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Towards a decision-support tool for airport slot allocation: Application to Guarulhos (Sao Paulo, Brazil)

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ABSTRACT

In the vast majority of airports where demand exceeds capacity, landing and take-off slots are allocated according to the process established by the Worldwide Slot Guidelines (WSG). An optimization-based decision-support tool is introduced in this paper to assist slot coordinators in the initial slot allocation – the most important stage of that process. The WSG comprises both primary and additional criteria to be taken into account by slot coordinators at this stage. Considering all additional criteria specified in the WSG, this tool generates, in an acceptable amount of time, alternative efficient slot allocations against which the coordinators can evaluate the solutions obtained through the heuristic methods they apply. The decision-support tool also offers solution analysis features, such as visualization, ranking, comparison of multiple optimal solutions, and comparison of solutions regarding important characteristics not reflected in the WSG additional criteria. The tool is being tested at one of the largest airports worldwide – Guarulhos (Sao Paulo, Brazil) – with results that clearly illustrate its usefulness in practice.

1. Introduction

In the vast majority of airports in which demand significantly exceeds capacity, the allocation of slots – that is, the allocation of “permissions to use the full range of airport infrastructure necessary to arrive or depart at an airport on a specific date and time” – is performed according to IATA’s Worldwide Slot Guidelines (WSG) (IATA, 2017).¹ The number of such airports, designated in the WSG as coordinated or Level 3, is relatively small (204 in the Summer season of 2019, i.e., around 6% of the airports offering scheduled services), but the number of passengers they handle is very large (1.5 billion departing passengers, i.e., 43% of the world’s total; see IATA, 2019). Virtually all the busiest airports in the world are Level 3, with the exception of those in the United States, where the WSG are only being applied at New York’s JFK International Airport. Thus, optimizing airport slot allocation is a function of critical importance to global air transport and, more generally, to the global economy.

The slot allocation process prescribed in the WSG is conducted bi-annually (for the Winter and Summer seasons) by coordinators

appointed by the transport authorities of the respective countries, and involves several stages (see IATA, 2017; and Ribeiro et al., 2019b). The focus of this paper is on the most important stage of this process, the initial slot allocation, which takes place about five months before the beginning of each season. At this stage, the coordinators, after receiving airline requests for slots and considering the capacities declared by each airport, decide, for each request, whether it can be accepted, or needs to be displaced (and by how much) or rejected. “Displacing” a request means that the slot time assigned to the request is different from the time requested by the airline. At this stage, only series of slots – i.e., slots for the same flight on the same day of the week requested for at least five times over a season – are considered. It is important to distinguish between slot requests and series of slots. A slot request is a group of slots requested for different days of the week at the same time. Within a slot request, a series of slots corresponds to the slots requested for the same day of the week.

The coordinators are expected to perform the initial allocation of (series of) slots by applying, in a “neutral, transparent and non-discriminatory manner”, the primary and additional criteria specified

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¹ In 2019, some parts of the WSG were revised in two occasions. More recently, the WSG were replaced by the 1st edition of the Worldwide Airport Slot Guidelines – WASG (IATA, 2020), which became effective on June 1, 2020, and will be applied for the first time in the Winter season of 2020/2021. It should be noted that the WSG have been developed independently by IATA, while the WASG result from an agreement between IATA, ACI and WWACG.

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in the WSG (IATA, 2017, Sections 8.3 and 8.4). The primary criteria distinguish requests for four classes of slots to be allocated in this order: historic (“grandfathered”) slots, i.e., slots already held by an airline in the previous equivalent season (Winter or Summer) that were operated at least 80% of the time (“use-it-or-lose-it” rule); change-to-historic, i.e., historic slots for which an airline requests a change (e.g., in the flight time or aircraft type); new-entrant slots, i.e., slots requested by an airline for a day where it holds fewer than five slots; and other slots.² For each class, requests concerning year-round flights enjoy priority over other requests (IATA, 2017, Section 8.3.6). The primary criteria are straightforward to apply, but this is not the case with the additional criteria, which are used to break ties when requests in the same primary criteria class compete for the same slots. The WSG lists the following additional criteria: “effective period of operation”, “type of service and market”, “competition”, “curfews”, “requirements of the travelling public and other users”, “frequency of operation”, and “local guidelines” (IATA, 2017, Section 8.4). Detailed explanations of the additional criteria are provided in the next section.

The initial slot allocation is typically carried out by the coordinators using heuristic approaches with the support of software packages like PDC SCORE or T-Systems SAMS. These packages are certainly helpful, but do not offer optimization capabilities, and therefore may lead to slot allocation solutions that are not the most efficient possible (a solution is said to be efficient if it cannot be improved with respect to any objective without becoming worse with respect to, at least, another objective). Several models have been proposed in the literature recently that offer such capabilities (see, e.g., Zografos et al., 2012; Ribeiro et al., 2018; Zografos and Jiang, 2019; Ribeiro et al., 2019a; and Fairbrother et al., 2020). In particular, the optimization model presented in Ribeiro et al. (2018, 2019a) under the designation of Priority-based Slot Allocation Model (PSAM) has been shown through computational applications at several airports to provide slot allocations that are clearly better with respect to two key objectives than the ones coordinators have adopted (see Section 3.2.1). These objectives are the minimization of total displacement (i.e., the sum of the differences between the requested time and the allocated time for all the slots requested) and the minimization of maximum displacement (i.e., the maximum of such differences). However, these two objectives correspond to only a small subset of the additional criteria specified in the WSG.

The decision-support tool (or system) we describe in this paper is aimed to assist coordinators in the initial slot allocation stage. It is based on an extended version of PSAM that, in addition to the primary criteria, can cope with all the additional criteria that coordinators need or wish to consider, being therefore an optimization-based tool. Since the problem dealt with by coordinators is of a multi-objective nature, the tool includes solution generation, evaluation, visualization, ranking and comparison features to help them identify and analyze efficient solutions, as well as assess the solutions they develop through their heuristic approaches against those efficient solutions. In particular, the tool can support the exploration of multiple optimum slot allocation solutions (i.e., different solutions with the same optimum solution value). For the development of the tool, we have relied strongly on the collaboration of several coordinators, namely ANA (Portugal), ANAC (Brazil), BSC (Belgium), CNA (Norway), and, especially, COHOR (France). These collaborations were essential to help us better understand how coordinators use the additional criteria specified in the WSG in daily practice, and, subsequently, translate them into quantifiable objectives.

The application of the proposed tool is illustrated in this paper for the

² One of the most important changes brought about by the new WASG (IATA, 2020) relates to the primary criteria: change-to-historic, new-entrant and other slot requests will be allocated together with the same priority. Afterward, the complexity of the slot allocation process will increase because (many) more slots will have to be allocated at the same time while in the WSG they are allocated sequentially.

busiest airport in South America – Guarulhos (GRU), Sao Paulo, Brazil. In 2018, this airport was one of the world’s top-50 airports with respect to passenger and flight movements. The application examples we provide refer specifically to requests for change-to-historic slots submitted to ANAC for the Winter season of 2018/2019. In total, 80,162 such slots were requested, or approximately 50% of the total number of requests. Despite this very large number of requested slot changes (to the best of our knowledge, much larger than at any airports for which the initial slot allocation has been previously handled through optimization models), our tool has been able to provide efficient slot allocation solutions within a short amount of time (around 30 min at most for each objective or set of objectives considered).

The remainder of the paper is organized as follows. In Section 2, we focus on slot allocation objectives and, especially, on the objectives we had to incorporate into PSAM to account for the additional criteria specified in the WSG. Section 3 contains a comprehensive description of the decision-support tool and of the underlying optimization model. In particular, we describe here the methods used within the tool to generate and analyze slot allocation solutions. In Section 4, we provide detailed information on Guarulhos – in particular, information concerning the declared capacities and slot requests in the Winter season of 2018/2019. Results obtained for this airport through our decision-support tool are reported and discussed in Section 5. Finally, Section 6 concludes the article with a summary of the main features of the decision-support tool and of expected future developments.

To conclude this introductory section, we underline that the tool we have developed is not yet ready to “stand-alone”, i.e., to be used by slot coordinators in an independent way. Before this happens, we want to test it in real-life conditions. This was expected to take place last May in France for the Winter Season 2020/2021 focusing on two of the main airports under COHOR coordination (Paris Charles de Gaulle and Lyon Saint Exupéry). However, the covid-19 pandemic forced us to change our plans. Despite slot allocation issues did not disappear with the pandemic, the environment of instability and concern that currently affects the air transport industry is not ideal for this kind of experiments. Consequently, we have postponed the testing until aviation is back (or more close) to normalcy.

2. Slot allocation objectives

As stated earlier, the primary criteria specified in the WSG are straightforward to apply. But, except in the case of historic slots, there are often slot requests of the other classes (change-to-historic, new-entrant, and other), submitted by different airlines, that are in conflict with each other and compete for the same slots. The additional criteria defined in the WSG are then applied to decide which of the conflicting requests to accept and which to displace or possibly reject. These additional criteria are diverse and complex because they try to take account of the interests of the many types of aviation stakeholders (passengers, airlines, airports, residents in the vicinity of airports, etc.).

In this section, we first describe the additional criteria as stated in the WSG, then present the quantifiable objective(s) we have associated with them based on our discussions with slot coordinators, and finally compare the objectives we have selected with those that have been considered in the literature.

2.1. WSG additional criteria

The additional criteria considered in the WSG are as follows (IATA, 2017, Section 8.4)³:

³ In the new WASG, some additional criteria are modified or eliminated, and other criteria are introduced; see IATA (2020), Section 8.4.

- **“Effective period of operation:** The schedule that will be effective for a longer period of operation in the same season should have priority.”
- **“Type of service and market:** The balance of the different types of services (scheduled, charter and cargo) and markets (domestic, regional and long haul), and the development of the airport route network should be considered.”
- **“Competition:** Coordinators should try to ensure that due account is taken of competitive factors in the allocation of available slots.”
- **“Curfews:** When a curfew at one airport creates a slot problem elsewhere, priority should be given to the airline whose schedule is constrained by the curfew.”
- **“Requirements of the travelling public and other users:** Coordinators should try to ensure that the needs of the travelling public and shippers are met as far as possible.”
- **“Frequency of operation:** Higher frequency such as more flights per week should not in itself imply higher priority for slot allocation.”
- **“Local guidelines:** The coordinator must take local guidelines into account should they exist. Such guidelines should be approved by the Coordination Committee or its equivalent.”

Analyzing the criteria described above, it is evident that, at least some of them, are quite ambiguous, and thus need to be interpreted and clarified before being used in a decision-support tool like the one we introduce in this paper. As previously mentioned, we did this after discussions with slot coordinators from various countries aimed at understanding how they interpret the additional criteria and how they use them in practice. It is important to note in this respect that, while in the European Union slot allocation guidelines have been codified into a law – Regulation (EC) 793/2004 – and thus must be followed strictly, in other parts of the world the WSG are treated only as a set of recommendations and are not necessarily always applied to the letter.

2.2. Objectives to associate with criteria

We present below the objectives we have associated with the different WSG additional criteria, as well as our interpretation of each criterion.

- “Effective period of operation”

This is one of the easier criteria to interpret: priority is to be given to series of slots that are operated for a longer time (more weeks) during a season and particularly so to series that span the entire season (i.e., every week of the season). The two objectives that we have linked to this criterion are:

- o minimization of displacement of long series, e.g., series of 10 weeks or more (this objective is subsequently abbreviated to *long-series*);
 - o minimization of displacement of series that span the entire season (*whole-season-series*).
- “Type of service and market”

This criterion addresses not only the balance of the different types of services and markets, but also the development of airport route networks. The first aspect is related to the idea of distributing slot displacements fairly across services and across markets, whereas the second can be linked to the expansion of airport route networks in favor of destinations that are more profitable for airports (as long-haul and international flights generally are), or strengthen the airlines based in

airports of a given country (therefore supporting national aviation), or diversify and increase the options offered to passengers. We have associated this criterion with the following objectives:

- o maximization of inter-market fairness (*inter-market-fairness*), as measured, e.g., by the dispersion of displacements across different types of markets (domestic, regional and long haul);
- o maximization of inter-service fairness (*inter-service-fairness*), idem across different types of services (scheduled, charter and cargo). It is important to note that, in most Level 3 airports, scheduled passenger requests (J) are the predominant ones. For instance, in the Airport of Guarulhos, they have been in recent years around 95% of the total number of requests. In contrast, scheduled cargo/mail requests (F) have been near 2% and charter passenger requests (C) less than 1%.
- o minimization of maximum displacement (*maximum*), which, by making the range of displacements smaller, contributes to a more equal treatment of requests;
- o minimization of total long-haul flight displacements (*long-haul*);
- o minimization of total international flight displacements (*international*);
- o minimization of total home-carrier flight displacements (*home-carriers*);
- o minimization of total new route flight displacements (*new-route*).
- “Competition”

This criterion aims at ensuring that airlines are equitably treated, that is, some airlines are not favored to the detriment of others in slot displacement decisions. The objectives we have chosen to represent this criterion are:

- o maximization of inter-airline fairness (*inter-airline-fairness*);
- o minimization of maximum displacement (*maximum*).
- “Curfews”

This criterion favors requests that, if displaced, would eliminate flights due to curfews at the origin or destination airports. The corresponding objective we have selected is:

- o minimization of curfew-related slot displacements (*curfews*).
- “Requirements of the travelling public and other users”

This criterion focuses on users’ interests, notably those of passengers, but also those of cargo companies particularly when their activity in the airport is significant. These interests are protected if as few slots as possible are rejected (and thus the maximum number of flights is made), and if the flights with higher frequency over a season are less displaced. Since all flights do not carry the same number of passengers, it makes sense to take account of the size of aircraft in terms of seats in the allocation of slots. The protection of users’ interests can also be ensured by giving priority to slots requested for flights connecting to the most congested airports (i.e., Level-3 airports), where, in principle, flight time changes will be more difficult to accommodate. The objectives we have associated with this criterion are:

- o minimization of the number of slots rejected (slots-rejected);
- o minimization of the total displacement (total);
- o minimization of the seat displacement (seat);
- o minimization of displacement of flights between Level-3 airports (level-3).
- “Frequency of operation”

This criterion corresponds to a non-objective, since it states that priority should *not* be given to higher frequency flights (more flights per week). Thus, it is not necessary to formulate it as an objective.

- “Local guidelines”

This criterion aims to account for possible specificities of the country/airport where the slot allocation is being performed, and the corresponding objectives should be defined to capture those specificities.

2.3. Objectives addressed in the literature

In the last ten years, a significant number of articles has proposed optimization models for the initial slot allocation problem. As can be seen in Table 1, the first such models were designed for airports operated under the WSG and considered a single objective: the minimization of total displacement (Castelli et al., 2012; Pellegrini et al., 2012; Zografos et al., 2012; Corolli et al., 2014). This objective was coupled with the minimization of the maximum displacement by Jacquillat and Odoni (2015), with these authors being the first to have addressed the multi-objective nature of slot allocation problems. However, since their focus was on United States airports, the model they proposed does not consider the WSG. In following years, other objectives have been considered: minimization of the number of slots displaced (Pellegrini et al., 2017), maximization of inter-airline fairness, i.e., the displacement should be spread across all airlines in an equitable way (Jacquillat and Vaze, 2018), and minimization of the number of slots rejected (Ribeiro et al., 2018). The last one is an objective that can be relevant for busy airports unable to accommodate all slot requests within reasonable time limits. Maximization of satisfaction of airlines' preferences is another of the objectives considered in the literature (Fairbrother et al., 2020). Several other articles dealing with slot allocation optimization models have focused on one of the previous objectives or combinations thereof, e.g., Pyrgiotis and Odoni (2016), Benlic (2018), Androutsopoulos and Madas (2019), Ye et al. (2019), Zografos and Jiang (2019), and Androutsopoulos et al. (2020).

Table 1 shows that most of the additional criteria defined in the WSG have been addressed in the literature in one way or another. This is, in particular, the case of "requirements of travelling public and other users", "competition", and "type of service and market". With respect to the last one, we note the absence of objectives specifically related to the development of airport route networks. We also note that the "effective period of operation" has received scarce attention. In the decision-support tool we introduce in this paper, we take account of several objectives that were never considered before and that coordinators deem important in their slot allocation decisions.

3. Decision-support tool

This section presents the optimization-based decision-support tool introduced in this paper. It begins with a brief overview of the tool, and then provides details about its two modules.

We use the term decision-support to characterize our tool in accordance with the classical definition of Sprague (1980): it combines the use of models or analytic techniques with traditional data access and retrieval functions, focuses on features that facilitate utilization by non-computer-proficient people in an interactive mode, and can easily accommodate changes in the environment and the decision making approach of its users. Several other decision-support tools aimed for the aviation industry have been presented in the scientific literature through the years. Most of these tools were designed in response to the needs of airlines, and cover areas as diverse as flight cancellation management (Jarrah et al., 1993), aircraft maintenance planning (Chiu et al., 2004), crew planning (Freling et al., 2004), supplier selection (Chan et al., 2007), schedule recovery (Abdelghany et al., 2008), and flight delays prediction (Dey et al., 2011). With respect to airports, the tools described in the literature apply to airport terminal design (Foster et al., 1995), airport expansion planning (Vreeker et al., 2002), airport strategic planning (Stamatopoulos et al., 2004), and airport terminal performance analysis (Manataki and Zografos, 2009). To the best of our knowledge, a decision-support tool for airport slot allocation (optimization-based or not) has never been presented before in the literature.

Table 1
Slot allocation objectives addressed in the literature.

Authors	Year	Objectives addressed	WSG	WSG corresponding criterion
Castelli, Pellegrini, & Pesenti	2012	Minimization of total displacement	Yes	"Requirements of travelling public and other users"
Pellegrini, Castelli, & Pesenti	2012	Minimization of total displacement	Yes	"Requirements of travelling public and other users"
Zografos, Salouras, & Madas	2012	Minimization of total displacement	Yes	"Requirements of travelling public and other users"
Corolli, Lulli, & Ntaimo	2014	Minimization of total displacement	Yes	"Requirements of travelling public and other users"
Jacquillat, & Odoni	2015	Minimization of maximum displacement Minimization of total displacement	No	"Type of service and market"; "Competition" "Requirements of travelling public and other users"
Pyrgiotis, & Odoni	2016	Minimization of maximum displacement Minimization of total displacement	No	"Type of service and market"; "Competition" "Requirements of travelling public and other users"
Pellegrini, Bolić, Castelli, & Pesenti	2017	Minimization of number of slots displaced	Yes	–
Benlic	2018	Minimization of total displacement	Yes	"Requirements of travelling public and other users"
Jacquillat, & Vaze	2018	Minimization of maximum displacement Minimization of total displacement Maximization of inter-airline fairness	No	"Type of service and market"; "Competition" "Requirements of travelling public and other users" "Competition"
Ribeiro, Jacquillat, Antunes, Odoni, & Pita	2018	Minimization of total displacement Minimization of maximum displacement Minimization of number of slots displaced Minimization of number of slots rejected	Yes	"Requirements of travelling public and other users" "Type of service and market"; "Competition" – "Requirements of travelling public and other users"
Ye, Li, Bai, & Zheng	2019	Minimization of total displacement	Yes	"Requirements of travelling public and other users"
Zografos, & Jiang	2019	Maximization of inter-airline fairness Minimization of total displacement	Yes	"Competition" "Requirements of travelling public and other users"
Androutsopoulos, & Madas	2019	Minimization of total displacement	Yes	"Requirements of travelling public and other users"
Fairbrother, Zografos, & Glazebrook	2020	Maximization of inter-airline fairness Maximization of airlines' preferences satisfaction Minimization of total displacement	Yes	"Competition" –

(continued on next page)

Table 1 (continued)

Authors	Year	Objectives addressed	WSG	WSG corresponding criterion
Androutsopoulos, Manousakis, & Madas	2020	Minimization of total displacement Minimization of total squared displacement	Yes	“Requirements of travelling public and other users” “Requirements of travelling public and other users” “Competition”

3.1. Tool overview

The proposed decision-support tool consists of a solution generation module and a solution analysis module, as depicted schematically in Fig. 1.

The solution generation module aims at spawning a set of efficient slot allocation solutions to be used as reference by coordinators. This set is obtained by running a sequence of instances of an extended version of PSAM encompassing new slot allocation objectives, as well as year-round slot priorities. From the possible objectives we listed previously (in Section 2), we have only included in the decision-support tool the nine objectives considered to be important by the slot coordinators with whom we have talked. The remaining objectives on the list or even new ones will be added to the tool in the future according to the needs of coordinators. Most of the input data required to implement the extended PSAM are obtained from the airline slot requests. These input data are: the priority class, the start and end dates for the slots requested, the requested arrival and departure times, whether the slot is year-round or not, the days of the week the slots will be operated, the type of aircraft making the flight and respective number of seats, the last airport visited by the aircraft, and the next airport to visit. The declared capacities of the airport considered are also required. These capacities concern the runway(s), as well as, possibly, the terminals, the apron areas, and other aspects of airport operations (e.g., noise exposure limits). The output data are the efficient slot allocation solutions (that is, the time of day at which each slot is allocated) and the values of the solutions for each objective considered.

It should be noted that solving the PSAM for large airports can be time-consuming. Given that coordinators have only a couple of weeks to perform the initial slot allocation, the number of model runs must be kept under a reasonable limit. In this sense, our solution generation aim was not – and could not realistically be – to identify the entire set (known as Pareto frontier) of efficient solutions. For a multi-objective model with many objectives (and an extremely large number of decision variables), the Pareto frontier potentially consists of many millions of efficient solutions, and it would be practically impossible to find them all within the decision timeframe of slot coordinators.⁴

The solution analysis module allows visualizing and ranking the solutions considering their values, exploring multiple optima (i.e., different optimal slot allocation solutions with the same solution value), and comparing solutions at the individual slot level, for example, the number of slot request exchanges (or “swaps”) they contain, or the

⁴ Multi-objective optimization models with more than three objectives are commonly called many-objective optimization models since the mid 2000s. These models are extremely challenging, and were considered in a recent (and thorough) tutorial article as a “recent topic” on multi-objective optimization (Emmerich and Deutz, 2018). In the same article, another topic classified as recent is “optimization with costly function evaluations”; i.e., multi-objective optimization when the calculation of each efficient solution is time-consuming, which is precisely the case of slot allocation when busy airports are at stake.

requested time for a slot request versus the time allocated to it. The coordinator heuristic slot allocation solutions and the weights assigned to the different additional criteria are the input data for this module. The outputs are radar charts representing the optimal solutions, solution rankings (considering the weights for the criteria), multiple optimal solutions, and detailed comparisons between slot requests and slot allocations.

These modules are to be executed sequentially until the coordinators are satisfied with the slot allocation solutions they will communicate to airlines.

This decision-support tool relies on two different software packages for processing inputs, computing solutions and processing outputs. The inputs and outputs (slot allocations) are processed using RStudio (version 1.1.463), and the solutions to the extended PSAM are computed using GAMS/CPLEX 12.5.

3.2. Solution generation

In this subsection, we present the solution generation module of the decision-support tool. First, we describe the PSAM (Ribeiro et al., 2018), then the extensions we have added to it for incorporating year-round priorities and new slot allocation objectives, and finally the method used within the tool to generate efficient slot allocation solutions.

3.2.1. PSAM

The goal of the PSAM is to generate an optimized slot schedule. Its objective function includes four terms: “The first corresponds to the total number of slots rejected. The second indicates the maximum displacement imposed on any slot. The third quantifies the total displacement across all the flights throughout the season. The last term captures the total number of slots displaced” (Ribeiro et al., 2018). Weights are attributed to each term in order to express their relative importance. The model contains constraints to ensure that: all slots are allocated to some period (or rejected); airport declared capacities are never exceeded; and the time between two connected flights falls within the allowable limits. As previously noted, the WSG require that the priorities assigned to the various classes of slot requests (historic, change-to-historic, new-entrants and other) be respected. The model is therefore solved sequentially for each priority class. In addition to the constraints referred to above, the model includes constraints to express specific rules for some priority classes. In the case of change-to-historic slots, they can be divided into two different types according to the request code CL or CR. CL slots are allocated either at the requested slot time, when possible, or at the historic time, while CR slots may be allocated at any time between the requested and the historic slot time. When displacing two change-to-historic slots, the model ensures that the new connection time lies between the requested connection time (in the requested changes) and the historic connection time. For example, if the requested connection time between two change-to-historic connected slots is equal to 2 h and the historic connection time between these two slots is equal to 2.5 h, the model ensures that the connection time lies between 2 and 2.5 h. The WSG also require that 50% of the slots remaining after allocating historic and change-to-historic slots is allocated to new entrants, unless the number of requests for new entrants is smaller than that percentage.

As stated in the Introduction, the PSAM is able to provide slot allocations that are at least as good and often much better than the ones coordinators have implemented with respect to two key objectives (*maximum* and *total*) for airports of different sizes. This was the case with the airports of Madeira (which has a maximum declared capacity of 14 flight movements per 60 min), Porto (20), Lisbon (38) and Guarulhos (53). The improvements achieved are naturally greater for medium-size and large airports than for small airports. In the cases of Porto and Guarulhos, the benefits of using PSAM exceeded 20% both for the *total* and the *maximum* objectives when compared to the coordinator solutions, and in the former airport reached 31% with respect to the

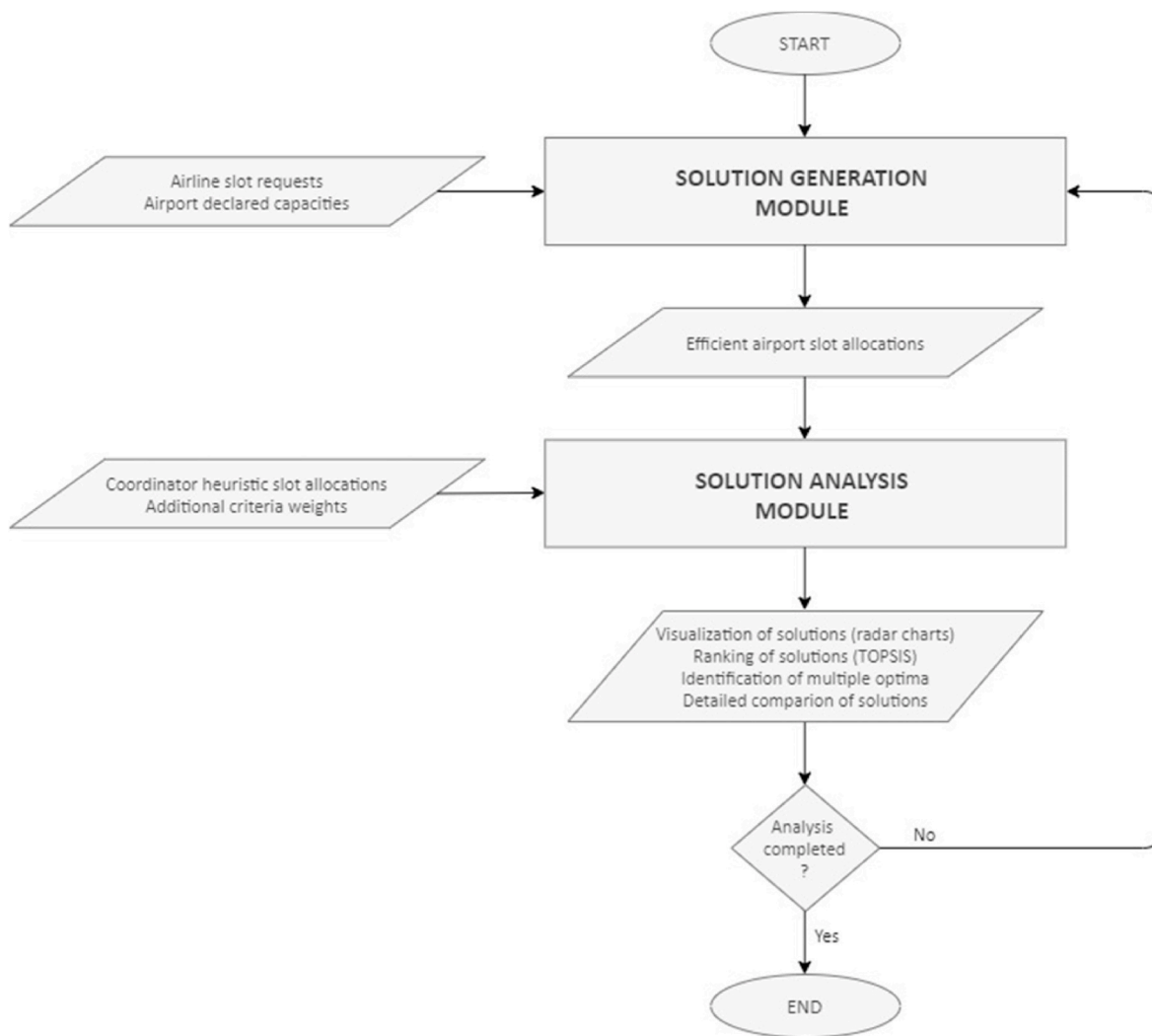


Fig. 1. Flowchart of the optimization-based decision-support tool.

maximum objective. In Lisbon, the gains of the PSAM solution over the coordinator solution were even greater. The computational times involved in each run of the PSAM ranged from only a few minutes in the small- and medium-size airports (Madeira and Porto) to several hours for Lisbon and Guarulhos.

3.2.2. PSAM extensions

The PSAM is extended here to integrate priorities for year-round slots and the additional optimization objectives, which only requires changing the objective function while keeping the same constraints.

The WSG specify that, in each slot request class, priority should be given to slots that correspond to year-round operations. In the PSAM, year-round slots priorities are not considered. Introducing this type of priority increases the number of times the model needs to be solved sequentially from four (historic, change-to-historic, new-entrants, and others) to eight (year-round historic, non-year-round historic, year-round change-to-historic, and so forth). As explained in the previous subsection, CL slots need to be allocated either at the requested slot time, when possible, or at the historic time, while CR slots need to be allocated at any time between the requested and the historic slot time. If a sequential approach were followed, then the year-round slots would be allocated first without taking into account the historic times of the remaining change-to-historic slots. This would mean that, when allocating the remaining change-to-historic slots there could be no more slots available at the historic and requested times or between these two

times, thus the problem could become infeasible. For instance, consider a CR request that is not year-round, and that was requested to take place at 8:00am, with historic time at 8:15am. If no more slots were available between 8:00am and 8:15am after the allocation of year-round change-to-historic slots, then the problem becomes infeasible because this request would be impossible to allocate between 8:00am and 8:15am. Therefore, year-round slot priorities for each class are introduced in PSAM through the use of weights. This means that a much larger weight is attributed in the objective function to year-round slot requests compared to the weight given to slots that are requested for only one of the seasons. In this way, the priority of year-round slots is respected without having to increase the number of times the model needs to be solved.⁵

⁵ The replacement of the WSG by the WASG has only two slight implications on the usability of the extended PSAM and, thus, of the proposed tool. One of them is that the extended PSAM will have to run only once to allocate slots (since there will be only one priority class other than historic slots) instead of three times. However, it is important to note that the size of the model will significantly increase, making it more challenging to solve. The fact that a fast large-scale neighborhood search metaheuristic is available for this purpose (Ribeiro et al., 2019a), make us confident that the tool will be able to handle even the busiest airports within reasonable computing effort. The other implication is that the extended PSAM may need some modifications to accommodate the moderate changes in the additional criteria considered in the WASG.

The formulation of the objectives currently considered in our decision-support tool are presented below. The formulation of the constraints is provided in [Ribeiro et al. \(2019a\)](#).

Sets

$S = \{1, \dots, S\}$ - set of slot requests, indexed by i

$D = \{1, \dots, D\}$ - set of days in the season, indexed by d

Parameters

w_1 = weight attributed to year-round slots (=10000). w_2 = weight attributed to non-year-round slots (=1)

$B_{id} = 1$ if slot request $i \in S$ is requested to operate on day $d \in D$, and 0 otherwise

$YR_i = 1$ if slot request $i \in S$ is a year-round slot, and 0 otherwise

$NYR_i = 1$ if slot request $i \in S$ is not a year-round slot, and 0 otherwise

$LS_i = 1$ if slot request $i \in S$ belongs to a long series of slots, and 0 otherwise

$WS_i = 1$ if slot request $i \in S$ belongs to a whole-season series of slots, and 0 otherwise

$LH_i = 1$ if slot request $i \in S$ corresponds to a long-haul flight, and 0 otherwise

$I_i = 1$ if slot request $i \in S$ corresponds to an international flight, and 0 otherwise

$HC_i = 1$ if slot request $i \in S$ is requested by a home carrier, and 0 otherwise

S_i = number of seats of the aircraft planned to be operated for slot request $i \in S$

$L3_i = 1$ if slot request $i \in S$ is from/to a level 3 airport, and 0 otherwise

Decision variables

X_i^+ (resp. X_i^-) = displacement of slot request $i \in S$ if rescheduled to a later (resp. earlier) slot request

$Xmax_{YR}$ = maximum displacement of year-round slots

$Xmax_{NYR}$ = maximum displacement of non-year-round slots

$Z_i = 1$ if slot request $i \in S$ is rejected, and 0 otherwise

Using this notation, the objectives considered in the decision-support tool were formulated as follows:

– Minimization of long series displacement (*long-series*)

$$\min w_1 \times \sum_{i \in S} \sum_{d \in D} B_{id} \times (X_i^+ + X_i^-) \times LS_i \times YR_i + w_2 \times \sum_{i \in S} \sum_{d \in D} B_{id} \times (X_i^+ + X_i^-) \times LS_i \times NYR_i$$

– Minimization of whole-season series displacement (*whole-season-series*)

$$\min w_1 \times \sum_{i \in S} \sum_{d \in D} B_{id} \times (X_i^+ + X_i^-) \times WS_i \times YR_i + w_2 \times \sum_{i \in S} \sum_{d \in D} B_{id} \times (X_i^+ + X_i^-) \times WS_i \times NYR_i$$

– Minimization of long-haul flights displacement (*long-haul*)

$$\min w_1 \times \sum_{i \in S} \sum_{d \in D} B_{id} \times (X_i^+ + X_i^-) \times LH_i \times YR_i + w_2 \times \sum_{i \in S} \sum_{d \in D} B_{id} \times (X_i^+ + X_i^-) \times LH_i \times NYR_i$$

– Minimization of international flights displacement (*international*)

$$\min w_1 \times \sum_{i \in S} \sum_{d \in D} B_{id} \times (X_i^+ + X_i^-) \times I_i \times YR_i + w_2 \times \sum_{i \in S} \sum_{d \in D} B_{id} \times (X_i^+ + X_i^-) \times I_i \times NYR_i$$

– Minimization of the displacement of slots requested by home carriers (*home-carriers*)

$$\min w_1 \times \sum_{i \in S} \sum_{d \in D} B_{id} \times (X_i^+ + X_i^-) \times HC_i \times YR_i + w_2 \times \sum_{i \in S} \sum_{d \in D} B_{id} \times (X_i^+ + X_i^-) \times HC_i \times NYR_i$$

– Minimization of maximum displacement (*maximum*)

$$\min w_1 \times Xmax_{YR} + w_2 \times Xmax_{NYR}$$

– Minimization of the number of slots rejected (*slots-rejected*)

$$\min w_1 \times \sum_{i \in S} \sum_{d \in D} B_{id} \times Z_i \times YR_i + w_2 \times \sum_{i \in S} \sum_{d \in D} B_{id} \times Z_i \times NYR_i$$

– Minimization of total displacement (*total*)

$$\min w_1 \times \sum_{i \in S} \sum_{d \in D} B_{id} \times (X_i^+ + X_i^-) \times YR_i + w_2 \times \sum_{i \in S} \sum_{d \in D} B_{id} \times (X_i^+ + X_i^-) \times NYR_i$$

– Minimization of seat displacement (*seat*)

$$\min w_1 \times \sum_{i \in S} \sum_{d \in D} B_{id} \times (X_i^+ + X_i^-) \times S_i \times YR_i + w_2 \times \sum_{i \in S} \sum_{d \in D} B_{id} \times (X_i^+ + X_i^-) \times S_i \times NYR_i$$

– Minimization of the displacement of flights between level-3 airports (*level-3*)

$$\min w_1 \times \sum_{i \in S} \sum_{d \in D} B_{id} \times (X_i^+ + X_i^-) \times L3_i \times YR_i + w_2 \times \sum_{i \in S} \sum_{d \in D} B_{id} \times (X_i^+ + X_i^-) \times L3_i \times NYR_i$$

In each of the previous equations, the first terms are related to the year-round slots and the second to the non-year-round slots, being both weighted according to their priority. In all the equations, but the ones related to the minimization of maximum displacement and the minimization of the number of slots rejected, the displacement ($X_i^+ + X_i^-$) is minimized by multiplying it by 1 or 0 depending on the objective under consideration. For the minimization of maximum displacement and the minimization of the number of slots rejected, the equations are similar, but instead of multiplying the displacement, the maximum displacement ($Xmax$) or the variable signaling the rejection (Z_i) are multiplied.

3.2.3. Epsilon-constraint-based method

The method used in the decision-support tool to generate efficient slot allocation solutions is based on the epsilon-constraint method ([Steuer, 1986](#); [de Weck, 2004](#); [Marler and Arora, 2004](#); [Chircop and Zammit-Mangion, 2013](#)). This is a classic method for handling a multi-objective optimization model: the model is solved sequentially for each of the objectives subject to constraints regarding the values of the other objectives. Specifically, we apply this method in the following way. First, we select the objectives considered one at a time. For each objective, we solve the model assigning a much higher weight to the objective considered than to the others, and store the optimal solution value. Through this process, as many efficient solutions as the number of objectives are generated. Next, again for each objective, we solve the model but requiring the values of the other objectives to be within a given percentage (say 5%) of their previously stored values. In this way, new efficient solutions are generated. This process can continue a number of times, until the number of efficient solutions generated is

enough to provide coordinators with a good set of alternatives against which they can compare their own solutions. Since a very large number of alternatives would make comparisons difficult, the proposed decision-support tool includes a clustering procedure to identify a smaller set of solutions representing well the full set.

3.3. Solution analysis

In this section, the solution analysis module of the decision-support tool is presented. We start by presenting the solution visualization and ranking features, then focus on the identification of multiple optimal solutions, and finish by describing the detailed solution comparison features offered by this module of the tool.

3.3.1. Solution visualization

Since a large number of efficient solutions may be generated through the procedure described in the previous section, the decision-support tool provides visualization capabilities to facilitate their analysis. A wide variety of types of plots could be chosen for this purpose, including radar charts, heat maps, parallel coordinate plots, and/or *radviz* (radial visualization) – see He and Yen (2016) and Zhen et al. (2020) for a detailed presentation and discussion of possible types of plots. After examining all alternatives, we concluded that radar charts – also known as spider or web charts among other appellations – despite some drawbacks would be the most appropriate in our case. Radar charts were first used by Georg von Mayr in 1877 (Friendly et al., 2001). They allow representing multivariate data in two-dimensional format. Each axis of the chart represents a variable; i.e., in our case, one objective. Axes are arranged radially starting from the center of the plot. A polyline is drawn to connect variable values for each solution represented in the chart. In this way, it is possible to understand how each solution performs with respect to each objective. In addition, by comparing the shapes of the polylines, it is possible to identify the solutions that perform similarly to one another.

3.3.2. Solution ranking

The analysis of the efficient solutions generated by the decision-support tool is also facilitated by its solution ranking features. Ranking the different solutions considering several evaluation objectives requires resorting to multi-criteria decision analysis (MCDA) methods. There are numerous such methods proposed in the literature, with different advantages and disadvantages, that could be used – see, e. g., Ishizaka and Nemery (2013) and Watróbski et al. (2019). Virtually, any one of the methods could have been chosen. For the moment, we have implemented only TOPSIS in the decision-support tool, but other well-known methods will also be made available in the future.

The TOPSIS method was introduced by Hwang and Yoon (1981), being further developed by Yoon (1987) and Hwang et al. (1993). It has been applied in a very wide variety of contexts (Behzadian et al., 2012). TOPSIS is based on the concept that the best alternative has the shortest Euclidean distance from a positive ideal solution (PIS) and the largest Euclidean distance from a negative ideal solution (NIS). The PIS is a (fictitious) solution characterized by the best performance for each criterion (maximum for benefit criteria and minimum for cost criteria) across all solutions. In contrast, the NIS is characterized by the worst performance for each criterion. This method is easy to explain and understand by slot coordinators (who are, in principle, unfamiliar with decision analysis methods). The main disadvantage of this method is that it does not deal properly with correlated objectives. This limitation can be overcome by using Mahalanobis distances instead of Euclidean distances (Mahalanobis, 1936; Wang and Wang, 2014). The former distances take into consideration the existence of correlations in the data and are unitless and scale-invariant.

3.3.3. Multiple optima

When an optimization model is run, the goal is to obtain the best

solution for the objective that is being optimized (or the efficient solutions, if several objectives are being considered). Nevertheless, it is possible that, for some problems, there are multiple optimal solutions for the same objective. These solutions present the same value for the objective function of the model, while the solutions themselves (i.e., the optimal values of the decision variables) are different. This means different solutions exist that lead to exactly the same value of the objective function. As an example, in the specific case of slot allocation, it is possible that, by switching a given number of slots from one solution to another solution, the same objective value is obtained.

Generally, optimization software allows searching for multiple optimal solutions of any given problem instance. The search is either made within a specified time limit or until all optimal solutions are found. In the proposed decision-support tool, the “Solution Pool” feature of CPLEX is called to generate and store multiple solutions of PSAM.

3.3.4. Detailed comparisons

The visualization and ranking features of the decision-support tool described previously allow comparing solutions with regard to the objectives considered. However, when the solutions are similar in terms of these objectives, a finer analysis and comparison of swaps of individual slot requests and of specific characteristics of slot requests may be necessary. The decision-support tool identifies the slot requests that swap among solutions, offering slot coordinators the ability to see tables describing the number of slot request swaps for each pair of solutions and other slot requests characteristics, such as requested time versus assigned time and departure and arrival airports. Figures representing how the slot requests swap between pairs of solutions are also generated by the tool. Moreover, it allows understanding the slot request swaps between solutions that happen with higher frequency. This gives slot coordinators the opportunity to identify the specific requests of slots that lead to different allocations, and thus select their preferred allocation on the basis of a very “fine-grain” analysis, when necessary. Section 5.2.4 contains several examples of these features.

4. Airport of Guarulhos

The application of the decision-support tool will be illustrated for the airport of Guarulhos (GRU), Sao Paulo, Brazil. In 2018, this airport – the busiest in South America – handled approximately 277,000 flight movements and 42.2 million passengers (GRU, 2018). It operates 24 h a day, has two runways (09 L/27R with length of 3.7 km, and 09R/27L of 3 km), and three terminals (Terminal 1 is used only for domestic flights, Terminal 2 for domestic flights and for some flights from/to other Latin America countries, and Terminal 3, the most modern one, for international flights).

Slot allocation at Guarulhos (and, more generally, in Brazil) is performed by Agência Nacional de Aviação Civil (ANAC) and regulated by Resolution 338 of July 22, 2014, with the amendments of Resolution 487 of August 22, 2018. Both resolutions have been in force since October 28, 2018. The priority rules established in these resolutions are essentially the same as those in the WSG, but they also specify three additional criteria to consider (in this order): length of the series of slots; number of aircraft seats; and on-time performance of flights in the previous corresponding season (Art. 23, Resolution 338).

In the Winter season of 2018/2019 (the season for which we illustrate the application of the decision-support tool), airport capacities were declared for the runways and the terminals (Table 2).⁶ For the runways, capacities are expressed in terms of flight movements, departures and arrivals, for intervals of 5, 15 and 60 min. For the terminals,

⁶ It should be noted that the Winter aviation season 2018/2019 corresponds to the period from October 28, 2018 to March 30, 2019, a total of 154 days. It, therefore, comprises the Summer season in Brazil, which is the busiest aviation season.

Table 2
Capacities declared by the Airport of Guarulhos.

Declared capacity indicators - Runways	
Total number of movements/60 min	53
Total number of departures/60 min	31
Total number of arrivals/60 min	31
Total number of movements/15 min	14
Total number of movements/5 min	5
Declared capacity indicators - Terminals	
Total number of passengers - International - Departures/120 min	9122
Total number of passengers - International - Arrivals/120 min	9410
Total number of passengers - Terminal 1 - Departures/120 min	2070
Total number of passengers - Terminal 1 - Arrivals/120 min	1879
Total number of passengers - Terminals 2&3 - Departures/120 min	7692
Total number of passengers - Terminals 2&3 - Arrivals/120 min	8336

they are expressed in terms of passenger arrivals and departures for an interval of 120 min separately for Terminal 1, for domestic passengers in Terminals 2 and 3 together, and for international passengers (Terminal 3). The load factor used to calculate the number of passengers corresponds to 85% of the total number of offered seats.

In Table 3, we provide descriptive statistics of the slot requests submitted to ANAC for Guarulhos. There were 3221 different requests involving 161,469 slots and 10,398 series of slots. Approximately 50% of the total number of slot requests were of the change-to-historic (CH) class. With respect to the other classes defined in the primary criteria of the WSG, the requested slots were divided into: 14% historic (H) slots, 1% new-entrant (NE) slots, and 35% other (O) slots. It is worth noting the small number of H slots. Since H slots are simply allocated to their historic time, the presence of a large number of them simplifies the slot allocation process. However, despite the small number of H slots in this case, the extended PSAM was able to perform the allocation of the CH slots for each objective (each run) in around 30 min. Of the 161,469 slots requested, 90% (145,319) belonged to long series (10 slots or more), 63% to whole-season series, and 16% were year-round slots. Almost 80% of the total number of slots were requested by the Brazilian airlines LATAM, GOL and Avianca Brasil. The remaining 20% were requested by 40 different other airlines. Slightly more than half of the slots corresponded to short-haul flights (≤ 1500 km), 35% to medium-haul flights (35%), and 13% to long-haul flights (> 4000 km). Despite their low percentage, long-haul flights are very important to the airport, which is investing significantly in expanding its long-haul network. Half of the slots requested are for flights connecting GRU with other Level 3 airports, notably CWB (Curitiba), POA (Porto Alegre), CDG (Paris Charles de Gaulle) and FCO (Rome Fiumicino).

In Figs. 2 and 3, we show the slot requests for each time interval in

Table 3
Descriptive statistics for the Airport of Guarulhos in the Winter season of 2018/2019.

No. days of the season	154	
No. requests	3221	
No. series	10398	
No. slots	161469	
No. historic slots	21716	(14%)
No. change-to-historic slots	80162	(50%)
No. new-entrants slots	2354	(1%)
No. other slots	57230	(35%)
No. year-round slots	26521	(16%)
No. airlines	43	
Most dominant airline	LATAM	(37%)
2nd most dominant airline	GOL	(21%)
3rd most dominant airline	Avianca Brasil	(21%)
No. short-haul flights (≤ 1500 kms)	82987	(51%)
No. medium-haul flights (> 1500 kms and ≤ 4000 kms)	56862	(35%)
No. long-haul flights (> 4000 kms)	21620	(14%)
No. slots between level 3 airports	80849	(50%)
No. long series slots (≥ 10 slots)	145319	(90%)
No. whole-season slots	101354	(63%)

the busiest day of the season (February 28, 2018). It can be seen that GRU faced runway capacity shortages in all the time intervals (60, 15 and 5 min) for which runway declared capacities were specified. These shortages occurred mainly between 6am and 10am and between 8pm and 11pm, with some problems in mid-afternoon (3–4pm), as well. Capacity utilization during the night is much lower. Both departure and arrival movements exceed capacity in some periods of the day (Fig. 2, right). Terminal declared capacities were never exceeded (Fig. 4). Thus, runway capacity was the main constraint at Guarulhos for the season under study.

5. Tool application

We describe in this section the results of the application of the proposed decision-support tool to the Airport of Guarulhos. To facilitate the presentation, the structure of this section parallels that of Section 3 (Subsections 3.2 and 3.3).

5.1. Solution generation

We focus on only nine solutions, obtained through the solution generation module by assigning a very high weight to one objective at a time (excluding the *slots-rejected* objective because at Guarulhos there was no need to reject slots in the season considered) and a very small weight to the others.

The solution values obtained for each of the nine objectives are displayed in Table 4 (year-round slots) and Table 5 (all slots). The latter presents the sum of the solution values for the year-round slots and the non-year-round slots, respecting the year-round priority. The values correspond to each of the objectives considered, while the bottom row shows the number of slot requests displaced (*slots-displaced*) in each solution. Minimizing *slots-displaced* is not an objective by itself, but the fewer slots that are displaced the easier it will be, in principle, to implement a slot allocation solution. We have therefore considered the number of slots displaced as a criterion for breaking possible ties between solutions with equal objective values. The solution values (columns) are designated according to the objective that was assigned the higher weight. For the different objectives (rows), the solutions with the best and the worst performance are highlighted in green and red, respectively. The second-best solution values are highlighted in light green and the third-best in yellow. With respect to year-round slots (Table 4), the different solutions generally present low displacement values for the different objectives. This is natural because these slots have higher priority and represent a small percentage of the total CH slots. When they are allocated there is still plenty of capacity available (recall that the number of historic slots at Guarulhos is small). Obviously, the best solution value for any objective is obtained when that same objective is optimized. For this reason, the best values appear in the diagonal of Tables 4 and 5. The *whole-season* objective leads to the worst solution values for most of the other objectives, and the *maximum* and *home-carriers* objectives result in the worst solution values for two of the other objectives. The remaining objectives do not lead to worst solution values for any one of the other objectives. The solution values for the *long-haul* objective are very similar to those of the *international* objective, but the number of *slots-displaced* is greater for *long-haul*. The *long-series* objective results in second-best solution values for *total*, *whole-season-series* and *home-carriers*, and to third-best for *maximum*, *seat* and *slots-displaced*.

Choosing the slot allocation solution to implement based on Table 5 is not an easy task, even considering the second-best values (light green) and the third-best values (yellow). Indeed, some solutions perform well with respect to some objectives, but not so well or poorly with respect to others. Moreover, the differences between the first- and the second-best solution values, the second- and the third-best, and so on, are not constant. As an example, the difference between the first-best solution value and the second-best in terms of the *maximum* displacement is equal to

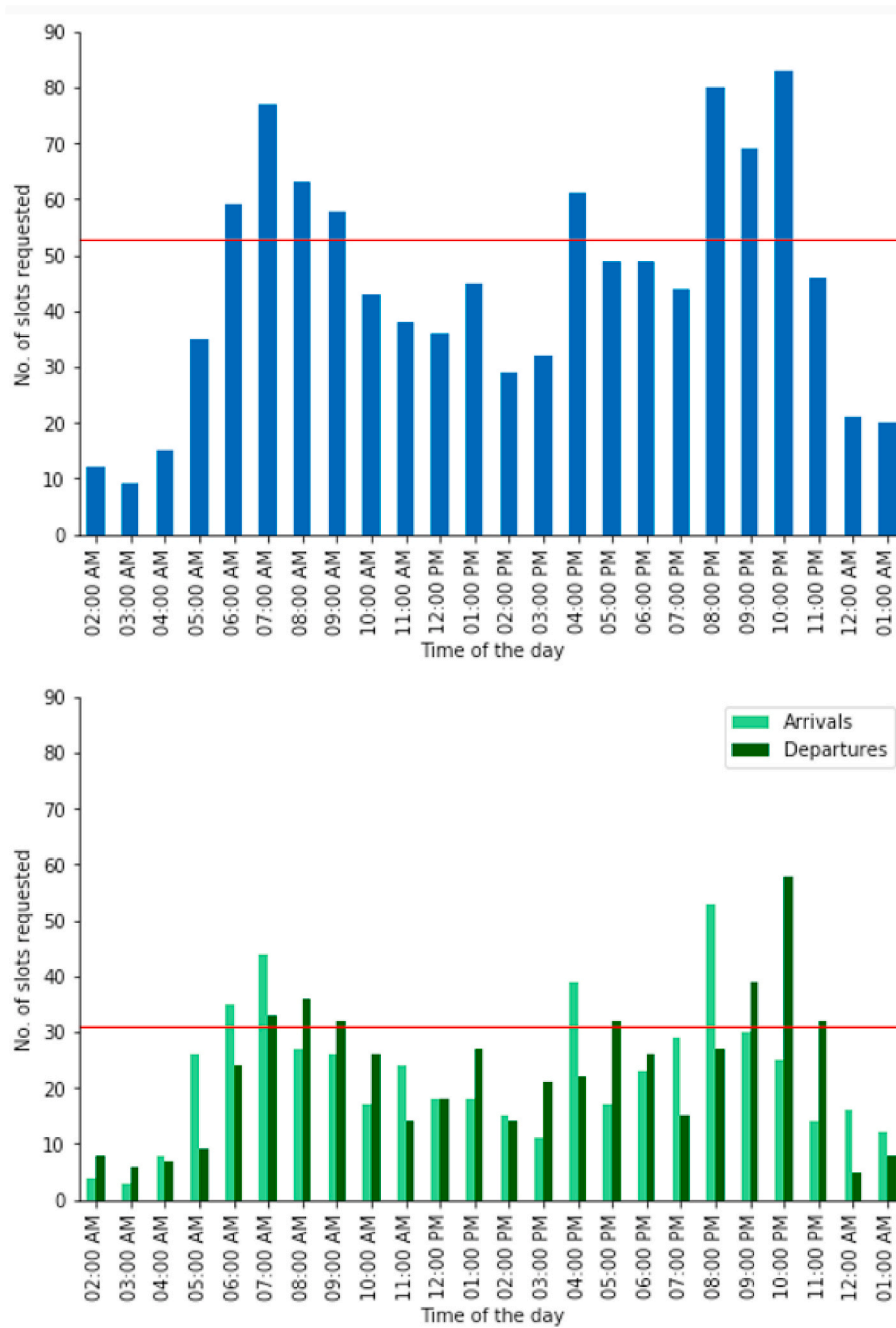


Fig. 2. Total number of hourly slots requests (top) and of arrival and departure slots (bottom) at the Airport of Guarulhos in the Winter season of 2018/2019.

65 min, while the difference between the second-best and the third-best is just 5 min.

5.2. Solution analysis

This subsection is divided into four different parts, corresponding to solution visualization, solution ranking, multiple optima and detailed comparisons as in Subsection 3.3.

5.2.1. Solution visualization

In order to facilitate the analysis and comparison of solutions, the decision-support tool provides radar charts like the one displayed in Fig. 5. In this figure, the polylines represent the solutions obtained when each objective is optimized, as well as the solution adopted by ANAC (coordinator). The positions of their vertices correspond to the values of

the solutions considering the different objectives under analysis normalized between 1 (best solution found) and 0 (worst) using min-max normalization (Marler and Arora, 2005). It may not be easy to understand the relative performance of the solutions through this chart because, in some cases, the polylines are very close to each other and partially or completely overlap, but it is very easy to observe the similarity of solutions. For instance, it can be seen that the *total* and *long-series* solutions are similar, which happens because long series of slots are a high percentage of all CH slots (90%). The *international* and *long-haul* solutions are also similar, which could be expected because most international flights are long-haul flights, while the *level-3* and *seat* solutions are quite different. Moreover, it can be concluded that the coordinator's solution (black triangle) is not efficient, being outperformed in all respects by several other solutions. This solution is represented by a triangle because it corresponds to the worst performance (equal to

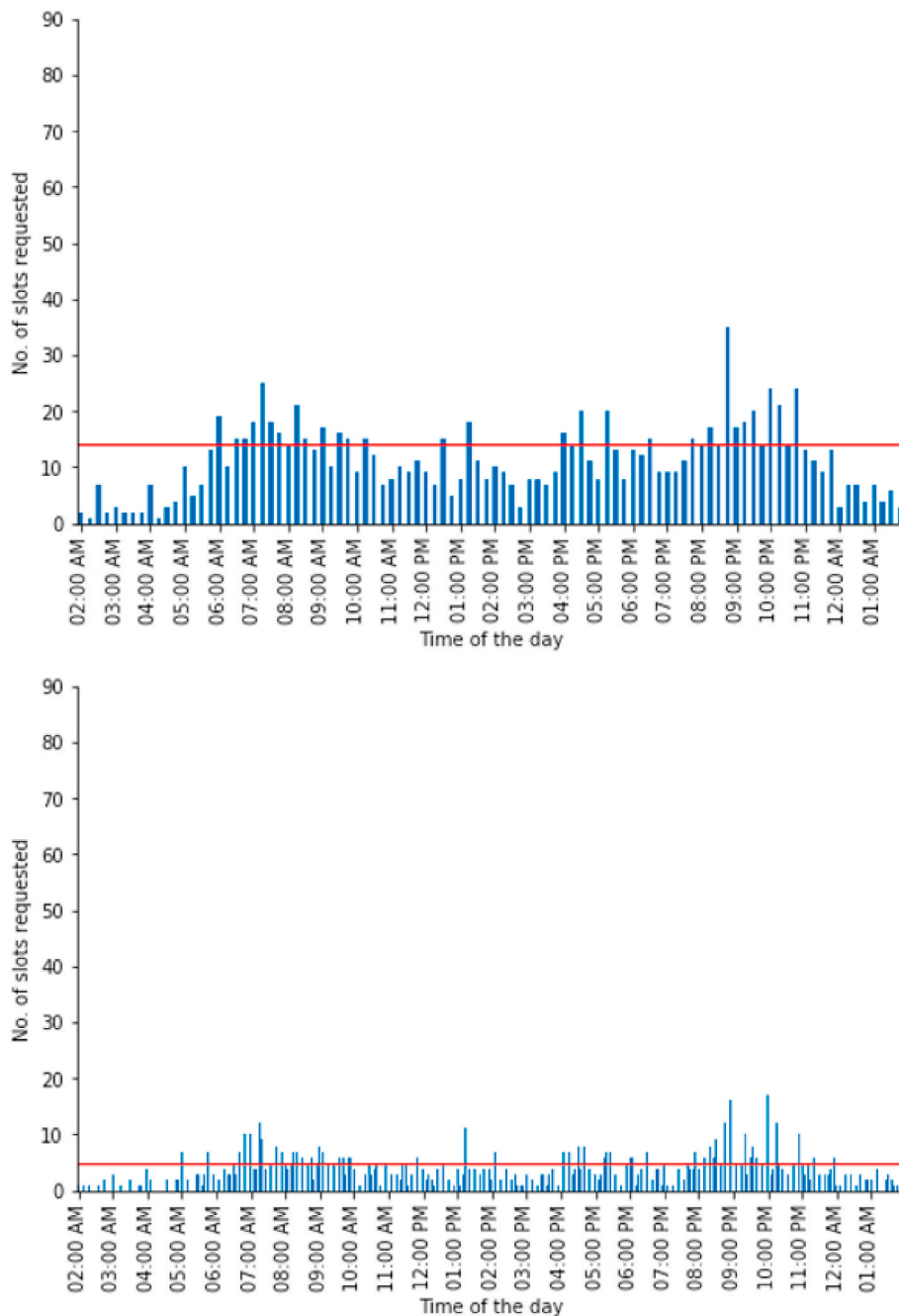


Fig. 3. Total number of slots requested per 15 min (top) and 5 min (bottom) at the Airport of Guarulhos in the Winter season of 2018/2019.

0 after normalization) for most of the objectives – *long-series*, *whole-season-series*, *home-carriers*, *maximum*, *total*, *seat*, and *level-3* – as well as for *slots-displaced*.

5.2.2. Solution rankings

For ranking solutions, the (current version of the) decision-support tool resorts to the TOPSIS method. In this case, we have 9 different solutions to evaluate and 10 objectives against which to perform the evaluation. The TOPSIS method requires the definition of a weight for each objective, to be defined by the slot coordinators according to the priorities they think each objective should have. Weights should be proportional to the priority attributed to each of them.

In order to illustrate how TOPSIS can be used and the type of results it provides, two different sets of weights (priorities) are considered:

- 1) The weight for every objective is the same; i.e., 1/10 (total equal to 1).
- 2) The weight for the objectives most frequently considered in the literature – *maximum* and *total* – is twice the weight for the other objectives; i.e., 1/6 vs. 1/12 (total equal to 1).

The application of the TOPSIS method with the set of weights indicated above using both Euclidean and Mahalanobis distances leads to the solution rankings presented in Table 6.

Considering the Euclidean-distance-based rankings, the optimal solutions for the objectives *international*, *long-haul* and *seat* occupy the top-3 positions of the rankings in the same order under both sets of weights. The *total* and *maximum* solutions appear in the fourth and fifth position for weights (1), and in reverse order when weights (2) are applied. The last four positions of the rankings are occupied by the same four

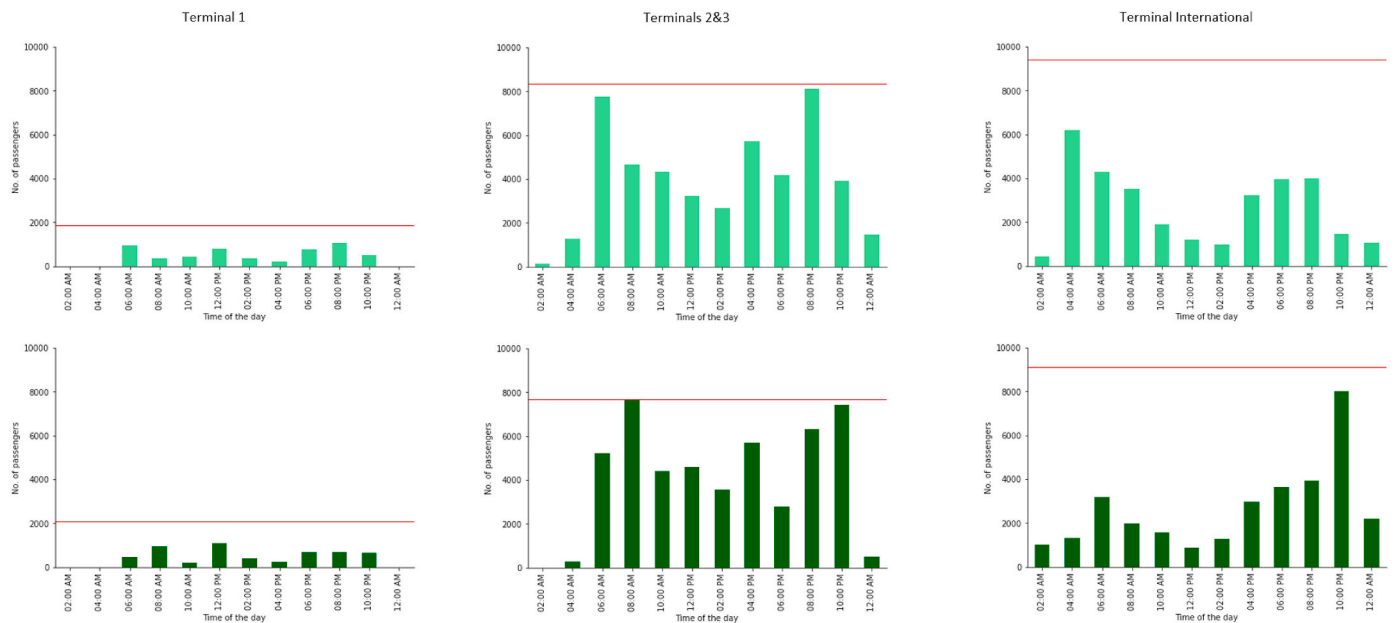


Fig. 4. Total number of arrival passengers (top) and departing passengers (bottom) per terminal (2 h) at the Airport of Guarulhos in the Winter season of 2018/2019.

Table 4
Value of the nine solutions under analysis for year-round slot requests.

Objectives	Solution values (displacement in minutes)								
	maximum	total	seat	long-series	whole-season-series	international	long-haul	level-3	home-carriers
maximum	5	5	5	5	5	5	5	5	5
total	1805	595	595	595	595	1155	1155	690	595
seat	330270	105210	105210	105210	105210	214830	214830	122880	105210
long-series	1595	385	385	385	385	1155	1155	480	385
whole-season-series	1210	0	0	0	0	770	770	0	0
international	210	210	210	210	210	0	0	210	210
long-haul	210	210	210	210	210	0	0	210	210
level-3	825	385	385	385	385	385	385	0	385
home-carriers	1595	385	385	385	385	1155	1155	480	385
slots-displaced	361	119	119	119	119	231	231	138	119

Table 5
Value of the nine solutions under analysis for year-round and non-year-round slot requests.

Objectives	Solution values (displacement in minutes)								
	maximum	total	seat	long-series	whole-season-series	international	long-haul	level-3	home-carriers
maximum	85	155	155	155	185	155	155	150	155
total	356750	315830	326855	319790	406715	363155	351130	378460	329385
seat	64816135	58083655	56451200	59351855	73624025	61454015	60411075	69119720	63719505
long-series	332270	287825	296960	282570	349230	334170	326755	342805	285635
whole-season-series	214940	163350	161590	144320	78650	188870	193930	206690	148720
international	43940	45780	24915	51840	58550	5280	18910	64355	73585
long-haul	32990	32690	16485	38450	47820	4050	3360	51365	58435
level-3	197100	162080	170200	173330	242710	211665	190455	91755	167725
home-carriers	332160	288570	314360	288290	364105	361120	345285	352865	273140
slots-displaced	18378	16906	16604	16548	16471	15896	17085	17506	16946

solutions (objectives): *long-series* occupies the 6th position in both rankings while the other three solutions switch positions among them. In the ranking calculated with the weights defined in (1), the last position is occupied by the *home-carriers* solution, while the *whole-season-series* solution is in the last position of the ranking calculated with the weights

defined in (2). The similarity of both Euclidean-distance-based rankings (with different weights) indicates that the results are quite consistent when the weights change slightly, and that only substantial variations of the weights will lead to significant modifications of the solutions' positions.

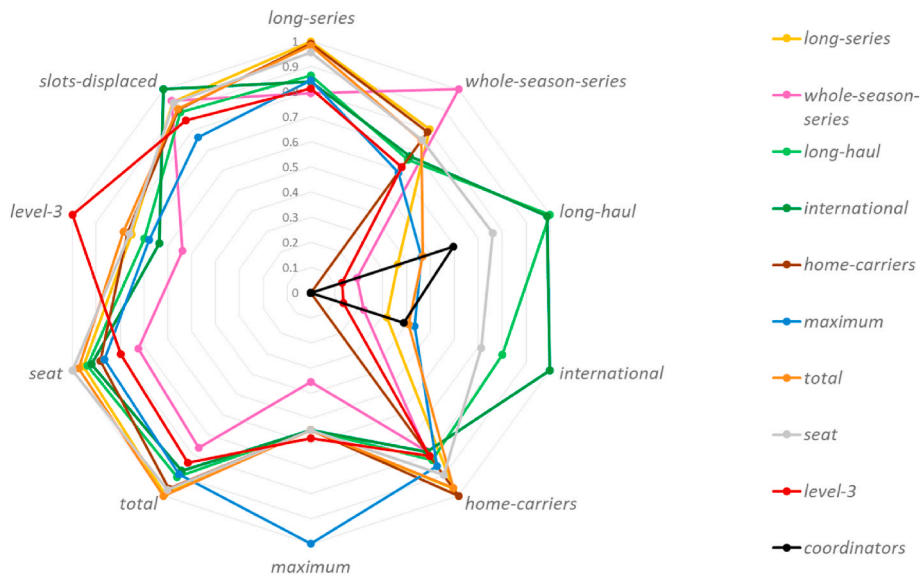


Fig. 5. Radar chart of the nine solutions.

Table 6
TOPSIS scores and rankings for two different sets of weights.

Solution	Same weight for all objectives		Double weight for <i>maximum</i> and <i>total</i> objectives	
	Euclidean	Mahalanobis	Euclidean	Mahalanobis
	TOPSIS score (rank)	TOPSIS score (rank)	TOPSIS score (rank)	TOPSIS score (rank)
<i>long-series</i>	0.4003 (6)	0.3139 (2)	0.4019 (6)	0.3379 (2)
<i>whole-season-series</i>	0.3109 (7)	0.2948 (5)	0.2783 (9)	0.3153 (5)
<i>long-haul</i>	0.6459 (2)	0.2937 (6)	0.5971 (2)	0.3131 (6)
<i>international</i>	0.6579 (1)	0.2877 (8)	0.6087 (1)	0.3073 (7)
<i>home-carriers</i>	0.2533 (9)	0.2896 (7)	0.2789 (8)	0.3067 (8)
<i>Maximum</i>	0.4350 (5)	0.2987 (3)	0.5170 (4)	0.3198 (3)
<i>Total</i>	0.4559 (4)	0.2697 (9)	0.4469 (5)	0.2899 (9)
<i>Seat</i>	0.6325 (3)	0.3227 (1)	0.5821 (3)	0.3443 (1)
<i>level-3</i>	0.3093 (8)	0.2983 (4)	0.3147 (7)	0.3191 (4)
<i>Coordinators</i>	–	–	–	–

When the rankings are based on the Mahalanobis distance, the top-3 positions are occupied by the *seat*, *long-series*, and *maximum* solutions in this order regardless of whether weights (1) or (2) are used. The conclusion is that, when correlations among objectives are taken into account, the ranking of solutions can change radically with respect to when they are not.

5.2.3. Multiple optima

With the objective of illustrating this particular functionality of the tool, we chose one of the objectives, the minimization of international flight displacements (*international*), and let the “Solution Pool” feature of CPLEX run for three days. Over this period of time, 23 optimal solutions

Table 7
Solution values for the six efficient solutions.

Solutions	Solution values (displacement in minutes)									
	long-series	whole-season-series	long-haul	international	home-carriers	maximum	total	seat	level-3	slots-displaced
1	334140	188760	4050	5280	361120	155	363155	61518255	205015	15806
2	334140	188760	4050	5280	361120	155	363155	61492955	213415	15918
3	334140	188760	4050	5280	361120	155	363155	61492955	214745	15764
4	334140	188760	4050	5280	361120	155	363155	61435755	216175	15764
5	334140	188760	4050	5280	361120	155	363155	61443675	215515	15764
6	334140	188760	4050	5280	361120	155	363155	61518255	205015	15806

with the same value were found. However, 17 of these solutions were not efficient, being dominated by at least one of the remaining six solutions (i.e., they were not better than any of these six solutions in terms of any objectives, and were worse than at least one of them with respect to at least one of the objectives). The six efficient alternative slot allocation solutions are described in Table 7 (where solutions are numbered according to the order in which they were found). As expected, the *international* objective has the same value for all solutions. The same happens for the *long-series*, *whole-season-series*, *long-haul*, *home-carriers*, *maximum*, and *total* objectives. In contrast, some solution values change with respect to the *seat*, *level-3* and *slots-displaced* objectives.

5.2.4. Detailed comparisons

We now illustrate, for the six efficient solutions identified in the previous subsection, the features included in the decision-support tool that provide coordinators with the capability of performing detailed comparisons between pairs of solutions.

The first feature is a symmetric matrix showing the number of slot requests whose allocation differs between pairs of solutions; i.e., the number of slot requests that must be exchanged (swapped) in order to transform one of the solutions in the pair into the other solution (Table 8). The swaps may be “direct” or “circular”. A direct swap between two requests, A and B, simply moves A to the slot time assigned to B and vice versa. A circular swap, on the other hand, means that requests exchange slot times sequentially – a “musical chairs” effect. In the matrix shown in Table 9, each solution appears both in the rows and the columns. All the values in the diagonal of the table are equal to 0, because each solution is compared to itself. The color scale varies between red and green with yellow in between. Shades of red represent more differences between two solutions, while shades of green represent fewer. For example, when Solution 1 is compared with Solution 6, only two

Table 8
Number of slot requests swaps across pairs of the six efficient solutions.

Solution	1	2	3	4	5	6
1	0	6	10	16	13	2
2	-	0	5	11	8	5
3	-	-	0	7	4	8
4	-	-	-	0	3	14
5	-	-	-	-	0	11
6	-	-	-	-	-	0

requests of slots swap their times, whereas 16 requests swap times when Solutions 1 and 4 are compared. In this sense, Solutions 1 and 6 are much more similar to each other than Solutions 1 and 4. Note that each set of swaps consists of a combination of direct and circular stops. For instance, a set of five swaps may consist of one direct swap and one circular swap involving three requests or of a single circular swap involving five requests.

In Table 9, we identify the 16 slot requests that swap across the pairs of the 6 solutions under analysis, which correspond to only 0.5% of the total 3221 CH slot requests that were received at ANAC for Guarulhos. Table 9 specifies characteristics of each of the 16 requests (*long-series, whole-season series, etc.*) as well as provides some additional information about them, namely: the previous or next airport visited by the aircraft for arrivals and departures, respectively; the number of days for which the request is made; and the time of the day for which the slot is requested. The “request ID” is the unique identifier of each request.

For every pair of solutions, the decision support tool allows analyzing how exactly the slot requests swap. This is illustrated in Fig. 6 for three different pairs of solutions. Comparing Solution 1 with Solution 6, there is only one direct swap between two slot requests (416 and 433), with identical characteristics in every respect (Table 9). These two requests can obviously be exchanged no matter which slot allocation is adopted. Between Solutions 2 and 6, the number of swaps is more significant. There are five slot requests swapping between allocations: one direct swap between slot requests 647 and 2289 and a cycle with three slot requests (433 swaps with 418, 418 with 1989, and 1989 with 433). In this case, the changes involve slot request characteristics associated with two of the objectives (*seats and level-3*) and flight movements (arrival/departure). Both changes can be considered in detail by coordinators using Tables 7 and 9. The third pair of solutions compared in Fig. 6 (Solutions 5 and 6) involves eleven swaps of slot requests and combines

two direct swaps with two cycles of swaps, one involving three requests and the other four.

The tool also allows slot coordinators to identify groups of slot requests that swap between each other across most pairs of the solutions generated. Considering just the pairs compared in Fig. 6, it can be observed that slot request 647 swaps with slot request 2289 for both the pair of solutions 2 and 6 and the pair 5 and 6. Similarly, 418 and 1989 appear in two different circular swaps. This suggests that slot requests 418, 647, 1989 and 2289 may constitute a group of good candidates for swaps across multiple solutions.

The decision-support tool also allows the construction of tables, such as Table 10, that facilitate the task of exploring in more detail the impact of alternative swaps between allocation solutions. The table refers to the 16 requests whose characteristics are described in Table 9.

Table 10 lists the requested times and allocated times for the slot requests that were allocated to different times than requested across the six efficient solutions described in Table 7. The color scale varies between shades of green when the displacement is small and shades of red when it is large. As far as differences between the requested times and the allocated times are concerned, a solution is better the more shades of green cells and the less shades of red it has. According to the TOPSIS method, Solutions 1 and 6 are the best. The two solutions are identical, except for the allocation of slot requests 416 and 433. Both of these requests are for the same time (07:15), but 416 is allocated at 08:05 and 433 at 09:20 in Solution 1, while exactly the reverse happens with Solution 6. While the two solutions, 1 and 6, may be ranked as equal according to the TOPSIS method, it is quite possible that coordinators may

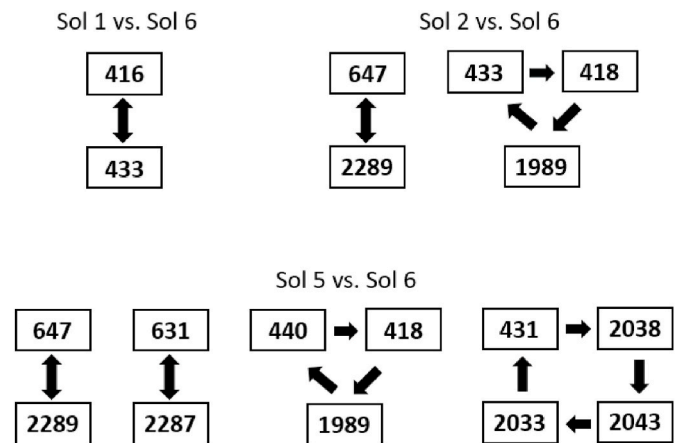


Fig. 6. Examples of slot requests swaps.

Table 9
Slot requests that swap across pairs of the six efficient solutions.

request ID	flight movement	previous/next airport	long-series	whole-season-series	long-haul	international	home-carriers	seats	level-3	days (season)	requested time
416	arrival	POA	1	0	0	0	1	162	1	112	7:15
418	arrival	CNF	1	0	0	0	1	162	0	112	7:40
431	arrival	GYN	1	1	0	0	1	162	1	154	20:30
433	arrival	SSA	1	0	0	0	1	162	1	112	7:15
440	arrival	NAT	1	0	0	0	1	162	0	112	7:25
631	arrival	CGB	1	1	0	0	1	174	1	110	20:45
647	arrival	REC	1	1	0	0	1	174	1	110	13:15
727	arrival	IMP	1	1	0	0	1	174	0	132	6:00
1989	departure	FOR	1	0	0	0	1	162	1	112	8:00
2033	departure	GIG	1	1	0	0	1	186	0	154	20:30
2038	departure	REC	1	1	0	0	1	162	1	154	21:20
2043	departure	NAT	1	1	0	0	1	162	0	154	21:25
2217	departure	POA	1	1	0	0	1	162	1	44	6:00
2287	departure	CWB	1	1	0	0	1	118	1	110	20:25
2289	departure	REC	1	1	0	0	1	220	1	110	13:15
2453	departure	POA	1	1	0	0	1	162	1	88	6:00

Table 10
Requested time vs. allocated time for slot requests that swap across pairs of the six efficient solutions.

request ID	requested time	Solution											
		#1		#2		#3		#4		#5		#6	
		displac.	allocated time	displac.	allocated time	displac.	allocated time	displac.	allocated time	displac.	allocated time	displac.	allocated time
416	7:15	0:50	8:05	2:05	9:20	2:05	9:20	2:05	9:20	2:05	9:20	2:05	9:20
418	7:40	1:40	9:20	0:25	8:05	0:25	8:05	0:25	8:05	0:25	8:05	1:40	9:20
431	20:30	0:15	20:15	0:15	20:15	0:00	20:30	0:05	20:25	0:05	20:25	0:15	20:15
433	7:15	2:05	9:20	0:45	8:00	0:50	8:05	0:50	8:05	0:50	8:05	0:50	8:05
440	7:25	0:40	8:05	0:40	8:05	0:35	8:00	0:35	8:00	0:35	8:00	0:40	8:05
631	20:45	0:35	20:10	0:35	20:10	0:35	20:10	0:30	20:15	0:30	20:15	0:35	20:10
647	13:15	0:00	13:15	0:05	13:10	0:05	13:10	0:05	13:10	0:05	13:10	0:00	13:15
727	6:00	0:05	6:05	0:05	6:05	0:05	6:05	0:00	6:00	0:05	6:05	0:05	6:05
1989	8:00	0:00	8:00	1:20	9:20	1:20	9:20	1:20	9:20	1:20	9:20	0:00	8:00
2033	20:30	0:05	20:25	0:05	20:25	0:05	20:25	0:00	20:30	0:00	20:30	0:05	20:25
2038	21:20	0:45	20:35	0:45	20:35	1:05	20:15	1:05	20:15	1:05	20:15	0:45	20:35
2043	21:25	0:55	20:30	0:55	20:30	0:50	20:35	0:50	20:35	0:50	20:35	0:55	20:30
2217	6:00	0:00	6:00	0:00	6:00	0:00	6:00	0:05	6:05	0:00	6:00	0:00	6:00
2287	20:25	0:10	20:15	0:10	20:15	0:10	20:15	0:15	20:10	0:15	20:10	0:10	20:15
2289	13:15	0:05	13:10	0:00	13:15	0:00	13:15	0:00	13:15	0:00	13:15	0:05	13:10
2453	6:00	0:00	6:00	0:00	6:00	0:00	6:00	0:05	6:05	0:00	6:00	0:00	6:00

Note: displac. = displacement

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prefer one over the other. For instance, if flights corresponding to request 433 will be bringing in many passengers who will be connecting to subsequent flights and 416 does not, then the coordinators may prefer Solution 6 that gives an earlier arrival time to request 433. A second example is offered by a comparison between Solutions 2 and 3. As Table 7 indicates, the two solutions have the same values for all the objectives except for *level-3* and *slots-displaced*. These are but two examples in which a detailed evaluation of the solutions, down to the level of individual slot requests and swaps, may be important. Such evaluations are facilitated by our optimization-based tool, making the slot coordinator’s task easier.

6. Conclusion

The decision-support tool described in this paper is aimed to assist slot coordinators in the difficult task of performing the initial slot allocation at Level 3 airports. The tool is based on PSAM, an optimization model that fully complies with IATA’s World Slot Guidelines (WSG) primary criteria. This model was augmented with the objectives corresponding to the additional criteria specified in the WSG that several coordinators considered to be the most important in practice, and was changed to handle year-round priorities. In the future, it can be augmented with other objectives, as well as with solution generation and analysis features, if and when necessary. The results that can be derived through the application of the tool were illustrated for the airport of Guarulhos, Sao Paulo (Brazil). This is, up to now, the busiest airport for which slot allocation was dealt with through optimization models.

The kind of tool we propose does not exist today, and we believe its application will contribute substantially to facilitate the task of coordinators at making more informed decisions. It will also help them at better explaining their decisions. In particular, we highlight the tool’s capabilities to analyze slot allocation solutions in detail. The literature on slot allocation optimization models has focused on solution values (in terms of, e.g., the total displacement of allocated slots vs. requested slots and/or the maximum displacement), but never, to our best knowledge, on the solutions themselves. As we have shown for Guarulhos, there are many solutions for which the solution value is exactly the same, and the coordinators should not choose one over the others in an arbitrary manner. With the tool, they can quickly compare solutions (with the same solution value or a different one) with respect to several issues that

can be important for their decisions.

Finally, we recall that the tool is not yet ready to be used by slot coordinators in an independent way. Despite we have already shown it to some coordinators and received a positive feedback, we want to test it in real-life conditions, to understand whether coordinators can use it on their own and, based on their reactions, to make the user interface more friendly. As already said, this testing was planned to take place in May 2020, but we had to postpone it. Indeed, it would not make much sense to rely on tests performed in a context as abnormal as the one the air transport industry is currently going through due to the covid-19 pandemic.

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