and on the use of data link systems for communications between pilots and controllers (CPDLC).

In the case of air traffic control systems predominantly based on voice communications, this type of modeling becomes inappropriate. The use of continuous decision variables generates a high range of different outcomes in terms of time deviations to be absorbed by the aircraft, which may not even be integers. The transmission of such information to the pilot could increase the occurrence of noise in communications as well as increase the workload of the controller, especially if a dynamic approach is used, because, at each entry of aircraft into the system, new sequences and new arrival times are determined. Therefore, in this case, the controller would still be responsible for determining the control actions (speed adjustment, altitude adjustment, holding procedure, route lengthening/shortening etc) required for each aircraft to reach the metering fix at a given time that is the closest to the optimal time resulting from the scheduling. Thus, in case of voice communications systems or in case other types of control actions are still necessary to provide the separations, especially in the terminal area, a broader underlying flow control conception (in other words, a conception that offers a range of control actions other than speed adjustment) is required. Moreover, if the air traffic controller is still responsible for implementing an arrival sequencing and scheduling solution, an optimization approach that incorporates this broader control problem becomes more appropriate.

The optimization approach proposed in this work has the objective to help the controller in determining the configuration of the STAR to be traversed and the number of holding procedures to be performed. The configuration of the STAR would be selected from a set of standard procedures that would have been previously tested, validated and implemented by air traffic control bodies. Since the output is directly linked to a specific control action and an executable flight command, it tends to be more effective in supporting air traffic controller decisions. In other words, air traffic controllers are supported not only in the establishment of an arrival sequencing and scheduling solution but also in the implementation of this solution.

It is worth mentioning that it is beyond the scope of this work to establish alternative arrival procedures that are operationally suitable and to precisely determine the delays and time advances that can be imposed with these procedures. In order to do so, a long process within the air traffic bodies would have to be performed with a sequence of stages such as procedure design, real time simulation, performance evaluation, risk analysis, validation and so on. However, once all the possible configurations of STAR are tested and implemented, their parameters can be introduced into the model, becoming an option of trajectory assignment for air traffic controllers.

5. Conclusions

This work aimed to develop an optimization approach for aircraft sequencing and scheduling under the sustainability tripod viewpoint, which states that the development of ATFM models should attempt to achieve the following objectives: reduction of congestion and delays, computational tractability and effectiveness as a decision support tool. In this context, we developed a mixed integer linear programming model that encompasses part of the control problem associated with the stage of managing the arrival flow towards an airport. The contribution of the paper to the literature of arrival sequencing and scheduling is the introduction of the air traffic control system infrastructure, in terms of route network and control actions, into an optimization approach that provides air traffic controllers with operationally feasible solutions and enhances decision support. For this, the model introduces the concept of alternative arrival routes, ties the arrival sequencing and scheduling to the configuration of the terminal area in terms of Standard Terminal Arrival Routes and generates an output that is directly linked to executable flight commands. Moreover, we developed a dynamic approach for running the optimization and representing the dynamic environment where decisions need to be taken.

A real case study was used to analyze the performance of the model under different operating scenarios in terms of computational tractability and delay reduction potential. For this, we used a radar database of a typical day of operations from Sao Paulo/Guarulhos International Airport (SBGR). The results show reasonable computational times for obtaining the optimal solution with CPLEX solver, in other words, feasible computational times if the dynamic approach developed is implemented in a real time situation. Also, the results show delay reductions of up to 35% for the scenarios that are the closest to the actual operations of SBGR. It is worth noting that the results in terms of computational time are affected by CPLEX performance and they will vary if other solvers are used. However, it is also possible to attempt to develop heuristics for obtaining good solutions, close to the optimum, with smaller computational times.

The optimization approach proposed incorporates practical real world constraints, addresses the case of mixed operations and can be optimized under a dynamic environment. These features are essential for an effective real-time implementation. Moreover, since the output is directly linked to a specific control action, it tends to be more effective in supporting air traffic controller decisions under a broader flow management conception. It means that air traffic controllers can be supported both in the establishment and in the implementation of an arrival sequencing and scheduling solution.

It is worth mentioning that the mathematical model developed in this work is essentially a concept that requires further investigation regarding the aircraft operating performance side. In this sense, further research should focus on detailing the aircraft performance for the range of control actions used in the approach in order to adjust the input parameters and to enable an implementation test and validation.

References

AIMMS, Advanced Interactive Multidimensional Modeling System, 2012. AIMMS version 3.12. Available at: <http://www.aimms.com/academic/free-academic-license/>.

Andreussi, A., Bianco, L., Ricciardelli, S., 1981. A simulation model for aircraft sequencing in the near terminal area. Eur. J. Oper. Res. 8, 345–354.

Frankovich, M., 2006. Unified optimization of traffic flow through airports. In: AGIFORS Annual Symposium, 52, 2012, Scottsdale. Proceedings. . .. AGIFORS, Scottsdale.

Balakrishnan, H., Chandran, B., 2010. Algorithms for scheduling runway operations under constrained position shifting. Oper. Res. 58 (6), 1650–1665.

Ball, M., Barnhart, C., Nemhauser, G., Odoni, A., 2007. Air transportation: irregular operations and control. In: Laport, G., Barnhart, C. (Eds.), Handbook in Operations Research and Management Science. Elsevier, Amsterdam, pp. 1–73.

Beasley, J.E., Krishnamoorthy, M., Sharaiha, Y.M., Abramson, D., 2000. Scheduling aircraft landings – the static case. Transp. Sci. 34 (2), 180–197.

Beasley, J.E., Krishnamoorthy, M., Sharaiha, Y.M., Abramson, D., 2004. Displacement problem and dynamically scheduling aircraft landings. J. Oper. Res. Soc. 55 (1), 54–64.

Bennell, J.A., Mesgarpour, M., Potts, C.N., 2011. Airport runway scheduling. 4OR Q. J. Oper. Res. 9 (2), 115–138.

Bertsimas, D., Patterson, S.S., 1998. The air traffic flow management problem with enroute capacities. Oper. Res. 46 (3), 406–422.

Bertsimas, D., Lulli, G., Odoni, A., 2011. An integer optimization approach to large-scale air traffic flow management. Oper. Res. 59 (1), 211–227.

Bianco, L., Bielli, M., 1993. System aspects and optimization models in ATC planning. In: Bianco, L., Odoni, A. (Eds.), Large Scale Computation and Information Processing in Air Traffic Control. Springer-Verlag, Berlin, pp. 47–99.

Brinton, C.R., 1992. An implicit enumeration algorithm for arrival aircraft scheduling. In: IEEE/AIAA Digital Avionics Systems Conference, 11, 1992, Piscataway. Proceedings.... IEEE, New York.

D'Ariano, A., D'Urgolo, P., Pacciarelli, D., Pranzo, M., 2010. Optimal sequencing of aircrafts take-off and landing at a busy airport. In: International IEEE Annual Conference on Intelligent Transportation Systems, 13, 2010, Madeira Island. Proceedings.... IEEE, New York.

D'Ariano, A., Pistelli, M., Pacciarelli, D., 2012. Aircraft retiming and rerouting in vicinity of airports. IET Intell. Transp. Syst. J. 6 (4), 433–443.

Dear, R.G., Sherif, Y.S., 1989. The dynamic scheduling of aircraft in high density terminal areas. Microelectron. Reliab. 29 (5), 743–749.

Dear, R.G., Sherif, Y.S., 1991. An algorithm for computer assisted sequencing and scheduling of terminal area operations. Transp. Res. Part A 25 (2/3), 129–139.

Dias, D.P., Müller, C., Porto, P.P., 2011. Aircraft spacing for continuous descent approach in a terminal area based on required time of arrival at a metering fix. J. Braz. Air Transp. Res. Soc. 7 (1), 25–34.

Eun, Y., Hwang, I., Bang, H., 2010. Optimal arrival flight sequencing and scheduling using discrete airborne delays. IEEE Trans. Intell. Transp. Syst. 11 (2), 359–373.

Eurocontrol, 2011. The European organization for the safety of air navigation. In: Standard Inputs for Eurocontrol Cost Benefit Analyses. Eurocontrol, Brussels, available at: <http://www.eurocontrol.int/agdl/public/standard_page/SYSconnCPDLC.html> (Last access on: June 24, 2012).

Frankovich, M., 2012. Unified optimization of traffic flow through airports. In: AGIFORS Annual Symposium, 52, 2012, Scottsdale. Proceedings.... AGIFORS, Scottsdale.

Liu, Y.-H., 2010. A genetic local search algorithm with a threshold accepting mechanism for solving the runway dependent aircraft landing problem. Optim. Lett. 5, 229–245.

Mesgarpour, M., Potts, C.N., Bennell, J.A., 2010. Models for aircraft landing optimization. In: International Conference on Research in Air Transportation, 4, 2010, Budapest. Proceedings.... ICRAT, Budapest.

Murça, M.C.R., 2013. An optimization approach for scheduling aircraft landings in a terminal area under the concept of alternative arrival routes. In: Thesis of Master in Science in Aeronautical Infrastructure Engineering, Field of Airports and Air Transportation. Aeronautics Institute of Technology, São José dos Campos.

Odoni, A.R., 1987. The flow management problem in air traffic control. In: NATO Advanced Research Workshop on Flow Control, 1987, Capri. Proceedings... NATO, Brussels.

Salehipour, A., Modarres, M., Naeni, L.M., 2013. An efficient hybrid meta-heuristic for aircraft landing problem. Comput. Oper. Res. 40, 207–2013.

Samà, M., D'Ariano, A., Pacciarelli, D., 2013. Rolling horizon approach for aircraft scheduling in the terminal control area of busy airports. Transp. Res. Part E 60, 140–155.

Saraf, A.P., Slater, G.L., 2006. An efficient combinatorial optimization algorithm for optimal scheduling of aircraft arrivals at congested airports. In: IEEE Aerospace Conference, 2006, Big Sky. Proceedings.... IEEE, New York.

Tavakkoli-Moghaddam, R., Yaghoubi-Panah, M., Radmehr, F., 2012. Scheduling the sequence of aircraft landings for a single runway using a fuzzy programming approach. J. Air Transp. Manag. 25 (1), 15–18.

Vranas, P., Bertsimas, D., Odoni, A.R., 1994. The multi-airport ground-holding problem in air traffic control. Oper. Res. 42, 249–261.

Willemain, T.R., Fan, H., Ma, H., 2004. Statistical Analysis of Intervals between Projected Airport Arrivals. Rensselaer Polytechnic Institute, Troy, NY (DSES Technical Report No. 38-04-510).

Wong, G.L., 2000. The Dynamic Planner: The Sequencer, Scheduler, and Runway Allocator for Air Traffic Control Automation. NASA, Washington, DC (NASA/TM-2000-209586).

Zhan, Z.-H., Zhang, J., Li, Y., Liu, O., Kwok, S.K., Ip, W.H., Kaynak, O., 2010. An efficient ant colony system based on receding horizon control for the aircraft arrival sequencing and scheduling problem. IEEE Trans. Intell. Transp. Syst. 11 (2), 399–412.